

## **Annotated Bibliography of Urban Wet Weather Flow Literature from 1996 through 2006**

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## Abstract

This paper is a compilation of urban wet weather flow (WWF) literature reviews for the eleven years from 1996 through 2006. This subject, urban wet-weather flows, is comprised of three basic subareas – combined-sewer overflows (CSOs), sanitary-sewer overflows (SSOs), and stormwater discharges. The following therefore includes literature citations and reviews for each of these main subareas.

These reviews were originally published in the annual literature review issues of *Water Environment Research*. Many of these citations have been expanded since the initial publications. Over this eleven year period of time, many people were involved in preparing these urban wet weather flow reviews, associated with several universities and with the EPA’s Wet-Weather Flow Research Program. See the acknowledgements section for the complete list of contributors. This paper reorganizes and combines these individual reviews into a single document for easier use. Over this eleven year period, the field of urban wet weather flow research has expanded dramatically, mostly due to increased interest in the US because of the NPDES stormwater permit program, plus increased awareness of the seriousness of urban WWFs throughout the world. More than 6,000 references are included in this compiled review, indicating the magnitude of interest in this topic. In addition, the number of references for any year generally greatly increased compared to the previous year. Another indication of the increasing interest in urban WWFs is the large number of specialized stormwater conferences that are now scheduled each year, plus the increasing number of wet weather flow sessions at large international conferences.

The major proceedings related to wet-weather flow (WWF) published during 2006 are included in this literature review are the following: (1) WEFTEC 2006, 79th Annual Conference and Exposition (WEF, 2006); (2) Intelligent Modeling of Urban Water Systems, Monograph 14 (CHI, 2006); and (3) World Environmental and Water Resources Congress of ASCE/EWRI (EWRI, 2006). The proceedings from these conferences are not indexed in the databases used to compile this literature review. The reader is directed to the respective organizations that sponsored the conference to locate additional papers related to this topic. In addition to the conferences listed above, the 2006 Annual Conference of the American Water Resources Association had several sessions that contained presentations concerning wet-weather flows. However, no paper proceedings were published and these presentations are therefore not included in this literature review.

Major conference proceedings related to wet-weather flows (WWF) published during 2005 included: (1) WEFTEC 2005, 78th Annual Conference and Exposition (WEF, 2005); (2) Effective Modeling of Urban Stormwater Systems, Monograph 13 (CHI, 2005); and (3) 2005 Watershed Management Conference - Managing Watersheds for Human and Natural Impacts (EWRI, 2005). In addition to the conferences listed above, the 2005 Annual Conference of the American Water Resources Association, EWRI’s World Environment and Water Resources Congress the 10<sup>th</sup> International Conference on Urban Drainage had significant sessions on wet-weather flows. In addition, many regional conferences also had significant sessions on wet-weather flow issues, such as the 2005 Pennsylvania Stormwater Management Symposium.

Major proceedings related to WWFs published during 2004 were: (1) WEFTEC 2004, 77th Annual Conference and Exposition (WEF, 2004); (2) Innovative Modeling of Urban Stormwater Systems, Monograph 12 (CHI 2004); (3) Watersheds 2004 Conference (WEF 2004); and (4) World Water and Environment Congress of ASCE/EWRI (EWRI 2004). In addition to the conferences listed above, the 2004 Annual Conference of the American Water Resources Association and the Low-Impact Development Conference had significant sessions on wet-weather flows.

Major proceedings related to WWF published during 2003 included: (1) WEFTEC, 2003, 76th Annual Conference and Exposition (WEF 2003); (2) Best Modeling Practices for Urban Water Systems, Monograph 11 (CHI, 2003); (3) WEF/CWEA Collection Systems, 2003 Conference (WEF, 2003); (4) 9<sup>th</sup> Annual Industrial Wastes Technical and Regulatory Conference (WEF, 2003); and (5), 2003 National TMDL Science and Policy Conference (WEF, 2003). In addition to the conferences listed above, the 2003 Annual Conference of the American Water Resources Association and the Stormwater Management in Cold Climates had significant sessions on wet-weather flows. However, no paper proceedings were published by AWRA. Viklander et al. (2003) presented an overview of the conference on urban

drainage and highway runoff in cold climates. Other papers at the conference addressed the implementation of stormwater treatment practices for urban snowmelt and winter runoff quality. Many of these conferences produced summary papers of what is known and where the knowledge gaps still exist. Moeller (2003) reviewed the “frontiers of research” in stormwater as seen by the Water Environment Research Foundation based on their survey of stormwater program managers, consultants and others. The paper also addressed WERF’s efforts to advance stormwater research based on the identified needs. Delleur (2003) summarized the evolution of urban hydrology from 6000 B.C. to modern times and advocated the industry moving away from compartmentalized views of the environment (especially as it related to computerized models) and toward an integrated approach based on sustainability of water resources.

Major proceedings related to wet-weather flow (WWF) published during 2002 were the following: (1) Engineering Foundation Conference “Linking Stormwater BMP Designs and Performance to Receiving Water Impact Mitigation” (ASCE, 2002); (2) “Global Solutions for Urban Drainage,” Ninth International Conference on Urban Drainage (ASCE, 2002); (3) WEFTEC, 2002, 75th Annual Conference and Exposition (WEF, 2002); (4) Best Modeling Practices for Urban Water Systems, Monograph 10 (CHI, 2002); (5) Watershed, 2002 Conference (WEF, 2002); (6) WEF/CWEA Collection Systems, 2002 Conference (WEF, 2002); (7) 8<sup>th</sup> Annual Industrial Wastes Technical and Regulatory Conference (WEF, 2001); and (8), 2002 National TMDL Science and Policy Conference (WEF, 2002).

Many of these conferences produced summary papers of what is known and where the knowledge gaps still exist. Heaney (2002b) reported on research needs to quantify the impacts of urbanization on streams. Keyes (2002) presented the EWRI/ASCE perspective on urban watershed needs in the 21<sup>st</sup> century. Swetnam et al. (2002) reviewed the collation, management and dissemination of urban environmental research in the UK. Urbonas and Jones (2002) summarized the emergent urban stormwater themes that were highlighted at the Engineering Foundation Conference on “Linking Stormwater BMP Designs and Performance to Receiving Water Impact Mitigation.” Walesh (2002) described the threats and opportunities facing the urban water field. The paper urged more diligence in applying the state-of-the-art, guarding against software misuse, adopting a holistic approach to watershed development, and rejecting price-based selection for clients needing consulting services.

Schiff and Bernstein (2002) reported on the stormwater monitoring coalition in Southern California and the stormwater research needs identified by the coalition. The projects identified by the research panel fell into one of three broad categories including developing a stormwater-monitoring infrastructure, understanding fundamental stormwater mechanisms and processes, and assessing receiving water impacts. A further refinement identified seven projects that relate to identifying receiving water impacts. These projects included identifying the causes of impacts in receiving waters, developing bioassessment indicators and protocols, developing improved toxicity testing procedures, developing rapid response indicators for microbial contamination, developing microbial source tracking protocols, evaluating BMP effects on receiving waters, and developing improved indicators of peak flow impacts.

Major proceedings related to WWFs published during 2001 were: (1) ASCE EWRI Conference – Bridging the Gap: Meeting the World’s Water and Environmental Resources Challenges (ASCE, 2001); (2) WEFTEC 2001, 74th Annual Conference and Exposition (WEF, 2001); (3) 5<sup>th</sup> International Conference: Diffuse/Nonpoint Pollution and Watershed Management (IWA, 2001); (4) Models and Applications to Urban Water Systems, Monograph 9 (CHI, 2001); (5) 2001 A Collection Systems Odyssey: Integrating O&M and Wet Weather Solutions (WEF, 2001); (6) 7<sup>th</sup> Annual Industrial Wastes Technical and Regulatory Conference (WEF, 2001); and (7) Proceedings of the Third International Conference on Watershed Management (ASCE, 2001).

Major proceedings related to WWFs published during 2000 included: (1) 2000 Joint Conference on Water Resources Engineering and Water Resources Planning & Management (ASCE, 2000); (2) WEFTEC 2000, 73<sup>rd</sup> Annual Conference and Exposition (WEF, 2000); (3) Collection Systems Wet Weather Pollution Control: Looking into Public, Private and Industrial Issues (WEF, 2000); (4) Watershed Management 2000 (WEF, 2000); (5) Applied Modeling of Urban Water Systems, Proceedings of the Conference on Stormwater and Urban Water Systems Modeling (CHI, 2000); and (6) 2000 Annual Meeting and International Conference of the American Institute of Hydrology (AIH, 2000).

During 1999, the major published WWF related conference included: (1) National Conference on Retrofit Opportunities for Water Resource Protection in Urban Environments; (2) Comprehensive Stormwater & Aquatic Ecosystem Management, Auckland, New Zealand; (3) the Eighth International Conference on Urban Storm Drainage, Sydney, Australia; (4) Water Environment Federation 72<sup>nd</sup> Annual Conference and Exposition, New Orleans, LA; (5) American Society of Civil Engineers 26<sup>th</sup> Annual Conference, Water Resources Planning and Management, Tempe, Arizona; (6)

American Water Resources Association 1999 Annual Water Resources Conference – Watershed Management to Protect Declining Species, Seattle, WA; and (7) New Applications in Modeling Urban Water Systems, Guelph, Canada.

For 1996, much of the literature cited came from documents covering noteworthy global conferences (Bathala, 1996; Eng. Foundation, 1996; EPA 1996a; Hallam *et al.*, 1996; Int. Water Res. Assoc., 1996; Maxwell *et al.*, 1996; Sieker and Verworn 1996; Soc. Environ. Toxicol. and Chem., 1996; Water Environ. Fed., 1996a, 1996b, and 1996c.). In addition, the U.S. Environmental Protection Agency (EPA) (EPA, 1996b, 1996c, 1996d, and 1996e) published guidance documents which are discussed in more detail in the subsection entitled “Regulatory Policies and Financial Aspects”. The proceedings of several global conferences on urban stormwater management were also published in 1996. James (1996) edited a book overviewing 18 papers dealing with the modeling aspects of urban stormwater. These papers address a variety of topics including the use of the models themselves, data management including GIS, and the interrelationships between stormwater treatment practices and water quality. The two-volume proceedings of RIVERTECH96 (Maxwell *et al.*, 1996) provided many papers related to urban-stormwater management. The proceedings from a national conference on SSOs provide an excellent information source on SSO problems generally and infiltration/inflow (I/I) problems in particular (EPA, 1996a). The three-volume proceedings of the 7th International Conference on Urban Storm Drainage, held in Hannover, Germany, provide an excellent source of information regarding new developments throughout the world (Sieker and Verworn, 1996).

## Introduction

There has been a dramatic shift in the objectives associated with drainage design over the past decades. Burian, et al. (1999) presented a historical development of WWF management as part of the EPA-sponsored research effort on developing designs for the future (Pitt, et al. 1998a). An extensive annotated bibliography was prepared containing several thousand references tracing the history of drainage design and associated hydraulic and water quality issues. This bibliography (in both text form and in searchable ProCite formats) is available from the student organization AWRA web page at the Department of Civil Engineering, University of Alabama.

An overview of the evolution of urban drainage, illustrating where the concept of a single design objective was replaced by the sustainability concept, was provided by Marsalek (2000a). The advances highlighted by Marsalek included improved (dynamic) control of urban drainage, source controls, integrated modeling, public and political support, innovative university training, sustainable funding, adaptive water management, and investment in research and development (Marsalek 2000b). The paper also highlighted the future challenge of involving the public in the planning of drainage systems and protection of urban waters (Marsalek 2000c). Cigana and Couture (2000) advanced a list of key steps required to achieve a global approach to wet weather issues.

The overall challenges of urban drainage design and monitoring were discussed by both Marsalek and Kok (2000) and by Cigana (2000a). Cigana provided a discussion of the pollution resulting from stormwater runoff and combined sewer overflows (CSOs). The paper also reviewed the technologies available to control this pollution. Marsalek and Kok noted that the effectiveness of stormwater treatment practices is not fully understood, and advocated future research into the design, operation and maintenance of these pollution control practices. Field (2000) presented an overview of the U.S. Environmental Protection Agency's (EPA's) urban watershed wet-weather flow (WWF) research program. U.S. EPA divided its 1996 research plan into five major areas: characterization and problem assessment, watershed management, toxic substances characterization and control, control technologies, and infrastructure improvement. Since that time, other organizations, notably the Water Environment Research Foundation (WERF), have reviewed WWF research programs and developed associated research needs reports, an effort that EPA endorses.

Sullivan and Field (1999) presented an overview of the Environmental Protection Agency's (EPA's) WWF research program, which was expanded in October 1995 with the establishment of the Urban Watershed Management Branch at Edison, New Jersey. Research priorities for 1999 were presented as well as efforts to collaborate with other government organizations and professional societies. Watershed management research at ORD's National Risk Management Research Laboratory (NRMRL) addressed the following question: what effective watershed management strategies were available and how do communities select the most appropriate subset from these to match specific watershed needs? (Borst and O'Shea, 1999). Heaney et al. (1999) presented the results of a national assessment of research needs in urban WWF management. Three interrelated categories of urban WWF management were discussed: CSO, SSO, and urban stormwater discharges.

Based on the past 30 years of research on urban WWF water quality, impact, modeling, control, and treatment demonstrated results, Field *et al.* (1997a) delineated a framework of future research directions for risk management of urban WWF.

## **Characterization**

### ***General***

Sources of urban runoff pollutants in China were researched by Li *et al.* (2006a), as part of an effort to develop universal regression equations. These equations would then be used to predict quality of runoff in areas where no on-ground investigations had been performed. Wang *et al.* (2006b) investigated the presence of first flushes in urban runoff. They proposed a new definition of first flush based on cumulative volume.

Sosiak and Dixon (2006) investigated the factors impacting water quality in the upper Elbow River in Alberta, Canada. Urban runoff was one potential source for both nutrients and fecal coliforms. Salmore *et al.* (2006) delineated the chemical and biological signature of stormwater runoff in an urban river. The study demonstrated that there is a considerable *E. coli* load to receiving waters from stormwater and that sanitary sewage inputs may not be limited to recognized sewer overflows.

Angelakis *et al.* (2005) reviewed urban wastewater and stormwater drainage technologies in ancient Greece. The authors noted that the efforts and technologies of the ancient Greeks were comparable to that of modern Europe when evaluating the systems for hygienic and functional requirements

Alternative unit hydrographs have been proposed for the coastal plains region of the United States because traditional methods typically overpredict the storm flow by an order of magnitude or more (Huynh-Ba *et al.* 2005). This paper evaluates those alternative hydrographs in the development of regional stormwater management plans of southern New Jersey. Connor and Hiroko (2005) promoted the use of a Flood Vulnerability Index (FVI) to compare the vulnerability between basins, as well as identify those factors most responsible for a basin's vulnerability.

The paper by Bicknell (2002) reviewed the discussion at the Engineering Foundation Conference on linking stormwater BMP design and performance to receiving water impacts mitigation. The paper described the roles, types and considerations for use of environmental indicators in characterizing receiving water conditions and monitoring stormwater program effectiveness. It also addressed data needs for future application of indicators, incorporating the comments made during the discussion.

Brandt *et al.* (2002) described two case studies of the development of two systems that will be monitored for land use and ecological change. The purpose of this project will be to collect reliable, quantifiable and independent data for monitoring these effects. The two case studies were the Small Biotype project of Denmark and the Countryside Survey project of Great Britain. These systems illustrated the problems involved in studies at the landscape level and the way satisfactory results can be achieved. Monitoring is considered to be effectively repeated surveillance and needs especially strict protocols to separate real change from the artifacts of sampling.

Morrisey *et al.* (2002) investigated the factors that affect the distribution of benthic macrofauna in estuaries that have been contaminated by urban runoff. Distributions of benthic invertebrates were significantly related to those of environmental variables, and were ordinated along axes that correlated with both natural environmental variables (nature of the sediment, position in estuary) and contaminants. Differences in faunas between the urban and non-urban estuaries were not, however, clear-cut and nor were relationships between faunal assemblages and environmental variables (including contaminants) consistent between two times of sampling. Papanicolaou *et al.* (2002) investigated the impacts of watershed changes on the fish population in the Clearwater River, Idaho. The study was a statistical analysis performed at the macroscale (watershed-wide) level. Factor analysis, along with linear regression, was used to develop relationships between fish indicators and fifty man-made disturbances, watershed landscape, water discharge and geometry, channel morphology, river water depth, and temperature. The statistical analysis indicated that some macroscale parameters such as, landscape and water discharge could be strong predictors of Fish Indicators and should be considered in restoration plans in the region.

Patwardhan and Kreutzberger (2002) linked sediment loads to biotic integrity for developing clean sediment TMDLs. The

WISE (Watershed Improvements through Statistical Evaluations) Model was designed to link the watershed pollutant loads to narrative standards, i.e., biological indices. Specific biological standards, based on biological indices such as Index of Biological Integrity (IBI), Fish Score, and Invertebrate Community Index (ICI), were used as measurement tools and were linked to various pollutant loads from the watershed.

Fan et al. (2001b) reviewed the transport of toxic pollutants through multiple media and drainage systems in the urban watershed during wet-weather periods. Field studies have identified that a major portion of hazardous waste priority pollutants including benzene, polynuclear aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), pesticides, and heavy metals (e.g., arsenic, cadmium, chromium, copper, lead, mercury, and zinc) contained in urban stormwater runoff are in particulate form or sorbed onto particles. Fatoki and Mathabatha (2001) investigated the distribution of heavy metals (zinc, cadmium, copper, iron, manganese and lead) in seawater and in sediment samples from the East London and Port Elizabeth harbors. The results indicate the contribution of heavy metal pollution from storm drains. Ship repair activities were also suspected to a source of elevated concentrations in the upper reaches of the harbor. Kayhanian et al. (2001b) analyzed the impact of 'non-detects' or 'NDs' on stormwater data because dissolved fractions of stormwater constituents often are not detected above laboratory reporting limits. Analysts and stormwater modelers have represented these NDs in stormwater data sets using a variety of methods. In the paper, different methods of data analysis were used to determine constituent mass concentrations from water quality datasets that include ND values. Depending on the number of NDs and the method of data analysis, differences ranging from 1 to 70 percent were in mean values, which would have significant impacts on estimations of constituent mass loading.

For California's implementation of industrial stormwater discharge control, Shaver and Duke (2000) characterized Los Angeles industrial facilities as to the types of operations and exposures to rainfall that occur on a site. The results of the survey showed that the majority of sites were impervious, conducted more than one regulated activity, and had a wide range of housekeeping practices and intensities of activity that were exposed to rainfall. The authors questioned whether the general permit should be applied equally to all industrial sites or whether resource allocation should be based on sites where pollutant load reduction potential would be greatest.

The known thermal pollution of Oregon's streams and rivers was reviewed by Bullock and Eimstad (2000), and included a review of sensitive habitats for salmonid species. They presented information on the Oregon Department of Environmental Quality temperature standards for receiving waters, as well as guidance for developing a Temperature Management Plan.

Ball (2000b) reported on the quantities of pollutants that entered the stormwater treatment facility at Centennial Park in Sydney, Australia, and showed that the gross pollutant trap when combined with a wetland or detention pond removed 87% of suspended solids and 50% of the entering phosphorus. Lieb and Carline (2000) investigated the effects of detention pond effluent on a headwater in central Pennsylvania and showed that the macroinvertebrate community immediately downstream of the pond was highly degraded, although recovery was seen farther downstream. Stormwater sediments in Ottawa, Ontario, Canada, were analyzed for their ecotoxic risk by vanLoon et al. (2000). The results indicated that the sediments present significant potential risks to the ecosystems that develop around passive stormwater treatment sites. Jones (2000a) reported on the results of using the US EPA's Rapid Bioassessment Protocol (RBP) in streams affected by stormwater runoff in Fulton County, Georgia. The results of their assessments from 30 stations showed that changes in habitat had a greater effect on the biological communities than did water quality and that control of total suspended solids entering the stream was necessary for habitat protection.

Smullen et al. (1999) compiled stormwater quality data collected from several large sampling programs that have been conducted over the past 20 years. They concluded that it was possible to differentiate stormwater quality based on land use, region of the country, and season. Duke et al. (1999) examined water quality data for separate storm sewer systems during storm event discharges and during dry weather conditions in the San Francisco Bay Area, California. Long-term mean concentrations for many parameters in most streams were higher during storm discharges than during dry-weather flows.

A three-year study on the distributions of concentrations of 14 contaminants in five sources of urban-stormwater-runoff was performed. The log-normal-probability distribution was more accurate in the calculation of pollutant loads than normal-probability distributions (Van Buren *et al.*, 1997).

The runoff on a 95 ha urban catchment in Aalborg, Den. was found to show significant first-flush effects and a strong



correlation in concentration between COD and SS and biochemical oxygen demand (BOD) and SS. The study further discussed the most appropriate way to characterize the quality of the outflow comparing average concentration and accumulated event mass methods (Larsen *et al.*, 1997a).

Numerous papers at the 7th International Conference on Urban Storm Drainage held in Hannover, Germany (Sieker and Verworn 1996), presented broad-based stormwater data from throughout the world, including data from Denmark and the Netherlands (Grum *et al.*, 1996), from Poland (Bartkowska and Królikowski, 1996), and from Japan (Uchimura *et al.*, 1996).

Bannerman *et al.* (1996) conducted a study for the USGS in conjunction with the Wisconsin Department of Natural Resources in which water-quality data from four urban stormwater-monitoring projects conducted between 1989 and 1994 were compiled. Concentrations of many of the constituents including Pb; Zn; Cu; Ag (silver); Cd; nine PAHs (polycyclic aromatic hydrocarbons); bis(2-ethylhexyl) phthalate; DDT; atrazine; alachlor, 2,4-D; SS; chlorides; total phosphorus (P); BOD<sub>5</sub>; and bacteria were high enough to say that stormwater runoff may be contributing to the degradation of the streams.

### ***Rainfall Monitoring and Urban Hydrology***

Raimer *et al.* (2006) studied the water budget of streets both experimentally and through modeling over three years. The results showed that runoff losses may be important and not constant, resulting in highly variable runoff coefficients. Infiltration and evaporation caused losses between 20% and 30% of the rain.

Burns *et al.* (2005) investigated the effects of suburban development on runoff generation and groundwater supply. Impacts were seen on runoff generation but these effects were mitigated by the remaining wetlands and human effects on groundwater and septic discharge.

Ho and Valeo (2005) studied urban snow and snowmelt properties in Calgary, Canada. Their results showed that the energy balance for urban snow was significantly different than for rural snow. Urban snow could be classified into four categories, all of which had separate behavior patterns: snow piles, snow on road shoulders, snow on sidewalk edges and snow in open areas.

The effect of urbanization on the diurnal rainfall pattern was evaluated for the City of Houston by Burian and Shepherd (2005). Compared to pre-development conditions in reference watersheds and in the City prior to substantial development, urbanization affected rainfall patterns in the afternoon time periods with an increase seen post-urbanization. Wilson and Boehland (2005) advocated smaller housing as a way to promote resource conservation, including the reduction in the increase in stormwater runoff due to increasing impervious surface coverage.

Li *et al.* (2004) investigated the recovery of water (rainwater harvesting) in China as a function of the surface type. Recovery was highest on the asphalt fiberglass, followed by the plastic film, gravel-covered plastic film, concrete, cleared loess slope and natural loess slope.

The changes in the arterial drainage schemes (ADS) in River Brosna (Ireland) due to the implementation of the ADS were summarized by Bhattarai and O'Connor (2004). In addition to the expected pre/post-drainage change, the results show that the catchment response to rainfall reverted to virtually pre-drainage-like conditions after just one-and-a-half decades but surprisingly changed back again, over the last decade, to early post-drainage-like conditions.

Dahl (2004) presented an overview of hydrology on the volume of urban stormwater runoff and reviewed the impacts of these changes on a roadway widening/reconstruction project in Salt Lake City, Utah. Cape Town (South Africa) also performed a hydrologic study to investigate the impacts of urbanization and increased stormwater runoff on flooding potential in the city (Whittemore *et al.* 2004). The modeling was performed using Visual SWMM.

Dakin *et al.* (2004) reviewed the use of volunteer monitors in the Huron River to provide an early warning of changes in stream discharge and cross-sectional channel shape. The goal is to provide early warning of erosion and habitat degradation.

Dutt and Nikaido (2003) developed wet-weather events for Oakland, CA from historical rainfall data collected at the airport and compared the results to other types of wet-weather design events used in analyzing a sewer system (historical

rainfall events, design storms, IDF curves and long-term continuous simulation). Walter, *et al.* (2003) demonstrated that Hortonian flow (which was assumed to occur whenever the rainfall exceeded the soil permeability) was not a dominant process for undeveloped areas in the New York City watersheds.

Ragab, *et al.* (2003a) investigated the effect of slope and aspect on the proportion of the rainfall that was captured by residential roofs and that evaporated from the roof. Noticeable differences in rainfall, runoff and evaporation were found for different roof slopes, aspects and heights. The authors also (2003b) investigated the effect of road infiltration and evaporation on the proportion of rainfall on UK residential roads that became runoff. Six to nine percent of the annual rainfall infiltrates through the road surface while evaporation removes 21-24% of annual rainfall.

Current forecasting systems from meteorological offices have not been well suited for accurate rainfall forecast in urban areas (Aspergren *et al.*, 2001). This project provided a short-term small-scale prediction of rain based on radar images. The extrapolation part of the methodology, based on a sophisticated cross correlation of images, was optimized by a neural network technique. Three different application sites in Europe have been used to validate the system. Burian *et al.* (2001a) reported on one technique for disaggregating long-term hourly rainfall records into subhourly increments that involved the use of artificial neural networks (ANNs). The research evaluated the influence on performance of several ANN model characteristics and training issues including data standardization, geographic location of training data, quantity of training data, number of training iterations, and the number of hidden neurons in the ANN. Results suggested that data from rainfall-gauging stations within several hundred kilometers of the station to be disaggregated would be adequate for training the ANN rainfall disaggregation model.

Schreider *et al.* (2000) predicted the impact that global warming due to increased carbon dioxide concentrations would have on flood frequencies in the urban areas near Sydney and Canberra, Australia. Their results showed that storms that currently cause the 1 in 100-year flood become the 1 in 44-year event for one basin, and the 1 in 10-year event for another local basin.

Pitt (1999) reports that different drainage design criteria and receiving water use objectives often require the examination of different types of rains for the design of urban drainage systems. These different (and often conflicting) objectives of a stormwater drainage system can be addressed by using distinct portions of the long-term rainfall record. Most of the urban hydrology methods currently used have been successful for large “design” storms, but were inappropriate for use when evaluating many water quality problems.

### **Urban hydrology**

Doll *et al.* (2002) investigated hydraulic geometry relationships relating bankfull stream channel dimensions to watershed drainage area for the Piedmont of North Carolina. The focus of this study was on the development of an urban curve that showed the bankfull features of streams in urban and suburban watersheds throughout the North Carolina Piedmont. Comparisons were made with regional curves developed previously for the rural Piedmont, and enlargement ratios were produced. These enlargement ratios indicated a substantial increase in the hydraulic geometry for the urban streams in comparison to the rural streams. A comparison of flood frequency indicates a slight decrease in the bankfull discharge return interval for the gaged urban streams as compared to the gaged rural streams.

The impact of long-term land use change on the hydrological regime of the Dyle catchment (Belgium) was reviewed by El Idrissi *et al.* (2002). The consequences of the land use dynamics on the hydrological cycle were studied by means of a distributed hydrological model, which was coupled to a geographical information system of the land use dynamics. The researchers concluded that the change in the hydrological behavior of the Dyle catchment in terms of the historical land use change was attenuated by the presence of compensating effects within the changing land use patterns. However, if the Sector Development Plan is executed, urbanization will increase by up to 21% of the total area, considerably increasing thereby the flooding risk, even if rainfall events with a small return period occur.

Herricks (2002) presented the observed stream responses to changes in runoff quality. Toxicity was associated with the frequency of exposure to a given concentration or duration of exposure couple. Bioassessments indicated that the urbanization affects the integrity of receiving streams. Pilling and Jones (2002) reviewed the impact of future climate change on seasonal discharge, hydrological processes and extreme flows in the Upper Wye catchment in mid-Wales. Results indicated increased seasonality of flows, with markedly drier summers. Analysis of extreme events suggested significant increases in the frequency of both high-and low-flow events.

Sheeder et al. (2002) investigated the hydrograph responses to dual rural and urban land uses in three small watersheds. Two important conclusions were deduced from this investigation. First, in all cases, the researchers found two distinct peaks in stream discharge, each representing different contributing areas to direct discharge with greatly differing curve numbers and lags representative of urban and rural source regions. Second, the direct discharge represented only a small fraction of the total drainage area with the urban peak becoming increasingly important with respect to the rural peak with the amount of urbanization and as the magnitude of the rain event decreases.

The L-THIA (Long-Term Hydrologic Impact Assessment) model can be used to assess how land-use changes affect annual average runoff (Bhaduri et al., 2001). Looking at runoff calculations, SWMM was compared with L-THIA. Applications of L-THIA and SWMM to two small watersheds in Chicago showed that L-THIA predicts annual average runoff between 1.1 and 23.7% higher than SWMM, and was easier and quicker to use than SWMM. Results suggested that L-THIA could be an appropriate tool for initially assessing the relative impacts of land-use change scenarios. The runoff coefficient (ratio of total streamflow volume to the total precipitation over a certain area and time) has been shown to play a fundamental role in the planning, design and operation of water resources in a catchment (Kadioglu and Sen, 2001). In this paper, monthly runoff coefficient changes within an annual period were represented through a simple polygon diagram concept obtained from monthly precipitation and runoff data. The application of the polygon method was presented for catchments around Istanbul, Turkey. Kojiri et al. (2001) reviewed the flood management system used for urban rivers in Japan. The system is composed of three subsystems: an on-line data collection subsystem for collecting rainfall and water level data; a flood prediction subsystem based on the previous 3-hour hydrologic data; and a results display subsystem. This system has been used for practical flood prediction. Semadeni-Davies et al. (2001) investigated the radiation balance of urbanized catchments as it relates to snowmelt. Snowpacks experience either enhanced or decreased irradiance depending on snowpack location and condition, and changes to localized irradiance (and melt rates) have implications for urban runoff generation. Net allwave radiation measurements over snow made in Lulea, Sweden during April 1997 and 1998 were presented. The results showed that urban structures significantly alter radiation over snow, and therefore, including snowmelt energetics within design and management techniques is needed.

A model (based on dynamic wave equations) for characterizing overland flow on paved surfaces was evaluated by James et al. (2000) and tested successfully using a laboratory-scale rig. Using chloride tracers, Kirchner et al. (2000) showed that many catchments do not have characteristic flushing times. Travel times in the catchments and streams followed an approximate power-law distribution, where contaminants initially were flushed rapidly, but then low-level contamination was delivered to the streams for a long time after the initial flush.

James and Johnson (1999) examined simplified, nondeterministic theories regarding the link between rainfall at the ground surface and the resulting runoff. They showed that linear unit hydrograph theory overlooks the inherent non-linearity in the time dimension of the process. A modified approach, the *initial storage theory* (IST), was therefore proposed and tested in the laboratory. They concluded that the IST was an improvement over the basic unit hydrograph method.

Becker et al. (1999) described the results of detailed field studies investigating lateral flow along different pathways, especially along hillslopes at small catchment scales. Grimmond and Oke (1999) directly measured detailed evapotranspiration mechanisms for urban areas and found that evapotranspiration varied for different land uses and land covers. Hakonson (1999) studied the effects of the burrowing of pocket gophers and vegetative covers on water runoff amounts and erosion losses and resulted in large decreases in runoff and erosion, while vegetation alone slightly decreased runoff but also greatly decreased erosion. Nagasaka and Nakamura (1999) examined the influences of landuse changes on the hydrologic response and the riparian environment in a northern Japanese area. Temporal changes in a hydrological system and riparian ecosystem were examined with reference to landuse conversion in order to clarify the linkages between the two. The results indicated that the hydrological system has been altered since the 1970s, with increasing flood peaks of 1.5-2.5 times and shortening the time of peak flow appearances by 7 hours. The ecological systems were closely related to and distinctly altered by the changes that have occurred in the local landuse.

During studies in Scotland, Soulsby et al. (1999) found that  $^{18}\text{O}$  was a useful tracer to indicate the relative influence of spring snowmelt and summer rainfall on stream waters along with their mean residence times. Preliminary estimates of the various waters' residence times in the catchments were < 0.5 year for near-surface soil water and storm runoff, 2.5 years for shallow groundwater, and >5 years for deeper groundwaters. The effects of frozen soil on snowmelt runoff in Vermont were studied by Stanley and Chalmers (1999). The depth of the soil frost varied greatly during the 15 years of observation, with annual maximum frost depths varying from 70 to 390 mm. The enhancement of runoff due to soil frost

was most evident on small plots and during extreme events, such as when rain occurred on frozen, snow-free ground.

In the On-Cheon Stream watershed in Pusan, Korea, the peak discharge of runoff increased and the mean lag time of the study area decreased due to urbanization over the past two decades (Kang et al., 1998). It was not possible to determine a priori what mechanism dominated storm runoff in suburban and forested basins (Borges et al., 1998). While 12—30% of annual precipitation became runoff in the forest basin, 44—48% became runoff in the suburban basin, emphasizing the need to consider surface flow from all sources in the catchment when evaluating mitigation measures. An evaluation of precipitation records revealed that the majority of storms at most locations are relatively small and produce less precipitation and runoff than is often used in the design of traditional drainage networks (Urbonas, 1998). These storms need to be targeted when attempting to mitigate the effects of urbanization on the receiving waters.

### **Rainfall errors and flow forecasting**

Kawaguchi et al. (1999) presented a case study of short-term rainfall characteristics that showed considerable changes in rainfall intensity during the past 40 years, where the 20-minute rainfall intensity having a 10-year return period increased by 20 mm/hr. This increase in the design storm characteristics has a profound effect on the performance of urban drainage systems. Fo and Crawford (1999) examined rainfall data having a 2 km x 2 km grid resolution over time intervals of 15, 30, 60, and 120 min. to quantify runoff prediction errors in Oklahoma. They found that the test watershed had an average underestimated rainfall error of about 28% which resulted in significant prediction errors when modeling stream flows in the Dry Creek watershed in north-central Oklahoma. Fo et al. (1999) further described new forecast systems using high-resolution rainfall data-sets from the WSR-88D radar system, the Oklahoma Mesonet, and the Oklahoma Local Analysis and Prediction System (OLAPS). They found that because of the lag time between the peak in precipitation and the peak in stream-flow in Dry Creek, the greatest impact upon the accuracy of hydrologic forecasts resulted from improvements in analyzing the precipitation data.

Krejčík et al. (1999) described rainfall data monitoring needs for urban drainage design in the Czech Republic. They verified the need for a high-density network of rain gauges for sewer system design and evaluations, especially when using single-event simulations. The need for high-resolution data was not as great when conducting long-term simulations and when preparing statistical evaluations of the modeling results. Willems et al. (1999) examined intensity/duration/frequency (IDF) relationships for different types of storms and seasons in Belgium. For every re-occurrence time period between 10 min. and 15 days, they identified two separate distributions, one associated with convective thunderstorms and the other with cyclonic/frontal storms.

Nguyen and Nguyen (1999) presented a scaling approach for estimating the distribution of short duration rainfall extremes (e.g., less than 1 hour) from rainfall data having longer durations (e.g., 1 day), using recently developed “scaling” theory. The scaling concept implies that statistical properties of the extreme rainfall processes for different temporal scales were related to each other by a scale-changing operator involving only the scale ratio. Rainfall monitoring with radar. In spite of the highly positive outlook of the obvious benefits, Einfalt and Maul-Kotter (1999) were concerned about the lack of a standard for the use of radar-based precipitation measurements in conjunction with hydrologic models. They described current efforts by the State Environmental Agency in North Rhine-Westphalia, Germany, to investigate the possibilities of developing a standard for radar data use from the German Weather Service for standard hydrological watershed modeling.

Faure et al. (1999) described some limitations for using radar rainfall data to aid sewage system management. They concluded that weather radar seems an important tool in evaluating the spatial structure of rain and in anticipating very short-term changes in precipitation over an urban area. However, the rainfall variability in space and time restricts the accurate forecasting period. In order to quantify the ability of radar data for forecasting, they examined the forecasting range limits for typical urban catchment areas (1 to 180 km<sup>2</sup>) in Nancy, France. They found that the limits varied greatly according to the rain conditions, leading them to propose a sewage system management strategy based on predefined management scenarios and real time identification of the type of the rain event. Koishikawa et al. (1999) also examined the application of rainfall radar information for use with operational support systems used for urban drainage facilities. They found that in order to be effective, the radar rainfall data must be collected accurately and with high resolution in both time and space. They demonstrated increases in the accuracies of runoff simulation modeling when adequate radar rainfall data were used. Vivekanandan et al. (1999) studied the influence of terrain on rainfall estimates from radar for a severe storm near Denver, Colorado. Estimates of rain intensities in areas having low or high beam-blockage were compared. They found that specific propagation phase-based quantitative precipitation estimates tend to be less influenced by terrain than reflectivity-based precipitation estimates, as they had hypothesized.

One of the most unappreciated tasks associated with stormwater characterization is an understanding of urban-rainfall patterns and rainfall-monitoring requirements. The Danish Meteorological Institute (Mikkelsen *et al.*, 1996a and 1996b) has established a nationwide-raingauge network for monitoring short- and intense-rain events. This was of special interest in designing stormwater-drainage systems. It was found that a large geographical variation in rainfall cannot be described by typical topographic or other standard factors. Therefore the way that rainfall data are being used by engineers for design and analysis is being revised. Arnbjerg-Nielsen and Harremoës (1996) coupled a stochastic time-series model with a model for the geographical variation of extreme point rainfall in order to make inference about extreme rainfalls at ungauged locations. The use of the U.S. NEXRAD-radar system for estimating point rainfalls was discussed by Seliga and Chen (1996). This information should be very useful, especially within an urban environment.

Desa and Niemczynowicz (1996) studied short-term- and long-term-rainfall patterns in Malaysia. These were the first rainfall data having very small-time and -space resolution in the humid tropics region.

The City of Philadelphia's modernized raingauge network provides the Water Department with a method of preplanning for events based on intensity and duration and the ability to determine publicly owned treatment works (POTW) effects on multiple events (Day and Nicolo, 1996). It provides information, which can be used for calibrating models, to aid in improving general effluent quality and plant operations.

Legg *et al.* (1996) investigated the rainfall-runoff relationship for 20 residential lawns in Madison, WI using a rainfall simulator, in order to identify the significant factors affecting infiltration in disturbed urban soils. All lawns were characterized as having silt-loam soils. The runoff coefficients for lawns younger than three years were significantly greater than for older lawns. Changes in rain intensity had little effect on runoff volumes, with total rainfall depth having the most significant effect. The effect of antecedent-soil moisture on infiltration was questioned, requiring more study.

### **Urban Snowmelt**

Glenn and Sansalone (2002) reviewed the accretion and partitioning of heavy metals associated with snow exposed to urban traffic and winter highway maintenance activities. Results from partitioning analysis indicate that Pb, Cu, Cd, Zn, Al, Mg, and Fe were all highly particulate bound, while Na and Ca were mainly dissolved for all highway sites. Partition coefficients for most heavy metals in snowmelt ranged from  $10^3$  to  $10^6$  L/kg.

Taylor *et al.* (2002) investigated how the isotopic fractionation of snowmelt affects hydrograph separation using the isotopic composition of meltwater samples from four seasonal snowpacks. Despite the very different climate conditions the  $\delta^{18}\text{O}$  of meltwater from all four snowpacks increased as melting progressed. The error in the new water fraction depended on: (1) the isotopic difference between the snow core and the old water; (2) the isotopic difference between the snow core and the meltwater; and (3) the new water fraction contributing to the stream flow, during a spring melt event. The error was large when snowmelt contributes a dominant fraction of the stream flow.

Thorolfsson and Brandt (1996) studied urban storm runoff during summer and winter in Norway from 1988 through 1994. It was found that snowmelt runoff is much greater in volume than typically considered in drainage designs, resulting in much more winter flooding and CSOs than during the summer. An urban storm-runoff model that considers snowmelt and rainfall was produced but it was concluded that there is still a notable lack of experience about urban storm runoff during the winter season.

Saxton *et al.* (1996) reported the results of a study conducted to quantify the pollutant characteristics of snow versus snowmelt runoff at Eielson Air Force Base, AK. The sampling results showed that snow is, in general, more contaminated than snowmelt runoff and that snowmelt runoff appears to be representative of what reaches surface water.

Sansalone (1996) investigated the forms of heavy metals in stormwater and snowmelt. It was found that zinc (Zn), cadmium (Cd), and copper (Cu) were mainly dissolved in stormwater, while only Cd was mainly dissolved in snowmelt. Lead (Pb) was associated with the finer particulate fractions in both stormwater and snowmelt. The dissolved fraction of the metals should be immobilized by sorption, while the particulate bound metals should be immobilized by filtration in a partial exfiltration trench.

### **Stormwater Quality**

Two large-scale general stormwater runoff characterization projects were reported in 2006. McLeod *et al.* (2006)

characterized urban runoff quality and load estimations in Canada. Both a site mean concentration approach and a multiple variable regression analysis were used to quantify pollutant loads in urban runoff. The urban runoff in two catchments in Macau was characterized by Huang et al. (2006a). The commercial-residential urban catchment showed high levels of COD, TN, and TP, while the park urban catchment had high TN and TP concentrations.

First-flush and composite storm analyses were conducted by Hudak et al. (2006) in small urban and rural watersheds in north-central Texas. Observed concentrations of most parameters were low. Fecal coliforms and lead were detected in most samples, with the highest lead concentrations observed in the most developed watershed. Dry weather pollutant buildup and subsequent washoff was investigated in Australia by Ashraf and Khan (2006). They concluded that total dissolved oxygen (DO) and associated pollutants present significant temporal and spatial variations.

Managaki et al. (2006) investigated the 3-D distributions of sewage markers such as fluorescent whitening agents (FWA) in Tokyo Bay. In summer, FWAs predominated in the surface water layers, with trace (but significant) concentration of FWAs in bottom waters due to stratification. In the winter, on the other hand, FWAs were extensively mixed into the bottom layers.

Azrina et al. (2006) examined the anthropogenic impacts on the distribution and biodiversity of macroinvertebrates, as they related to water quality changes in Malaysia. They found that urban runoff affected the distribution and species diversity in the river.

The relationship between land cover and the chemicals chloride, total organic carbon and lead were examined during winter rainstorms in Pennsylvania by Chang and Carlson (2005). As the basin percent urban land increased, the mean chloride and lead concentrations increased.

Mourad et al. (2005b) performed a sensitivity analysis on the calculation of the site mean stormwater pollutant concentrations. The concern was the influence of the errors in mean concentration calculations on the calculation of loads delivered to receiving waters. The results gave the order(s) of magnitude of the uncertainty. Principal component analysis was used to relate water quality parameters to measures of urbanization in six watersheds in Durham, North Carolina (Carle et al. 2005). Most of the variation was explained by extent and distribution of urban development, including house age, directly-connected impervious surfaces to the drainage system, and accessibility of city services. Anthropogenic sources and sea salt explained more than seventy percent of the variation in rainfall chemistry in Changhua City, Taiwan (Chang et al. 2005).

As part of an EPA 104(b)3 project, Pitt et al. (2004a and 2004b) developed and reported on the findings of the Nationwide MS4 Stormwater Quality Database (NSQD). Data from over 200 municipalities, collected as part of their NPDES permit monitoring, have been compiled in the database and conclusions drawn about the quality of U.S. stormwater runoff with the goal of helping municipalities better design their stormwater monitoring program. Stack et al. (2004) reported on the stormwater quality data in Salt Lake County, Utah. Their analysis showed that the stormwater quality based on event mean concentrations (EMCs) is similar to that of the Nationwide Urban Runoff Program (NURP) and of other municipalities with similar climates.

Lee et al. (2004) studied the impacts of a seasonal first flush of urban stormwater in California. Pollutant concentrations early in the wet season ranged from 1.2 to 20 times higher than concentrations near the end of the season, and mass emission rates were similarly higher at the beginning of the season. Sediment plumes in the Santa Barbara Channel were shown to be associated with winter runoff by Otero and Siegel (2004). Graves et al. (2004) investigated the relationship between land use and stormwater quality in South Florida. Runoff from most land uses had low dissolved oxygen, and sediment and nutrient concentrations were closely related to land use, particularly to the amount of fertilizer applied in each land use. Copper was the most frequently detected metal and was, along with arsenic, associated with golf course runoff. Taebi and Droste (2004b) investigated the pollutant loads in urban runoff compared to point source loads in Iran. Results indicate that the annual pollution load in urban runoff is lower than the annual pollution load in sanitary wastewater in areas with low precipitation but it is higher in areas with high precipitation.

Reeves et al. (2004) reviewed the data supporting the hypothesis that inland runoff contributes to the high fecal indicator bacteria concentrations at Huntington State Beach (Southern California). On a year round basis, the vast majority (>99%) of fecal indicator bacteria loading occurred during storm events when runoff diversions are not operating. During storms,

the load of fecal indicator bacteria in runoff follows a power law. Bacterial water quality in the Golden Horn estuary (Turkey) was investigated by Aslan-Yilmaz et al. (2004). Spikes in bacterial concentrations were related to urban runoff and were enhanced by domestic inputs during rainfall.

Sansalone and Cristina (2004) evaluated the definition of first-flush of suspended and dissolved solids (TDS) using two small paved urban transportation land use watersheds. The results indicated that two criteria must be used to describe the delivery of suspended sediment concentration and TDS as indices of particulate and dissolved matter, which then is often used to define the required treatment water quality volume. Taebi and Droste (2004a) investigated the first-flush phenomena in a semi-arid catchment in Iran. An elevated first flush concentration was seen for total solids (TS), TSS and COD, but no correlation was found between the first flush of TS and COD with rainfall-runoff characteristics. The first flush load of TSS increased when the rainfall's intensity and duration increased. Maestre et al. (2004) reviewed the nonparametric statistical analyses that were performed on the data included in the NSQD. First flush effects were not seen in all the land uses, and certainly not for all constituents.

The effect of stormwater controls on sediment transport in urban streams was investigated for both Fort Collins, CO, and Atlanta, GA (Rohrer et al. 2004). For each scenario examined, sediment transport potential is evaluated for two non-cohesive soil types: medium gravel and medium sand. Mishra et al. (2004a and 2004b) proposed a partitioning curve number (PCN) approach to describe the association of metals between particulate and dissolved phases in urban snowmelt, rainfall/runoff and river flow environments. In snowmelt conditions, the PCN was generally related to temperature, relative humidity, pH, and chloride content and during a rainstorm, PCN depended on the alkalinity and pH of the rainwater. Sansalone and Cristina (2004) examined snowmelt particulate and metal data from 10 similar urban land use sites. Results indicated a power-law relationship existed between mass or surface area (SA) of the particle and particulate-bound metal mass for particles of similar granulometry, land-use conditions, loadings, and exposure.

Stout et al. (2004) compared the hydrocarbon signature in surficial sediments in nine U.S. urban waterways and found that there is no single representative THC or PAH signature. The matter mean concentration of THC attributable to urban background was 415 mg/kg (dry wt). Two stormwater canals in Bayou St. John in New Orleans, LA were shown to contain measurable concentrations of pharmaceuticals, personal care products (PPCPs) and endocrine disrupting chemicals (EDCs) (Boyd et al. 2004). The concentrations of these chemicals increased with increasing rainfall. In Belgium and German, 4-nonylphenol (an EDC) concentrations were lower in the summer than in the winter runoff. Concentrations were lower in snow and were lower in rural areas as compared to urban areas (Fries and Puttmann 2004). Wakeham et al. (2004) studied sediment cores in Lake Washington (Seattle, WA) from the 1970s and 2000. Results showed that anthropogenic hydrocarbon contributions peaked between the 1950s and 1970s. Inputs of terrestrial organic matter (long-chain fatty alcohols) has increased due to erosion of the region's soils.

Brainwood et al. (2004) investigated the water quality in three farm dams in Australia which had varying land uses contributing water. Nitrogen was found to be primarily linked to upstream land uses. Vaze and Chiew (2004) determined nutrient loads associated with different particle size ranges for dry surface pollutants and stormwater samples collected from an urban road surface. Practically all the particulate TP and TN in stormwater samples are attached to sediments between 11 and 150  $\mu\text{m}$ .

Vedom (2004) quantitatively estimated the relative fraction of each transport pathway (direct runoff, interflow and baseflow) for deicing chlorides to receiving waters. The overall year average of chloride loads of the total flow for examined period was 26990 tons breaking into mentioned above components in amounts of 7899, 11252 and 7840 tons, respectively.

Dojiri et al. (2003) investigated the increasing pollutant loads to Santa Monica Bay due to urbanization with a focus on the temporal patterns of anthropogenic influence on the Bay. Davraz et al. (2003) used a case study in Burdur, Turkey, to demonstrate the need for hydrogeologic and hydrologic investigations in urban areas. These changes to the land surface would affect the groundwater-surface water interactions which affect flooding. Pitt et al. (2003) reviewed the results of a nationwide survey of municipal separate storm sewer system (MS4) stormwater permit holders, focusing on the results from their NPDES monitoring data. This data was reviewed to describe the characteristics of municipal stormwater runoff, to provide guidance for future sampling needs, and to enhance local stormwater management activities in areas having limited data.

Morrissey et al. (2003) reviewed the factors affecting the distribution of benthic macrofauna in estuaries contaminated by

urban runoff. Tests of differences in composition of benthic communities among estuaries showed that the two urban estuaries were not significantly different, but that they differed from both rural estuaries. Noble et al. (2003) compared total coliform, fecal coliform and enterococcus bacterial indicator counts along the southern California shoreline. The results suggested that replacing the total coliform standard with an enterococcus standard would lead to a five-fold increase in failures during dry weather and a doubling of failures during wet weather, while replacing the total coliform standard with one based on all three indicators will lead to an eight-fold increase in failures.

Fan et al. (2003) presented procedures for estimating solids pollutant loads in stormwater, including equations for litter and floatables, solids on highways, sand for highway-ice control, and solids due to resuspension of sediment in urban sewers with the results demonstrating the significant contribution due to resuspension of solids in combined sewers during storm events. Cristina and Sansalone (2003) investigated the solids (between 2 and 75  $\mu\text{m}$ ) loading in runoff from a transportation facility. Their results showed that particle delivery was not associated with a “first flush” but instead continued throughout the storm and followed the storm hydrology.

Morquecho and Pitt (2003) investigated the associations of heavy metals in stormwater with particulate and colloidal fractions. Turbidity, phosphorus, phosphate, magnesium, chromium, copper, iron, lead, and zinc had large decreases with filtration, especially for the more contaminated samples, while total solids and COD had much smaller changes with filtration, with substantial fractions associated with the filterable ( $<0.45 \mu\text{m}$ ) fraction. Robertson et al. (2003) analyzed urban sediment samples from roadways in the UK and determined that most sediment had an anthropogenic origin, primarily from automobiles. Mn, Fe, Zn and Pb were largely associated with the reducible fraction, whereas Cu was largely associated with the oxidizable fraction. Zn was the only metal with significant association with the exchangeable fraction.

Rose (2003) compared the solute-discharge hysteresis in an urbanized basin to a less-urbanized basin in the Atlanta (Georgia) metropolitan area. The less-urbanized stream’s hysteresis showed that the stream had much longer recession periods, allowing for more time for soil water to contribute to stream flow.

Kayhanian et al. (2002) addressed the impacts of non-detects (NDs) on estimation of constituent mass loading in water quality data. In this paper, different methods of data analysis were introduced to determine constituent mean concentrations from water quality datasets that include ND values. Depending on the number of NDs and the method of data analysis, differences ranging from 1 to 70 percent were observed in mean values.

McCorquodale et al. (2002) performed a study looking at the composition of urban rainwater in New Orleans. The samples were analyzed for water quality parameters: pH, total Kjeldahl nitrogen (TKN), nitrate ( $\text{NO}_3^-$ ), ammonia ( $\text{NH}_3$ ) and total phosphorus (TP). Average concentrations show clear seasonal variations with higher levels in spring and summer and lower levels in winter and fall for  $\text{NO}_3\text{-N}$  and TP. The findings suggest that for some species of nutrients such as  $\text{NH}_4^+$ ,  $\text{NO}_3^-$  and  $\text{PO}_4^{3-}$ , anthropogenic emissions are major sources. A strong inverse relationship generally was found between the observed nutrient concentration and the quantity of rainfall in a particular event; however, the total loading due to rainfall increased with increased amounts of rainfall but at a diminishing rate.

The research by McPherson et al. (2002) compared the pollutant loads in wet and dry weather in the highly urbanized Ballona Creek watershed. Models were used to compare the loading of the following pollutants: total suspended solids, biochemical oxygen demand, total nitrogen, total inorganic nitrogen, total Kjeldahl nitrogen, total phosphorus, copper, lead, arsenic, nickel, cadmium, and chromium. The results indicated that dry-weather flow contributed approximately 10-30% of the total annual flow discharged from Ballona Creek. The relative contribution to the annual pollutant load varied considerably between each pollutant. In general, the dry-weather-flow load was found to be significant, especially in years with lower precipitation totals.

Rose (2002) compared the major ion geochemistry of Piedmont streams in the Atlanta, Georgia region in order to investigate the effects of urbanization. The regression correlation coefficients for the ions that would evolve through mineral weathering (Ca, Mg, Na, and  $\text{HCO}_3^-$ ) were much higher in urban stream flow than in the less urbanized waters. This potentially indicated that stormwaters in the urban basin were more closely derived from a two-end member mixture (groundwater and street runoff) than waters from the less developed area, which represented a more complex mixture.

McPherson et al. (2001) compared the relative contributions of dry weather flow (DWF) and wet weather flow (WWF) from the highly urbanized Ballona Creek watershed (BCW) in Southern California using empirical and deterministic



models. DWF contributed approximately 10 – 30% of the total annual flow discharged from Ballona Creek, a significant contribution. Yamada et al. (2001c) compared the pollutant load from runoff that were collected from storm sewer pipes in 7 cities. The contribution of land use, soil, amount of rainfall, rainfall intensity and antecedent dry period was quantified. Choe et al. (2001) analyzed surface runoff from selected residential and industrial zones. The event mean concentrations of COD, SS, TKN, and TP in the residential zone were 313 mg/L, 279 mg/L, 8.45 mg/L, 1.98 mg/L, and those in the industrial zone were 80 mg/L, 106 mg/L, 5.07 mg/L, and 1.93 mg/L, respectively. The degree of first-flushing effect was in the following order: TKN > COD > SS > TP > PO<sub>4</sub>-P. The pollutant loads of the above constituents was highly correlated with SS. The report titled "The removal of urban litter from stormwater conduits and streams" (by Armitage et al.,) noted that little data was available on the nature and quantity of litter in stormwater drainage systems (Marais et al., 2001). The Council for Scientific and Industrial Research estimated in 1991 that 780 000 tonnes of waste a year entered the drainage systems of South Africa.

Smith (2001) presented a case study of stormwater and sediment analysis in flood control sumps in an urban watershed. The results suggested that: (1) first-flush samples may not reflect outfall concentrations of stormwater to the sump; (2) time-variable concentrations of pollutants in a sump can be related to the hydraulic characteristics of the basin; and, (3) post-event sediment analysis verified pollutant capture in the sumps. HEC-1 software was used to estimate the flow hydrograph for each outfall to a sump as part of the overall flow balance (Smith et al., 2001c). The results suggested that HEC-1 calculation provide a satisfactory estimate of the total runoff and its time-distribution to the sump. The hydraulic model was then used to estimate nonpoint loads of selected heavy metals to the sump and to the river

EMCs were analyzed by Behera et al. (2000) for areas of Toronto, Canada, that had both separate and combined sewer systems, and noted that the data followed the gamma and exponential probability distributions, in addition to the log-normal probability distribution. Lee and Bang (2000) investigated the relationship between pollutant loadings and runoff flows, especially the first flush in the urban areas of Taejon and Chongju, Korea. They found that the pollutant concentration peak occurred earlier than the flowrate peak in areas smaller than 100 ha where impervious area was more than 80%. However, in areas more than 100 ha with impervious area of less than 50%, the pollutant concentration peak followed the flow rate peak, with this second order occurring more frequently in watersheds with combined sewer systems. Mattson et al. (2000) investigated the event mean concentrations of a range of pollutants in urban stormwater runoff that entered the Severn Sound. In samples from the beach areas, they found *E. coli* concentrations exceeding 600 organisms/100 mL when rain events were greater than 20 mm. The model of the stormwater entering the Sound estimated a phosphorus loading of 1083 kg/yr.

The impact of experimental watershed acidification on xylem cation chemistry was evaluated in eight species at two sites in West Virginia (Clover Run and Fernow) and one site in Maine, BBWM. Experimental watershed acidification or N saturation using applications of (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> equivalent to twice the normal annual wet plus dry N and S deposition caused base cation mobilization followed by depletion that was detectable in sapwood xylem after about 8 yr. of treatment (Dewalle et al., 1999).

A study of stormwater-runoff quality from two adjacent urban watersheds in Singapore used continuous recording of rainfall and stream flow within the basins and systematic sampling of stormwater runoff during rainfall events. Correlations of EMC and SS and chemical oxygen demand (COD) loads to both antecedent-dry-weather period and rainfall characteristics were conducted (Chui, 1997). Muller *et al.* (1997) conducted a five-year study of the seasonal input variation and the distribution and residence time of herbicides in three Swiss lakes. The compounds investigated showed a conservative behavior in the water column of the lakes with triazine herbicides and the metabolites occurring in the epilimnion during or right after the application period and the annual input of atrazine depending on the rainfall during the application period. A three-year study (Vanburen *et al.*, 1997) of parking-lot discharges into an on-stream pond concluded that log-normal was a the better distribution for parking-lot runoff and creek baseflow while less suitable for creek event flow and pond baseflow. A normal distribution applied for soluble constituents (total dissolved solids [TDS], chlorides, sulphate, COD) and/or event outflow from the pond. Munn and Gruber (1997) studied the relationship between land use and organochlorine compounds in streambed sediment and fish in the Central Columbia Plateau in eastern Washington and Idaho and reported that most organochlorine compounds were still present in the environment.

A sampling program in North Carolina collected the first flush at 20 different sites covering ten different industrial groups (Line *et al.*, 1997). Zn and Cu were the most common metals found while other contaminants included volatile and semivolatile organics, pesticides, and conventional pollutants, especially, nutrients and solids, which had high concentrations when a significant amount of biological waste or exposed soil was present. Muscara *et al.* (1997) reported

typical pollutants, i.e., Fe, Zn, nickel (Ni), nitrate as nitrogen ( $\text{NO}_3\text{-N}$ ), and nitrite as nitrogen ( $\text{NO}_2\text{-N}$ ), leaving a highway construction site near Houston, Tex.

Thomson *et al.* (1997a) examined the relationships between surrogate parameters (i.e., SS, TDS, total volatile solids, and TOC) and other constituents of interest (e.g., metals, ionic species, and nutrients) by using the Minnesota highway stormwater quality database for regression analysis. The findings indicated that the metal and nutrient constituent relationships were limited to urban sites with similar environmental conditions. Further, statistical model analysis of monitoring results (Thomson *et al.*, 1997b) concluded that approximately 15 — 20 samples are required to provide reasonable estimates of the mean concentrations of runoff events for SS, TDS, TOC, and Zn.

### **Litter**

Litter in stormwater runoff was characterized by Kim *et al.* (2006a). The results showed that the litter was comprised of 90% vegetation and 10% non-vegetation material.

Armitage and Rooseboom (2000a) demonstrated that large quantities of litter are being transported in South Africa in urban stormwater runoff, and that the amount of litter produced was related to land use, vegetation, level of street cleaning and type of rainfall. The benefits of litter reduction were documented using their work in Australia and New Zealand, and design equations for sizing litter traps were proposed (Armitage and Rooseboom 2000b). Newman *et al.* (2000a) characterized the flotables found in urban stormwater runoff. The results of this study were to be used to develop transport models of the movement of and controls for these flotables.

The principal source of litter on the Bristol Channel of the United Kingdom was postulated as riverine derived from sanitary-wastewater debris originating from CSO (Williams and Simmons, 1997a). River bank clearances provided valuable information on litter accumulation and movement showing a distinctive correlation between flood events and litter movement. Some litter types have an increased input during flood events, e.g., sanitary-wastewater-derived material from combined sewer outfalls, whereas accumulation of other litter types could be due to their distribution throughout the catchment (Williams and Simmons, 1997b).

### **Nutrients**

Tsegaye *et al.* (2006) developed a chemical index to measure in-stream water quality in response to land-use/cover changes. Particulate, or total P, were shown to be early indicators of temporal changes in stream water quality. An investigation of nutrient loads from urban runoff showed that the total loads of nitrogen (N), zinc (Zn), etc., were nearly proportional to the length of the antecedent dry period, indicating that these loads were associated with atmospheric deposition (Shirasuna *et al.* 2006).

Groffman *et al.* (2002) studied the soil nitrogen cycle processes in urban riparian zones, through measurements of stream incision, water table depths, and pools, production (mineralization, nitrification), and consumption (denitrification) of  $\text{NO}_3^-$  in urban soils. The results suggested that urban hydrologic factors could increase the production and reduce the consumption of  $\text{NO}_3^-$  in riparian zones, reducing their ability to function as sinks for  $\text{NO}_3^-$  in the landscape.

Hranova *et al.* (2002) studied the qualitative, quantitative and environmental aspects of water resources management in the Chivero Basin, Zimbabwe, which is in the advanced stages of eutrophication. Background pollution in the basin varied from 0.1 to 0.3 mg/L and from 0.1 to 0.4 mg/L for nitrates and phosphates (as total P), respectively. At Marimba River confluence the annual median values recorded were 3.5 and 4.4 mg/L for ammonia and phosphates, respectively, thus exceeding the effluent discharge regulations 7-9 times. The major nutrient sources contributing to this status are associated with operational problems of the treatment facilities and diffuse sources of pollution from pastures irrigated with effluent, as well as from urban storm water.

Owens and Walling (2002) tested the phosphorus content of fluvial sediment in rural and industrialized basins in Yorkshire, UK. The total phosphorus (TP) content of fluvial sediment in the rural basin was generally within the range 500-1500  $\mu\text{g g}^{-1}$ , with little evidence of any major downstream increase in TP content. In contrast, fluvial sediment from the industrialized catchments exhibited both higher levels of TP content and marked downstream increases, with values of TP content ranging from less than or equal 2000  $\mu\text{g g}^{-1}$  in headwater areas upstream of the main urban and industrial areas, to values > 7000  $\mu\text{g g}^{-1}$  at downstream sites, due mostly to P inputs from point sources, such as sewage treatment works (STWs) and combined sewer overflows. Based on the sediment samples collected from the study basins, a simple four-fold classification which relates the TP content of suspended sediment to upstream land use has been established.

Both the range and the absolute values of TP content tend to increase with an increase in the level of urbanization and industrialization.

Ball and Abustan (2000) investigated the phosphorus export from an urban catchment in Sydney, New South Wales, Australia, and derived a relationship between inorganic suspended solids and particulate phosphorus for this catchment. These results were to be used to predict the performance of detention ponds and/or wetlands for treating this runoff.

Sixteen largely agricultural watersheds in the upper portion of the North Bosque River of central Texas were reported by McFarland and Hauck (1999). The proportion of total P (TP) in runoff represented by soluble reactive P (SRP) also increased as the percent of dairy waste application fields above a sampling site increased.

Fluxes of total phosphorus (P), total phosphate, and total organic P from seven small watersheds on the Atlantic Coastal Plain of Maryland for up to 25 years were reported by Correll et al. (1999), indicating cropland watershed's P flux were much higher than forested watershed and increased significantly with precipitation. The Bear Brook Watershed in Maine (BBWM) was the sight of a paired watershed study in which the West Bear (WB) catchment was being artificially acidified with  $1,800 \text{ eq ha}^{-1} \text{ y}^{-1}$  of  $(\text{NH}_4)_2\text{SO}_4$  resulting in changes in the soil and stream chemistry, while the East Bear (EB) serves as the control (Norton et al., 1999). P chemistry in streams was evaluated at the pair watershed study at the BBWM, indicating the export of Al and P was greater from the treated watershed because the induced acidification was translocating more Al from soils to the streams and the export of P was related to acid-soluble Al particulate material (Roy et al., 1999). One hundred and sixty-two rainfall-induced soil erosion tests were conducted to assist in predicting soil loss and subsequent increase in total suspended solids, indicating soil loss was dependent upon rainfall intensity, and the soil's shear and compressive strength (Liu et al., 1999). After six years of monitoring flow and water quality Jaynes et al. (1999) conclude nitrate appears to be the primary agriculturally related pollutant of concern in Walnut Creek, California thus management practices designed to reduce  $\text{NO}_3$  leaching from fields and increase removal within the watershed/stream system should receive primary consideration.

### **Microorganisms**

Traister and Anisfeld (2006) examined the variability of indicator bacteria at different time scales in the upper Hoosic River watershed. Bacterial levels were higher in more developed watersheds; higher in summer than in winter months; higher in storms compared to baseflows; and higher in early morning compared to afternoon runoff periods. Shanks et al. (2006) evaluated the dynamics of fecal sources and contamination in an Oregon bay. Fecal sources were statistically linked more closely to ruminants than to humans; there was a 40% greater probability of detecting a ruminant source marker than a human source marker across the basin. In southern Lake Michigan, rainfall events were found to increase *E. coli* counts in the near-shore sands and lake waters, but they rapidly declined to pre-rain concentration. The authors said that when examining indicator bacteria source, flux, and context, the entire "beachshed" should be considered as a dynamic interacting system (Whitman et al. 2006).

Selvakumar and Borst (2006) examined the variations of microorganism concentrations in urban stormwater runoff. Concentrations of microorganisms were significantly affected by the season during which the samples were collected. The relationships between indicator bacteria and pathogens were poorly correlated and were not statistically significant. Wickham et al. (2006) described empirical modeling of bacterial contamination of surface waters in Maryland. The likelihood of bacterial contamination was highest for small watersheds with well-drained and erodible soils and with a high proportion of urban land adjacent to streams. This was thought due to the efficient "connectedness" of urban lands to the streams through the sewer system.

Sullivan et al. (2005) assessed the water quality and land use association in the Tillamook Bay watershed (Oregon). The results to date demonstrated that storms with high fecal coliform bacteria concentrations were those that occurred during the fall and/or those that were preceded by relatively dry conditions. These storms also had high rainfall intensity. The die-off of pathogenic *E. coli* in sewage contaminated water was assessed by Easton et al. (2005). Die-off rates of the pathogenic strains were significantly greater than those of the indicator bacteria; however, the results indicated a bi-phase response with initial rapid decay and slower decay later in the study.

Dwight et al. (2002) investigated the associations between storm events, urban runoff and coastal water quality using a spatial and temporal analysis of 2 years of data in Orange County, California. Bacterial levels rose substantially across all sites during wet months, and river discharge and bacterial levels were all highest during the winter with the most rainfall. Precipitation was significantly associated (Spearman rank bivariate correlation,  $P$  less than or equal 0.01) with water

discharged from the rivers. River discharge was significantly associated with bacterial levels at 20 out of 22 beaches, with the strongest associations at sites next to rivers. The results indicated that urban river discharge is a primary source of Southern California's coastal water pollution and, as a result, swimming at beaches near rivers may pose a significant public health risk. Paul et al. (2002) reviewed the Bacterial TMDL for impaired water bodies in Texas. The primary aim of the study was to explore the possibility of clustering the waterbodies into groups having similar watershed characteristics. Studying the watersheds as a group would reduce the number of required TMDLs and thereby will help in reducing effort required for restoring the health of the impaired waterbodies in Texas. The main characteristics being considered for the classification of waterbodies were designated use of the waterbody, sources of pathogens, frequency of water quality violation, location and type of the waterbody, and the size of the watershed.

Jeng et al. (2002) investigated the fate of indicator organisms (fecal coliforms, *E. coli*, and enterococci) in stormwater runoff when the water enters brackish recreational waters. Results indicated that satisfactory water quality of Lincoln Beach was observed during dry weather periods. Concentrations of indicator organisms in both water column and sediment, however, significantly increased during and after heavy stormwater runoff, particularly at sites near the Jahncke Canal discharge point. However, the elevated titers of indicator organisms decreased to background levels after 24 to 48 hours. Overall removal rate constants for fecal coliform, *E. coli*, and enterococci from the water column ranged from 0.112 to 0.124 h<sup>-1</sup>, 0.106 to 0.170 h<sup>-1</sup>, and 0.101 to 0.110 h<sup>-1</sup>, respectively. Attachment of microbial indicators to suspended matter and subsequent sedimentation appeared to be a significant fate mechanism. Results indicated that enterococci may be a more stable indicator than *E. coli* or fecal coliform and consequently a more conservative indicator under marine water conditions.

Brion et al. (2002) investigated the prevalence of F-specific RNA coliphage serotypes as indicators of fecal contamination in the waters of a small, well-defined watershed. Results from laboratory studies showed that F+RNA differed in their survival in water and that Type IV strains were the least persistent. Type III F+RNA were found to be reliably related to the release of uncontrolled human fecal material in the watershed, but the results of this study suggest that further study is required before utilizing for fecal source identification in natural waters.

As part of a modeling exercise for predicting removal of beach closure restrictions after a storm event, Jin et al. (2000) characterized the movement of indicator organisms (*E. coli*, *enterococci*, and fecal coliforms) from stormwater outfalls in Lake Ponchartrain to Lincoln Beach in New Orleans. They found that, as expected, a rapid decrease in organism concentration occurred near the outfall and that two or three days after pumping, indicator organism concentrations at Lincoln Beach were below the health standards for swimming. Their data also showed that *E. coli* was a better indicator organism for fresh water environments, while *enterococci* was more suited for use in marine or brackish environments.

Francy et al. (2000) related potential sources of microorganisms (total coliforms, *Escheria coli*, and *Clostridium perfringens*) to receiving water quality. In general, fewer organisms were found in the groundwater. Land use was found to have the greatest influence on bacterial indicators in stream water, while presence of septic systems and well depth had the greatest influence on the bacteria concentration in groundwater. Skerrett and Holland (2000) found that *Cryptosporidium* oocyst occurrence in Dublin, Ireland, area waters increased after a heavy rainfall, likely due to increased the runoff volume into the receiving water. Their results also showed that *Cryptosporidium* oocysts were widely dispersed in the Dublin-area aquatic environment.

Waters adjacent to the County of Los Angeles, California receive untreated runoff from a series of storm drains year round, in which persons swim there were exposed to these untreated waters. Measures of exposure included distance from the storm drain, selected bacterial indicators (total and fecal coliforms, enterococci, and *Escherichia coli*), and a direct measure of enteric viruses. It was found higher risks of a broad range of symptoms, including both upper respiratory and gastrointestinal, for subjects swimming (a) closer to storm drains, (b) in water with high levels of single bacterial indicators and a low ratio of total to fecal coliforms, and (c) in water where enteric viruses were detected (Haile et al., 1999). Particulate fluxes of aliphatic and aromatic hydrocarbons were measured with a sediment trap moored at 80 m depth offshore of Monaco (200 m water column) during an 18-month period (Raoux et al., 1999). Timperley (1999) described the concepts of chemical bioavailability and its relevance to urban stormwaters and streams.

Water samples were collected from four locations within the Munnell Run Watershed in Mercer County, Pennsylvania, and analyzed for fecal coliforms by MPN and enteric phages by plaque assay using *Salmonella typhimurium* WG 49 and *Bacteroides fragiles* HSP 40 as hosts. The presence of host specific phages indicate the existence of septic discharges in the watershed, but both fecal coliforms and enteric viruses persist in stream systems, especially during the summer

months (Brenner et al., 1999).

Ferguson et al. (1998) found 50% of 34 first-flush samples taken from two major watersheds tested positive for *giardia* cysts and *cryptosporidium* oocysts. This information will be used to review the current source water monitoring program conducted by the Metropolitan Water District of South Calif. and to assist in the implementation of watershed management strategies to control protozoa in source waters. A literature review (Bagley et al., 1998) revealed that the cysts of *giardia lamblia* and *cryptosporidium* species oocysts are commonly detected over a wide range of concentrations in a wide variety of aquatic systems.

In a southern California study, eight of 12 plants were positive for *salmonella* at the chlorination/dechlorination site and effluents from 11 of 12 plants were positive for *salmonella* when sampled downstream of the chlorination/dechlorination site before merging with the receiving stream (Kinde et al., 1997). Two of the three control sites, i.e., an urban-stormwater-runoff and a raw-potable-water reservoir, were also positive for *salmonella*. Fecal coliform (FC) and fecal streptococci densities were detected at 12 sites in the Buffalo River watershed during 1992-1993 with the highest levels of indicator bacteria in the water column coinciding with rainfall events; however three sites closest to the Buffalo River violated New York State water quality standards of FC levels in 79% of all samples. SS were strongly correlated with FC ( $r = 0.86$ ) in the upper watershed during the summer months when flow velocities were greatest and solids may play an important role in transporting bacteria into the Buffalo River (Pettibone and Irvine, 1997). Urban stormwater runoff from various large urban developments in South Africa were investigated to establish the extent of fecal pollution (Jagals, 1997). The level of sanitation ranged from pit and bucket latrines to full-waterborne-sewerage systems. Stormwater runoff from developing urban settlements, as well as developed urban structures, constituted a major source of pollution for a downstream river catchment used as a source of water for human consumption and recreation.

### **Toxicity**

Parker et al. (2000) analyzed the sediment found in urban stormwater runoff in the Phoenix, Arizona, metropolitan area. They found that the inorganic content of the sediments was similar to that in soils that were not impacted by urban runoff. The metals concentrations (Cd, Cu, Pb, and Zn) were higher, but below levels that would recommend remediation. Arsenic concentrations were above recommended levels; however, this contribution likely was geologic not anthropogenic. Chlordane, DDT (and DDE and DDD), dieldrin, toxaphene, and PCBs were found in the sediments at all sampling locations. Sediment toxicity was seen, but could not be explained based on their chemical results. Vollertsen and Hvitved-Jacobsen (2000) investigated the resuspension of sewer solids in combined sewers. They found that sewer solids that were undisturbed for up to two weeks were more easily resuspended and their oxygen uptake rate was significantly greater than fresh solids, indicating that the flushing of these solids into receiving waters may cause oxygen depletion problems.

Love and Woolley (1999) found that stormwater was alarmingly more toxic than treated sewage. The Concord project, funded by EPA, examined the possibility of needed treatment for reuse of residential area stormwater before source area. Runoff from sawmills in British Columbia was monitored for toxicity by Bailey et al. (1999) and found that 42 of the 58 samples were toxic to juvenile rainbow trout. Divalent cations, especially zinc, were the most common source of the toxicity. Tannins and lignins, associated with bulk log handling, were responsible for the remaining toxicity.

A stormwater toxicity study for Santa Monica Bay, Calif. included analysis of surface water and sediment samples following four significantly-sized storms. Toxicity was present in water samples offshore and was proportional to the concentration of runoff in the plume and changes in sediment characteristics, such as grain size and total organic carbon (TOC), were also evident (Bay et al., 1998).

### **Heavy metals**

Selenium and mercury accumulations in the sediment, groundwater and surface water in the Las Vegas Wash were measured by Cizdziel and Zhou (2005). Selenium was higher in samples influenced by urban runoff and groundwater resurfacing. Morrison and Benoit (2005) investigated the temporal variability in physical speciation of metals and organic carbon during a rain-on-snow event. The majority of the metals were transported with the coarse silt fraction, while the organic carbon was mostly associated with the colloidal fraction.

Glenn et al. (2002) investigated the influence of chemistry, hydrology and suspended solids concentration on partitioning of heavy metals to particles and the applicability of this information to design of on-site controls for stormwater quality. Aqueous chemistry and residence time characteristics such as low alkalinity, low hardness and short pavement residence

time (less than 30 minutes) could result in a majority of the heavy metal mass remaining in solution at the edge of the pavement with trends in partitioning only approaching equilibrium conditions towards the end of the event as heavy metals partition to entrained solids.

Fatoki et al. (2002) investigated trace metal pollution in the Umtata River. High levels of Al, Cd, Pb, Zn and Cu were observed, which may affect the "health" of the aquatic ecosystem. Generally the sources of the metals in the river appeared to be diffuse, including rural, urban and agricultural runoff sources in the catchment. Tuccillo (2002) analyzed heavy metals in stormwater at six outfalls draining nonindustrial land uses in Monmouth County, New Jersey. Of the heavy metals, only Cu and Zn were found in all samples, mostly in dissolved form. Larger colloids ( $\geq 0.45 \mu\text{m}$ ) were composed mostly of Fe, Al, and Si. Organic colloids were found mostly in the 0.01-0.45- $\mu\text{m}$ -size range. Wardas et al. (2002) investigated the levels of heavy metals in sediments of the water and wastewater system in Cracow. Estimation of the quantity of metals in samples was done based on sediment samples from "Rudawa", "Dlubnia" and "Raba" drinking water plants and "Plaszow" and "Kujawy" sewage treatment plants.

Buffleben et al. (2002) investigated the concentrations of hazardous metal pollutants associated with the aqueous and suspended solids phases entering Santa Monica Bay from the Ballona Creek watershed during wet weather flow. Other objectives of this study were to evaluate during a storm event the relationship between (1) soluble and sorbed metals, (2) storm flow and pollutant loading, including a determination of a first flush was present, and (3) total mass loading of pollutants and relative pollution loading from three watershed sub-basins. The results indicated the suspended solids phase primarily transported the mass for five of the six hazardous metals studied: cadmium, chromium, copper, lead, and nickel. Arsenic was found primarily in the aqueous phase.

Ramessur and Ramjeawon (2002) determined the lead, chromium and zinc concentrations in sediments from the St. Louis River in Mauritius. The mean concentration of Cr ( $105 \pm 30 \text{ mg kg}^{-1}$ ), Zn ( $167 \pm 30 \text{ mg kg}^{-1}$ ) and Pb ( $14 \pm 7 \text{ mg kg}^{-1}$ ) in sediments in an urbanized and industrialized were well below the limits of 600, 2500 and 700  $\text{mg kg}^{-1}$  in the draft standards (24% clay and 10% organic matter by weight) from the Netherlands. Industrial contamination appeared to undergo rapid dilution in the estuary as Cr had high levels near point sources from industries, but decreased rapidly in amount in the estuary possibly because of dilution by other sediments. The significant Zn levels from upstream to the estuary suggest that the potential sources could be the adjacent motorway and road runoff. Pb was two folds higher in the sediments in the estuary of St. Louis River compared to upstream and downstream indicating accumulation of Pb in estuarine sediments. The potential sources of sediment Pb were from the adjacent motorway and road runoff.

Robertson et al. (2002) characterized the geochemical and mineral magnetic qualities of urban sediment particulates from both inner and outer city road surfaces in Manchester, UK. High metal concentrations, coupled with the largely ferrimagnetic multi-domain (MD) mineral magnetic composition of the particulates, indicated anthropogenic origin, primarily particulates derived from automobiles. Iron and Pb concentrations showed a clear spatial trend, whereby concentrations were enhanced in the inner city samples. Lead concentrations for inner and outer city samples averaged 354 and 185  $\mu\text{g g}^{-1}$ , respectively. Iron concentrations for inner and outer city samples average 11302 and 6486  $\mu\text{g g}^{-1}$ , respectively. Sequential extraction analysis showed Mn, Fe, Zn and Pb were largely associated with the reducible fraction, whereas Cu was largely associated with the oxidizable fraction. Zinc was the only metal showing significant association with the exchangeable fraction (up to 33%), suggesting that it may be the most susceptible metal to mobilization during runoff.

Gabriel et al. (2002) investigated the availability of atmospherically deposited mercury to runoff and receiving waters. The review illustrated the importance of the relationship between mercury deposition and runoff efficiency for common watershed surfaces. The purpose of the review was to illustrate that the availability of atmospherically deposited mercury is a function of watershed characteristics including: terrestrial sorption properties, surface water chemistry, rainfall intensity, antecedent dry weather periods, and photochemical reactions.

The fate and transport of metallic pollutants through a watershed were related to the characteristics of the solid particles to which they are bound (Magnuson et al., 2001). Because the particles most often associated with metal pollution have nominal diameters of  $< 50 \mu\text{m}$ , split-flow thin-cell (SPLITT) fractionation was investigated as a means to study the metal loading as a function of particle settling rate. Sansalone et al. (2001) showed that urban storm water levels of Zn, Cu, Cd, Pb, Cr, and Ni can be significantly above ambient background levels, and for many urban and transportation land uses, often exceed surface water discharge criteria for both dissolved and particulate-bound fractions. The authors advocated a multiple-unit-operation approach to stormwater treatment.

Turer et al. (2001) investigated the accumulation of metals in roadside soils at a site for which extensive runoff data were also available. The results demonstrated that heavy metal contamination in the top 15 cm of the soil was very high compared to local background levels. The maximum measured amount for Pb was 1980 ppm (at 10-15 cm depth) and for Zn was 1430 ppm (at 0-1 cm depth). The correlation to organic C is stronger than the correlation to depth. Cluster analysis of the heavy metal data showed that Pb, Zn and Cu were closely associated to one another, but that Ni and Cr did not show an association with each other or with either organic C or depth. Mass balance calculations for Pb in soil showed that most of the Pb came from exhausts of vehicles when leaded gasoline was in use, with about 40% of the Pb retained in the soil. Zinc and other trace metal (V, Cr, Co, Ni, Cu, Cd, and Pb) concentrations were measured in the Atlanta metropolitan region and in relatively undeveloped watersheds within the Georgia Piedmont and Blue Ridge Provinces (Rose et al., 2001). Zinc concentrations in street runoff [median (Zn) = 905 µg/L] were significantly greater than zinc concentrations in Peachtree Creek storm runoff [median (Zn) = 60 µg/L], which were, in turn, greater than zinc concentrations in non-storm baseflow in Peachtree Creek [median (Zn) = 14 µg/L]. A two end member mass balance model suggested that a large proportion of the zinc present in the street runoff was adsorbed and transported by the suspended sediment.

Mosley and Peake (2001) characterized urban runoff from a catchment in Dunedin, New Zealand during base flows and storm flows from five rainfall events. Fe and Pb were found to be predominantly particle-associated (>0.4 µm) with concentrations increasing significantly at the beginning of storm run-off. In contrast, the majority of Cu and Zn was found in the <0.4 µm fraction prior to rain but a significant proportion was present in the > 0.4 µm fraction during the initial period of storm flows. The results indicate that Cu and Zn may be more bioavailable, and more difficult to remove by stormwater treatment, than Pb. The pH level and the concentration of major ions (Ca<sup>+2</sup>, Na<sup>+</sup>, Mg<sup>+2</sup>, K<sup>+</sup>), dissolved PO<sub>4</sub>-P, and NO<sub>3</sub> generally decreased during storm flows due to rainwater dilution. Concentrations of total N and P often increased during the initial period of storm run-off, likely because of wash-off of particulate plant material. Significant amounts of non-point source runoff were shown to enter the Santa Monica Bay from the Ballona Creek Watershed during wet weather flow. Buffleben et al. (2001) monitored four storms in the watershed. The watershed is developed mostly with residential, commercial and light industrial land uses. They found that the suspended solids phase primarily transported the mass for five of the six metals studied: cadmium, chromium, copper, lead, and nickel. Arsenic was found primarily in the aqueous phase.

Williamson and Morrissey (2000) modeled the build-up of heavy metals (Pb, Zn, and Cu) in urban estuaries due to stormwater contamination, with the model being based upon the behavior of the metals in runoff and during transport in the estuarine system.

Urban stormwater runoff was targeted by Neto et al. (2000) as a potential source for the elevated metals (Pb, Zn, Ni, Cu and Cr) concentrations found in Jurujuba Sound in Southeast Brazil. Investigation of sediment cores indicated that the increase in sediment metals concentration occurred at approximately the time that rapid urbanization began in the watershed.

Barbosa and Hvitved-Jacobsen (1999) examined heavy metals in highway runoff in Portugal. Concentrations of Cd and Cr were usually lower than the detection limit (1 µg/L), copper levels were between 1 and 54 µg/L, lead from 1 to 200 µg/L, and zinc from 50 to 1460 µg/L. A lowering of the pH value increased the desorption of previously retained Zn, Cu and Pb from the soil lining the infiltration pond used to treat this water.

Barry et al. (1999) identified salinity effects on the partitioning of heavy metals in the stormwater canals entering Port Jackson (Sydney), Australia. Cu, Pb, and Zn was found increasingly in dissolved phases as the salinity increased in the lower sections of the canals. During high flows, most of the metals seemed to be rapidly exported from the estuary as a discrete surface layer, while low flows contributed most of the metals to the estuary. Birch (1999) also studied the Port Jackson estuary sediments. Historical industrial activity was responsible for much of the contaminated sediments, but atmospheric contributions were also likely important. Stormwater from small catchments, along with sewer overflows, had no observable effects on the distribution of heavy metals in surficial sediments.

Grout et al. (1999) studied the colloidal phases in urban stormwater runoff entering Brays Bayou (Houston, Texas). Colloids in the filtrate after 0.45 µm filtering and further separation by ultracentrifuging, accounted for 79% of the Al, 85% of the Fe, 52% of the Cr, 43% of the Mn, and 29% of the Zn present in the filtrates. Changes in the colloidal composition were caused by changes in colloidal morphologies, varying from organic aggregates to diffuse gel-like

structures rich in Si, Al, and Fe. Colloids were mostly composed of silica during periods of dry weather flow and at the maximum of the stormwater flow, while carbon dominated the colloidal fraction at the beginning and declining stages of the storm events. Garnaud et al. (1999) examined the geochemical speciation of particulate metals using sequential extraction procedures for different runoff sources in Paris, France. They found that most metals were bound to acid soluble particulates in the runoff but that copper was almost entirely bound to oxidizable and residual fractions.

Datta and Subramanian (1998) report that despite a very dense population in its watershed, the lower Ganges-Brahmaputra-Meghna drainage basin remains relatively-unperturbed alluvial basin with regards to heavy metal pollution, due in part to a very high rate of sediment deposition.

A study by Sansalone and Buchberger (1997) analyzed stormwater runoff at five sites on a heavily traveled roadway in Cincinnati, Ohio. They found that the event-mean concentrations (EMC) of Zn, cadmium (Cd), and copper (Cu) exceeded surface-water-quality-discharge standards. Further, it was noted that Zn, Cd, and Cu are mainly in the dissolved form while other metals, i.e., lead (Pb), Fe, and aluminum (Al) are mainly bound to particles.

Analytical techniques were used to determine the speciation of Cu and Ni in point and non-point source (NPS) discharges and found that the existence of a strong metal-complexing ligand in wastewater effluent, and to a lesser degree, surface runoff must be accounted for when evaluating metal treatability (Sedlak *et al.*, 1997).

### **Organic toxicants**

Hwang and Foster (2006) characterized the PAHs in urban runoff flowing into the tidal Anacostia River. Most PAHs were associated with the particle phase and the higher molecular weight PAHs were ascribed to automobile-originated pyrogenic PAHs. A comparison of agricultural, industrial and urban area runoff was performed by Masco et al. (2006). In this study, the industrial and agricultural sources were predominant. Wada et al. (2006) investigated the characteristics of refractory dissolved organics in stormwater runoff. Treatment by soil infiltration reduced their concentrations.

Suarez et al. (2006) examined the levels of dioxin present in Houston (Texas) stormwater runoff. Dioxin concentrations in runoff were generally the same as, or lower than, measured in the receiving water. Principal component analyses indicated that the dissolved runoff signatures matched those observed in dissolved ambient water in the channel, while the suspended-sediment runoff signatures were similar to those observed in dry air deposition in the Houston area.

Borden et al. (2002) evaluated the presence and concentration of MTBE and aromatic hydrocarbons in North Carolina stormwater runoff. m,p-Xylene and toluene were detected in over half of all samples analyzed, followed by MTBE; o-xylene; 1,3,5-trimethylbenzene; ethylbenzene; and 1,2,4-trimethylbenzene. Benzene, DIPE, TAME and 1,2,3-trimethylbenzene were detected in less than or equal 10% of the samples analyzed. Median contaminant concentrations (when detected) varied from 0.07 µg/l for ethylbenzene to 0.11 µg/l for toluene. All of the locations with significantly higher contaminant concentrations were associated with direct runoff from a gas station or discharge of contaminated groundwater from a former leaking underground storage tank.

Moillon et al. (2002) sampled runoff from different types of urban surfaces (11 roofs representing four different covering materials, two courtyards and six streets) and from drainage outlets in the 'Le Marais' experimental catchment in the center of Paris. The total aliphatic hydrocarbon concentration medians ranged from 345 to 827, from 297 to 790, and from 393 to 1359 µg L<sup>-1</sup> in the roof, courtyard and street samples, respectively. The levels found at the catchment outlet during dry and wet weather periods were of the same order of magnitude, i.e. 700 µg L<sup>-1</sup>. The particulate phase represented 85% of the total aliphatic hydrocarbon content whatever the sample.

The concentrations of polychlorinated dibenzo-p-dioxins and dibenzofurans in the sediments from the River Po (Italy) were studied by Fattore et al. (2002). The sum of polychlorinated dibenzo-p-dioxins (PCDDs) and dibenzofurans (PCDFs) concentrations, and the toxic equivalent content, ranged from 121 to 814 and from 1.3 to 13 ng/kg dry weight sediment, respectively. These levels of contamination seemed lower than in the sediments of rivers draining highly industrialized areas. Principal component analysis suggested that widespread sources, such as urban runoff and domestic wastewaters, were probably the main cause of these levels of PCDDs and PCDFs.

Mai et al. (2002) investigated the spatial distribution of chlorinated hydrocarbons and PAHs in riverine and estuarine sediments from the Pearl River Delta, China. Concentrations of chlorinated pesticides in the riverine sediment samples ranged from 12 to 158 ng/g, dry weight, while those of PCBs range from 11 to 486 ng/g, and estuarine sediments ranged



from 6-1658 ng/g for chlorinated pesticides, while concentrations of PCBs are in the range 10-339 ng/g. Total PAH concentration ranged from 1168 to 21,329 ng/g in the riverine sediment samples, whereas the PAH concentration ranged from 323 to 14,812 ng/g in the sediment samples of the Estuary. Possible factors affecting the distribution patterns were discussed based on the usage history of the chemicals, hydrologic condition, and land erosion due to urbanization processes.

Furumai et al. (2002a) performed a runoff monitoring study of a highway drainage system in Switzerland. The runoff samples with higher SS concentration had higher heavy metals and PAH concentrations. The particle-bound Zn, Cu, Pb, and PAH concentrations were 155-524 µg/L, 29-69 µg/L, 13-46 µg/L, and 1.3-3.3 µg/L. Particle size distribution analysis revealed that the runoff samples with higher SS concentrations contained coarser size fractions. The contents of heavy metals (Zn, Cu, and Pb) were about ten times higher in the runoff samples than in the three size-fractionated dusts (less than or equal 50, 50-125, 125-250 µm fractions). The PAH content was higher in the dusts than the runoff samples, although the contents were both in the same range of 10-50 µg/g. The PAH profiles in the fine size fractions (less than or equal 50, 50-125, and 125-250 µm) of the dusts looked similar except for higher percentage of B(a)A in the less than or equal 50 µm fraction.

Heberer (2002) tracked persistent pharmaceutical residues from municipal sewage to drinking water through the natural water system in Berlin (Germany). The results from several monitoring studies between 1996 and 2000, pharmaceutically-active compounds (PhACs) such as clofibric acid, diclofenac, ibuprofen, propylphenazone, primidone and carbamazepine were detected at individual concentrations up to the µg/l-level in influent and effluent samples from sewage treatment plants (STP) and in all surface water samples collected downstream from the STPs. Under recharge conditions, several compounds were also found at individual concentrations up to 7.3 µg/l in samples collected from groundwater aquifers near to contaminated water courses. Holthaus et al. (2002) investigated the potential for estradiol and ethinyl estradiol to sorb to suspended solids and sediments in British rivers. The purpose of determining this potential was because the endocrine-disrupting impact of steroid estrogens on fish will be strongly influenced by their distribution between sediment and water. Using anaerobic conditions to inhibit biodegradation, it was found that 80 to 90% of binding to bed sediments was complete within 1 d, but that an equilibrium had not been reached after 2 d. The  $K_d$  values for suspended solids suggested less than 1% removal of the steroid estrogens from the aqueous phase.

Kolpin et al. (2002) performed a nationwide survey of pharmaceuticals, hormones and other organic wastewater constituents in U.S. streams in 1999 and 2000. Organic wastewater constituents (OWCs) were prevalent during this study, being found in 80% of the streams sampled. The compounds detected represent a wide range of residential, industrial, and agricultural origins and uses with 82 of the 95 OWCs being found during this study. The most frequently detected compounds were coprostanol (fecal steroid), cholesterol (plant and animal steroid), N,N-diethyltoluamide (insect repellent), caffeine (stimulant), triclosan (antimicrobial disinfectant), tri(2-chloroethyl)phosphate (fire retardant), and 4-nonylphenol (nonionic detergent metabolite). Measured concentrations for this study were generally low and rarely exceeded drinking-water guidelines, drinking-water health advisories, or aquatic-life criteria.

Sherrard et al. (2002) investigated the comparative toxicity of chlorothalonil and chlorpyrifos to *Ceriodaphnia dubia* and *Pimephales promelas*. In the experiments *P. promelas* was more sensitive to chlorothalonil, and *C. dubia* was more sensitive to chlorpyrifos. The results of this study illustrated differences in species' sensitivities to chlorothalonil and chlorpyrifos as well as differences in the duration of the exposure necessary to illustrate effects that might be elicited from pesticide exposures.

Atmospheric deposition of particulate matter, organic carbon and PAHs was measured at two stations in an urban area (Ozaki et al., 2001). The deposition fluxes of particulate matter and organic carbon were nearly constant over the sampling periods, while PAHs had seasonal variability. The first flush phenomenon was clearly observed during all the rainy periods. Although the PAHs in runoff agreed with that of atmospheric deposition, their fluxes were several times larger. Loading of dissolved organic carbon (DOC) from parking lot storm runoff was found to be a significant, yet relatively neglected, source of elevated DOC concentration in urban streams (Lee and Schwartz, 2001). This study investigated DOC transport and loading from an paved parking lot during rainstorm events in order to elucidate impacts of the stormwater runoff on the chemistry of an urban stream. DOC measurements from the parking lot showed that the interevent period between storms and the precipitation intensity controlled the maximum DOC concentration and the time required to reach the maximum DOC concentration, respectively.

In the central Paris district of "Le Marais," Gonzalez et al. (2000) found PAHs primarily in the particulate phase in all

catchments, with the median concentration in combined sewer overflows of 204 ng/L. Phenanthrene, anthracene, fluoranthene and pyrene were the most observed compounds. The results indicated that atmospheric deposition was an important source of PAHs in urban stormwater runoff. Ngabe et al. (2000) analyzed urban stormwater runoff in coastal South Carolina for PAH content. The authors found the highest concentrations (5590 ng/L) of PAHs in runoff from Columbia, a major metropolitan area, and lower concentrations (282 ng/L) from the small town of Murrells Inlet. The PAH profiles in the runoff from the two urban areas were similar to those found in atmospheric deposition and unlike those in used crankcase oil. However, the aliphatic fraction of the organics in Columbia's runoff were more similar to used crankcase oil than to urban aerosols.

Shinya et al. (2000) investigated the concentrations of metals and PAHs in the runoff from four urban-highway rainfall drains. The results showed a first flush of both metals and PAHs. Most of the metals were tied up with the particulate matter, as were the higher molecular weight PAHs. Phenanthrene, fluoranthene, and pyrene comprised about 50% of the quantified PAH constituents in each sample. Smith et al. (2000a) analyzed for PAHs in stormwater runoff from four locations in an urban area: a gas station, a highway off-ramp, and a low- and a high-traffic volume parking lot. The gas station site produced the highest total PAH loading (2.24 g/yr/m<sup>2</sup>), followed by the high-traffic-volume parking lot (0.0556 g/yr/m<sup>2</sup>), the highway off-ramp (0.052 g/yr/m<sup>2</sup>), and the low-traffic-volume parking lot (0.0323 g/yr/m<sup>2</sup>). PAH concentrations were usually highest during the 'first flush' of storm-water runoff and tapered off rapidly as time progressed. The concentrations and characteristics of organic carbon (as DOC) in surface waters in Arizona were studied by Westerhoff and Anning (2000). Fluorescence measurements indicated that DOC in desert streams was from autochthonous sources; however, DOC in unregulated upland rivers and desert streams shifted from autochthonous to allochthonous sources during runoff events. The urban water system affected temporal variability in DOC concentration and composition.

Analysis of patterns in pesticide use revealed that concentrations of herbicides and insecticides in agricultural streams, and in most rivers in agricultural regions, were highest in those areas of the nation with the greatest agricultural use. More than 95% of the samples collected from streams and almost 50% of samples collected from wells contained at least one pesticide (Gilliom et al., 1999).

Fisher et al. (1999) found trace concentrations of dioxins and furans in urban runoff entering Santa Monica Bay, California over a 1-year sampling period. Concentrations of polychlorinated dioxin and polychlorinated furan peaked during storms. The congener and isomer profiles resembled profiles found in lake sediments and rainwater more than they resembled profiles found in urban sources such as dioxins from incinerators or dioxins in contaminated commercial products. Runoff from open land use areas had lower concentrations than runoff from developed land uses. Wenning et al. (1999) studied polychlorinated dibenzo-p-dioxins/dibenzofurans (PCDD/Fs) in stormwater collected from 15 outfalls entering San Francisco Bay, California. Monitoring locations were located both adjacent to and distant from petroleum refineries and included mixed urban/commercial/residential land uses. Few significant differences were found between stormwater in areas adjacent to vs. further from the petroleum refineries. They found that nonindustrialized urban locations may represent important sources of PCDD/Fs to San Francisco Bay.

The environmental fate, chemistry, and toxicity of aircraft deicing compounds (mainly ethylene, propylene, and diethylene glycol) commonly used in Canada was investigated by Kent et al. (1999). Glycols were miscible in water and they were highly mobile. Aerobic biodegradation was the most important environmental fate process affecting glycols in waters and soils. Glycols have relatively low aquatic toxicity, with algae being more sensitive than vertebrates or invertebrates, but the aircraft deicing/anti-icing fluids were more toxic than pure glycols.

Seasonal changes of the herbicides (diuron and simazine) in urban runoff were examined by Revitt et al. (1999). The herbicide concentrations were higher in storm events, with maximum levels of diuron at 238 µg/L and simazine at 2.2 µg/L recorded. The very high diuron level was during a storm event, which closely followed application of the herbicide. During this event, more than 45% of the applied diuron was lost to runoff. Qian and Anderson (1999) examined five commonly used herbicides and three pesticides in small streams in the Willamette River Basin, Oregon. Of the variables examined, landuse was the most important for all but one (simazine) of the eight pesticides studied, followed by geographic location, intensity of agriculture activities in the watershed, and the size of the watershed. There were significant differences in the variabilities of the stream concentrations for the urban and agriculture sites. While all 16 nonurban watersheds had significantly higher variations than the urban sites, the same was not necessarily true for the mean concentrations.

Several stormwater-runoff samples were accurately evaluated for oil and grease with an alternative analysis method using octadecyl siloxane ( $^{18}\text{C}$ ) solid-phase-extraction columns. The amount of the solvent was reduced and more reproducible results were obtained using this alternative method (Lau and Stenstrom, 1997).

Crunkilton and Devita (1997) investigated the concentrations of freely dissolved polycyclic aromatic hydrocarbons (PAH) in an urban stream at high flow and baseflow by an equilibrium partitioning model (EPM) and by use of lipid-filled semipermeable membrane devices (SPMD). The results, compared to direct measurements made on bulk (unfiltered) water samples, indicated that concentrations of freely dissolved PAH and total PAH at high flow are about 20 times greater than at baseflow. In another study, Kucklick *et al.* (1997) investigated the contamination of PAH in surface sediment of Winyah Bay, Charleston Harbor and the North Edisto River estuary in South Carolina. Concentrations of total PAH (i.e., analyzed for 24 PAH, two to six rings), were extremely variable; however, this observed variability was not explained by total organic carbon (TOC) or grain size, indicating that other factors were more important. Loganathan *et al.* (1997) evaluated sources of polychlorinated biphenols (PCB) in CSO to the Buffalo River, N.Y. by analyzing combined and sanitary wastewater, atmospheric wet and dry deposition, and street dust samples from the Babcock Street sewer district. PCB congener composition suggested that the local contaminated street dusts are one of the potential sources of PCB in CSO and to the Buffalo River.

### **Particle size/settling**

Li *et al.* (2006b) provided a dynamic characterization of particles sizes in highway runoff. Most of the particles were less than 30  $\mu\text{m}$  and more than 90% were less than 10  $\mu\text{m}$ . Bzdusek *et al.* (2005) investigated the potential for fine-grained sediment transport and deposition in Wisconsin using sediment-core tracer profiles. Cesium-137 activity versus depth showed distinct peaks related to peak river discharges in specific years. Sediment deposition has continued near one urban bridge.

Furumai *et al.* (2002b) studied the dynamic behavior of suspended pollutants and particle size distribution in highway runoff. Except for Pb, the concentrations of TSS and heavy metals in runoff were within the range of the EMC reported in recent highway runoff research. Particle-bound heavy metals (Zn, Pb, and Cu) accounted for more significant pollutant loads than soluble fractions. Their content decreased with increasing total SS concentration in runoff samples. The results of particle size distribution (PSD) analysis of runoff samples indicate that high TSS concentration samples contained coarser particles. Based on the PSD results, a stepwise wash-off phenomenon of TSS under varying runoff rate conditions was explained by the different washoff behavior of fine (less than or equal 20  $\mu\text{m}$ ) and coarser particles.

Hijioka *et al.* (2000) investigated the behavior of suspended solids in runoff from a 67-ha urban watershed by looking at the behavior of two separate fractions (fine – less than 45  $\mu\text{m}$ ; coarse – greater than 45  $\mu\text{m}$ ). They found that the two fractions behaved similarly; however, the pollutant loadings were different with the coarse fraction needing a more intense storm to generate runoff containing that fraction.

The composition and morphology of colloidal materials entering an urban waterway (Brays Bayou, Houston, Texas) during a storm event was investigated. Analyses of organic carbon, Si, Al, Fe, Cr, Cu, Mn, Zn, Ca, Mg, and Ca were performed on the fraction of materials passing through a 0.45  $\mu\text{m}$  filter. This fraction, traditionally defined as "dissolved", was further fractionated by ultra-centrifugation into colloidal and dissolved fractions (Grout *et al.*, 1999).

Lloyd and Wond (1999) presented examples of particulate size fraction distributions for road and highway runoff collected in Australia and compared the information with United States and European samples. They found that the particle size distribution of suspended solids in stormwater runoff from roads and highways in Australia were relatively finely graded. Sansalone and Hird (1999), in contrast, found that the particle sizes of stormwater particulates investigated at a freeway site in Cincinnati, Ohio were much larger than typically found elsewhere. In their samples, particles several hundred  $\mu\text{m}$  in size were common. They stressed the need to carefully collect stormwater samples for particle size analyses considering the difficulty of representing large particles in samples collected with automatic samplers. Pitt *et al.* (1999), during pilot-scale testing of a critical-source-area-treatment device, monitored particle size characteristics both in the influent and effluent. The parking lot stormwater had median particle sizes ranging from 3 to 15  $\mu\text{m}$ . They also monitored particle sizes from 75 source areas in the Birmingham, Alabama, area as part of treatability tests during an earlier phase of this research and found similar small-sized particles. Corsi *et al.* (1999) measured stormwater particle sizes as part of a treatment system evaluation at a public works yard in Milwaukee, Wisconsin, and found median particle sizes in the influent of about 18  $\mu\text{m}$ .

Andral et al. (1999) analyzed particle sizes and particle settling velocities in stormwater samples collected from eight storm events from the A9 motorway in the Kerault Region of France. They concluded that to effectively treat runoff, particles smaller than 50  $\mu\text{m}$  in diameter (which represented approximately three-quarters of the particulates analyzed, by weight) must be captured. The median particle size for their samples averaged about 15  $\mu\text{m}$ . Settling velocities of these particulates were also studied. The median settling velocities of the particulates smaller than 50  $\mu\text{m}$  ranged from 2.5 to 3.3 m/h, while the larger particles between 50 to 100  $\mu\text{m}$  in diameter had median settling velocities ranging from 5.7 to 13 m/h. Krishnappan et al. (1999) examined particle size distributions of suspended solids in a wet detention pond. They used a submersible laser particle size analyzer that enabled them to examine the particulate characteristics without disturbance by sampling. They found that the suspended solids were mostly composed of flocs, with maximum sizes ranging from 30 (winter) to 212  $\mu\text{m}$  (summer). They concluded that flocs in the size range from 5 to 15  $\mu\text{m}$  would settle faster than both smaller primary particles of higher density, and somewhat larger flocs of lower density. The larger flocs were also found to be susceptible to break up by turbulence.

Organic matter in sediments from pipes and silt traps in combined sewers was divided into fractions with different settling velocities. The largest fraction of organic material was found in the faster settling material, however the faster settling material had a slower biodegradability than the slower settling fraction (Vollersten et al., 1998). The efficiencies estimated using particle size distribution and settling velocities as suggested in the Ministry of the Environment and Energy Stormwater Management Practices Planning and Design Manual of Ont., Can., which is used to design best management practices (BMP), were less than those estimated using the observed particle distribution and settling velocities estimated from these sites. Suspended solid removal estimation based on the manual would result in removal efficiencies more conservative than observed (Liang et al., 1998).

Jones and Washburn (1998) mapped the three-dimensional distribution of dissolved and particulate components associated with stormwater runoff in Santa Monica Bay, Calif. The three major particles types in the bay were particles associated with the stormwater runoff, phytoplankton in the water column, and resuspended sediments.

Water quality and particle-size distribution were characterized from urban-stormwater runoff from two storms that indicated potential relationships between zinc (Zn)/organic carbon and iron (Fe)/macrocolloid (0.45  $\mu\text{m}$  — 20  $\mu\text{m}$ ) pairs. Results also indicated that concentrations of particle ion number, organic carbon, suspended solids (SS), Fe, and Zn increased during storms but showed no evidence of the “first flush” (Characklis and Wiesner, 1997).

Solids-settling characteristics are very important for designing many CSO- and stormwater-sedimentation-control facilities. Pisano (1996) summarized more than 15 years of settling data obtained in the United States, separated by wastewater types.

### ***CSOs and SSOs***

Bares et al. (2006) found that the bottom shear stress in unsteady sewer flow varied along the generated flood hydrograph. The variation was a function of the flow unsteadiness. The kinematic approximation was not adequate to represent the bottom shear stress in these unsteady flow conditions.

Jo et al. (2004) developed curves to predict the probability of combined sewer overflows. Applying a rainfall exponential decay function, normalized curves were derived to explain the non-exceedence probability distributions, which will aid in determining the required size for water quality structures.

CSO pollutant concentrations were compared to pollutant concentrations in sewer systems under wet-weather conditions by Weeks et al. (2004). Chebbo and Gromaire (2004) reviewed the changes in water quality in the combined sewer system (‘Le Marais’ catchment in France). They showed that concentrations of suspended solids, volatile suspended solids, chemical oxygen demand (COD), biochemical oxygen demand (BOD), copper and the particulate settling velocities increased as the water neared the outfall, whereas the cadmium, lead and zinc concentrations in the water were from roof runoff. Hydrocarbons and metals in the combined sewer were strongly associated with the gross bed sediment, less with the organic layer and very little with the biofilm (Rocher et al. 2004a). Urban runoff was the primary source of pollutants in the gross bed sediment. Lift station sediment constituents were similar to literature values for organics. Decreased lead (likely due to reduction in traffic emissions of Pb) and increased copper (likely from brake lining abrasion) was seen in the sediments (Rocher et al. 2004b).

El Samrani et al. (2004) characterized the mineral species found in a combined sewer. During rain, metal plating particles,

barite from automobile brake, or rare earth oxides from catalytic exhaust pipes were seen, whereas PbSn alloys and lead carbonates were attributed to zinc-works from roofs and paint from building siding. However, the most abundant heavy metal carriers in CSO samples were the sulfide particles eroded from sewer sediments.

Katayama et al. (2004) surveyed the occurrence of enteric viruses and coliforms in a coastal area after a COS event. Measurable concentrations of these organisms were still present 4 days after the CSO event.

Zhang et al. (2004a) investigated the presence of organic priority pollutants in CSOs in the Chicago metropolitan area. The total number of organic pollutants detected in at least one sample ranged from 26 to 40 at three different locations in an earlier study and 8 to 50 at nine different locations in the later study. Some of one- and two-carbon chlorinated alkanes and alkenes were the frequently detected VOCs in both studies. Acetone, which was not analyzed in the former study, was the most frequently detected compound in the later study period with highest mean and individual concentrations among all detected VOCs (Zhang et al. 2004b).

A case study to establish measures against damages caused by heavy storms was presented by Kinoshita et al. (2002). Manhole covers were blown away due to the sudden rise in the water level in the sewer, resulting in the submergence of sewerage facilities due to the increased sewage flow coming in from the open manholes. Joannis et al. (2002) reviewed a method for validating dry-weather data a posteriori. The method relies on flow-rate forecasts, a combination of standard daily wastewater flow profiles and an estimation of infiltration flows, and then the measurement results are then compared with the forecast and an appropriate series of statistical tests are run to detect all major anomalies. The diagnostic rules are then applied to derive an initial interpretation of these anomalies and, in particular, to identify the influence of rainfall events.

The paper by Agbodo and Rowe (2002) evaluated available approaches to selecting the appropriate design storm criteria for sizing SSO relief facilities and assessed techniques for establishing peak flows in sanitary sewer systems. Agbodo et al. (2002b) introduced the use of gage-adjusted radar data to estimate precipitation volumes for wastewater and water resources planning studies for either sanitary or combined sewer systems; the methods to estimate the optimum number of rain gages for precipitation-volume measurement; the advantages and disadvantages of alternative measurement approaches; and the use of radar precipitation data for enhancing collection systems planning, development, and operations and maintenance. The paper reviewed the data collected in South Florida and contained a cost comparison of gage-adjusted radar and rain gage methods for precipitation measurement. Mau et al. (2002) evaluated the spatial and temporal variability of storm events and the application of this to CSO facility design. The data from 6 Spokane-area rain gages was correlated with the measurements at the airport and these regressions were used to predict CSO design storm events for the individual CSO watersheds. The results showed that CSO facilities designed with basin-specific storm events were overdesigned by up to 70%, while using airport data directly caused an underdesign of approximately 35%. The paper by Dent et al. (2002) described methods available (including advantages and disadvantages) for determining the size of the design storm for sizing collection systems and treatment plants. The paper also offered approaches to develop wet weather design events for the system and the plant, including examples from several municipal master-planning studies to illustrate how the results can vary from one approach to another.

Hannan et al. (2001) reviewed the ASCE study that developed a guidance manual for identifying Sanitary Sewer Overflows (SSOs). The project surveyed twelve medium-to-large utilities for their SSO-identification protocols, with protocols organized into three major categories: Hydraulic, Maintenance and Inspection, and Structural. King County (Washington) has been assessing inflow and infiltration (I/I) in the county's service area (Swarner et al., 2001a). The program included rainfall and flow monitoring, computer modeling, economic analyses, field investigations and pilot projects. The results will be used to determine the cost effectiveness of removing I/I from the system. This project has developed detailed information about the location of I/I sources and potential cost-effective improvements to remove or reduce critical sources of I/I. Inflow/infiltration values were estimated in the South Beaches regional wastewater collection system (Brevard County, FL) through re-examining pump flow data (Fernandez 2001). Operating station data was used in a custom-designed hydraulic model. Pump operating points were deduced through an interactive process of balancing flows from tributary pump stations.

Ahyerre et al. (2001a) investigated the solids composition of dry weather flow in the "Le Marais" combined sewer network in Paris after it was noted that there was an increase in the solids concentration in the lower part of the sewer's flow. The study results showed that the accumulation rate of the organic solids layer was 215 g/(m<sup>2</sup>-day) with the particles heavily loaded with pollutants (VSS to TSS = 66 – 75%). Flushing experiments showed that this organic layer is

easily eroded by small storm events. A second publication by Ahyerre et al. (2001b), as part of the same sewer investigation, reported that the erosion does not occur only locally but along the entire length of the section even at low shear stresses ( $0.5 \text{ N/m}^2$ ). Cigana et al. (2001) investigated the impacts of underflow baffles on the retention of floatables in a combined sewer system. The study showed that a critical horizontal velocity can develop in overflow chambers and when this critical velocity is exceeded, floatables that would normally rise to the surface and be skimmed off are kept in the flow and therefore are not intercepted.

Gromaire et al. (2001) documented the sources of pollutants (SS, VSS, COD, BOD<sub>5</sub>, Cd, Cu, Pb, and Zn) in the Paris combined sewer area called the “Marais” catchment. The erosion of in-sewer pollutants was the main source of particles and organic matter in wet weather flows, whereas heavy metal loads mainly originated from runoff due to the corrosion of metallic roofs. A change of the chemical form of heavy metals was noted during sewer transport. It was hypothesized that a fraction of the dissolved metals from the runoff adsorbed onto sewer sediments. Griffin et al. (2001) reported on the CSO Control System Evaluation report for the City of Atlanta, Georgia. Based on the testing, the main pollutants of concern for meeting water quality standards were copper (Cu), zinc (Zn) and bacteria (fecal coliform). The two metals exceeded the baseline dissolved criteria frequently enough for remedial measures to be needed. Supplemental stormwater runoff sampling from parking lots and parks demonstrated high levels of metals (Cu and Zn) and bacteria. The frequency of exceedences for the stormwater runoff were similar to that of CSOs; thus, similar water quality compliance issues would remain even if the sewers were fully separated.

Sacramento County, California has completed a two-year project on the impact of grease accumulation in selected areas of the collection system (Hassey and Joyce 2001). Current grease handling policies of CSD-1 and local food producing facility wastewater flows result in heavy localized grease accumulation in the collection system that account for approximately seven percent of the annual grease related sewage overflows, and 36 percent of the flooded structure mitigation costs related to the overflows.

Servais et al. (1999) studied suspended solids, COD, and BOD in CSO affecting the River Seine (France). These basic measurements were compared with values of the biodegradable and refractory fractions of particulate and dissolved organic carbon. They found very similar numeric ratios between these parameters, even in areas having highly different conditions, making it possible for reasonable predictions of the biodegradable and refractory fractions of dissolved and particulate organic matter and of the bacterial biomass in combined sewage. CSO and source area runoff was investigated in Paris (France) by Chebbo et al. (1999). Resuspended material from the sewers contributed a larger fraction of the pollutants (suspended solids, organic matter, copper, and total hydrocarbons) than from the runoff during a runoff event. The results were quite different for lead, zinc, and cadmium whose main source was roof runoff due to corroding roofing materials.

Kerbs et al. (1999) found that the wave front that formed when a significant increase in flow occurred in a combined sewer was composed of the sewage that was present in the sewer before the flow rate increased and not the stormwater component that comprised most of the flow volume. By means of measurements and numerical simulations, they showed that this effect may cause the significant increase of dissolved constituents found in the first flush during CSO events. The vertical (rise) velocity of CSO floatable material, in addition to other basic measurements, was investigated by Cigana et al. (1999) in Montreal (Canada). They found that 80% of the floatables had a vertical velocity greater than 0.07 m/s.

### **Solids transport in sewers**

McIlhatton et al. (2002) reviewed the influence of solids eroded from the bed of the combined sewer on receiving waters and treatment plants using data obtained from field studies carried out in the main Dundee interceptor sewer in Scotland. In addition, the paper described some of the methods used to investigate the pollutant characteristics associated with the solids erosion in combined sewers. Sakrabani et al. (2002) described the efforts using an endoscope that allowed visualization of combined sewer deposits (Near-Bed Solids) in a non-destructive way. Based on this work, several models have been proposed to estimate near-bed solids and predict the pollutant loads of consequence from CSOs. Pollert and Stansky (2002) reported on the use of computational techniques (a 1-D MOUSE model and the 3-D FLUENT model) to evaluate the separation efficiency of suspended solids in a CSO system. A combination of the two models was used to describe the CSO behavior.

Modeling the transport of sediment and other debris in sewers was investigated by Babaeyan-Koopaei et al. (1999). Using correct velocity distributions were found to be critical in order to obtain accurate predictions of sediment transport. A sensitivity analysis investigated the influence of some important parameters involved in the model, especially the drag

coefficient, the lift coefficient, solid density, and pipe roughness. Arthur et al. (1999) proposed a new design approach to minimize sedimentation in sewers. They also compared the results of laboratory investigations with real sewer conditions. Johnstone et al. (1999) described on-going research concerning the disposal of large sanitary solids in combined sewers, assessing the relative sustainability of conventional disposal methods using an integrated, holistic approach, incorporating economics, sociology, life cycle data, and a risk assessment. They also described a project designed to study the behavior of the sanitary solids in the sewerage system through laboratory, field, and modeling studies. Skipworth et al. (1999) sampled and analyzed combined sewer sediment deposits and found coarse, loose, granular, predominantly mineral material that was overlain by a mobile, fine-grained cohesive-like sediment deposit in the invert of pipes. The erosion of this more mobile fraction was identified as the major source of the first flush of pollutants associated with CSO events. They presented a new approach to model the erosion and subsequent transport of these mobile sediments.

Rushforth et al. (1999) examined the relationships between the erosion of in-sewer organic deposits and the sediment composition. They found that sewer sediments consist of mixtures of organic and inorganic material and exhibit a much wider range of particle sizes and densities than typically assumed. Specifically, the characteristics of the fine organic sediment found in combined sewer deposits fall outside the applicable range of grain size and density for typically used sediment transport models. Their laboratory experiments showed that the addition of granular material in sewer deposits significantly increases the amount of organic material eroded, compared to a deposit composed entirely of organic material.

### **In-sewer processes**

Hass and Herrmann (1999) examined the problems associated with gas transfer in sewer systems through laboratory and field reaeration studies using volatile tracers and conservative dye tracers. They found that traditional empirical models for reaeration in open channels worked well, with modifications to account for the sewage matrix used instead of clean water. During the field studies in sewer systems having low gas transport rates, concentrations close to the Henry's law equilibrium near the wastewater surface were found to minimize the transfer of the volatile gases from the wastewater to the sewer gas. Huisman et al. (1999) studied oxygen mass transfer and the biofilm respiration rate in sewers. Oxygen transfer mass fluxes were found to be responsible for the major changes to wastewater as it flows to the wastewater treatment plant. They concluded that about 20% of the dissolved COD could be degraded in the investigated sewer system during the wastewater transport process.

Hvitved-Jacobsen and Vollertsen (1999) also developed a conceptual model for wastewater quality changes during transport in sewers. The model includes reaeration and major aerobic and anaerobic microbial processes in the water phase and in the sewer biofilm. Emphasis was placed on microbial transformations of the heterotrophic biomass and of the soluble and particulate fractions of the organic substrate. Vollersten et al. (1999) measured the effects of temperature and dissolved oxygen (DO) on the kinetics of microbial transformation processes of the suspended sewer sediment particles, suspended wastewater particles, and wastewater. The average Arrhenius constants found for sewer sediment particles and wastewater particles were found to differ significantly from the average Arrhenius constant found for the wastewater. However, no differences for the oxygen saturation coefficients were found between sewer sediment particles, wastewater particles, and wastewater. The anaerobic transformations of wastewater organic solids in sewers were studied by Tanaka and Hvitved-Jacobsen (1999), leading to a aerobic/anaerobic wastewater process model. During 19-25 hours of anaerobic conditions, a net production of readily biodegradable substrate, originating from hydrolyzable substrate, was observed. A small amount of methane production was also observed. Suguira et al. (1999) found that sewage stagnation at the downstream side of a separating tidal weir at a CSO discharge location caused an extraordinary generation of hydrogen sulfide, and associated nuisance odors.

## **Pollution Sources**

### ***General Sources***

Fujii et al. (2006) compared estimated annual pollutant loadings in runoff from two small Japanese urban catchments. Regional properties led to different runoff patterns, with the more urbanized basin showing an earlier and stronger influence of precipitation on runoff characteristics. Sargaonkar (2006) estimated land-use specific runoff flows and pollutant concentrations for a river in India. The National Stormwater Quality Database (NSQD) was described by Maestre and Pitt (2006). Version 3 of the database now has information for more than 8,500 runoff events from throughout the U.S., representing all the major land uses and geographical areas. The database can be used to identify significant factors affecting urban stormwater quality. One analysis showed that ignoring or improper replacement of the non-detected values can significantly affect the statistical summaries of many pollutant concentrations.

Barber et al. (2006) identified the sources and impacts of organic and inorganic contaminants in the Boulder Creek Watershed using a holistic watershed approach. The report documented a suite of potential endocrine-disrupting chemicals in a reach of stream with native fish populations showing indication of endocrine disruption. Hao et al. (2006) analyzed the quality of the runoff in Beijing and found that roadway runoff was oversaturated with respect to calcium carbonate while rainwater was undersaturated. Tournoud et al. (2006) investigated the origins of nitrogen into a French coastal lagoon. Compared to the other sources investigated, urban runoff was found to be a negligible source.

Sabin et al. (2006b) examined the dry deposition of trace metals in the coastal region of Los Angeles, California. Mean concentrations and fluxes were significantly higher at urban sites compared with the nonurban sites, although differences between urban and nonurban sites were reduced when sampling took place within 5 d after rainfall. An analysis of a wastewater treatment plant influent by Rule et al. (2006) showed that the heavy metals entered the plant from many diffuse sources. Runoff concentrations were higher in the light industrial samples than in the residential samples for all the heavy metals.

Stein et al. (2006) showed that PAHs exhibited a moderate first flush effect in Los Angeles, California, urban runoff. The relative distribution of individual PAHs demonstrated a consistent predominance of high-molecular-weight compounds indicative of pyrogenic sources.

Surbeck et al. (2006) fingerprinted fecal bacteria and suspended pollutants in runoff in a southern California coastal watershed. The different flow fingerprints observed for fecal pollutants and for TSS reflected different sources and transport pathways for these stormwater constituents. Scopel et al. (2006) examined the influence of nearshore water dynamics and pollutant sources on beach monitoring results in Lake Michigan. Areas near a stormwater discharge and a CSO outfall had *E. coli* levels above the recommended EPA limits for recreational waters.

The division of Biscayne Bay (Florida) into five zones of water quality based on contributing land use was reviewed by Caccia and Boyer (2005). Influencing water quality were sewage treatment plants, agriculture and general urban runoff. Zeng and Rasmussen (2005) used multivariate statistics to characterize water quality in Lake Lanier (Georgia). Tributary water was composed of three components – stormwater runoff, municipal and industrial discharges, and groundwater. These sources can be distinguished using TSS, total dissolved solids, and alkalinity and soluble reactive phosphorus.

A qualitative and quantitative budget of pollutants at the outlet of a storm drainage system was presented by Ruban et al. (2005). Heavy metal pollution was not substantial; however, pesticides (diuron and glyphosphate) were found in high concentrations, especially in the spring and autumn. Land use, surface-water-system characteristics, and human activities were demonstrated to impact the seasonal variation of nitrogen concentrations in inflows to a reservoir in Northern China (Chen et al. 2005). Chetalat and Gaillardet (2005) measured boron isotopes in the Seine River in the mid 1990s. Boron was found to be a conservative tracer and its concentration was heavily linked to the influence of anthropogenic activities in the watershed.

Pitt et al. (2005 a, b) reviewed the results of several source area monitoring projects. These large projects included a wide range of land uses, sources, pollutants. Much of the effort focused on sheetflow monitoring and also included an analysis of street dirt chemical quality. Noguchi et al. (2005) estimated the detachment rate of pollutants from urban surfaces by correlating them to the watershed land use but also to a rainfall-time series consisting of antecedent rainfall conditions and the current event data. Dean et al. (2005) investigated the partitioning of metals in runoff from a Portland cement watershed. Zinc was found equally between the particulate and dissolved species, while lead was highly particulate-bound.

In Ashdod, Israel, Asaf et al. (2004) investigated the temporal variations in the composition of urban stormwater from different land uses, and their dependence on physical parameters such as precipitation intensity, stormwater discharge and cumulative volume, and the size of the drainage area. Land use had only a minor effect on the concentrations of major ions and trace elements, but industrial areas had higher VOC and SVOC concentrations. The presence of fecal coliforms, ammonium, and ratios of oxygen and nitrogen isotopes, suggest that wastewater, possibly from overflowing sewers, contributed to the drained stormwater. Nsubaga et al. (2004) found that stormwater runoff contributed to pollutant migration into protected reservoirs in Kampala City, Uganda.



Gardner and Carey (2004) found that dissolved Pb and Zn were much lower than reported previously, while dissolved Cr, Ni and Cu were similar to previous studies. The storm sewer is shown to be a significant source of V, Ni, and Zn to the river, as well as a significant source of Na, NH<sub>4</sub>, Cl, and DOC. Higher nutrient levels were positively correlated to low flows in Wissahickon Creek (Pennsylvania), while siltation was associated with higher flows (Henry et al. 2004). Part of the sediment source is streambank erosion.

Hu et al. (2004) investigated the runoff concentration of suspended solids and found that the concentrations decreased with the increase in antecedent rainfall, while no relationship was seen with nutrients and COD. Land use associations to suspended solids concentrations, from highest to lowest, was dry land > residential area > grassland > woodland > paddy land.

Hetling et al. (2003) investigated the effect of water quality management efforts on wastewater discharges to the Hudson River (from Troy, NY to the New York City Harbor) from 1900 to 2000. The paper demonstrated a methodology for estimating historic loadings where data are not available and showed that nonpoint sources are now the significant contributor of contaminants to the river, except for total nitrogen and total phosphorus (which result from point sources).

Schiff et al. (2003) performed a retrospective evaluation of shoreline water quality along Santa Monica Bay beaches and showed that most of the water quality exceedences occurred near urban runoff drains even though the area represented by drains represent only a small part of the shoreline. Lim (2003) found that storm event characteristics and anthropogenic activities most influenced the loads of suspended sediment, nutrients and inorganics. The authors also suggested that the most appropriate sampling of stormwater quality should focus on conducting small-scale, relatively short-term studies to identify and assess specific water quality problems facing each catchment.

A hydrologic analysis was used by Lee and Heaney (2003) to demonstrate that imperviousness is an important indicator of the impact of urbanization on stormwater systems. The results of studies in Miami, FL and Boulder, CO suggested the need to focus on directly-connected impervious areas (DCIA) as the key indicator of urbanization's effect on storm water quantity and quality. Vaze and Chiew (2003) studied pollutant washoff from small impervious experimental plots and showed that the energy of the falling raindrops was important at the beginning of the event where the concentration/prevalence of easily detachable pollutants is greatest. The authors suggest that meaningful characteristic curves that relate event total suspended solids (TSS) and total phosphorus (TP) loads to storm durations for specific rainfall intensities could be developed from the experimental data.

Malmqvist and Rundle (2002) discussed the threats to the world's running water ecosystems. The main ultimate factors forcing change in running waters (ecosystem destruction, physical habitat and water chemistry alteration, and the direct addition or removal of species) stem from proximate influences from urbanization, industry, land-use change and water-course alterations. Concentrations of chemical pollutants such as toxins and nutrients have increased in rivers in developed countries over the past century, with recent reductions for some pollutants (e.g. metals, organic toxicants, acidification), and continued increases in others (e.g. nutrients); there are no long-term chemical data for developing countries. The overriding pressure on running water ecosystems up to 2025 will stem from the predicted increase in the human population, with concomitant increases in urban development, industry, agricultural activities and water abstraction, diversion and damming. Future degradation could be substantial and rapid (c. 10 years) and will be concentrated in those areas of the world where resources for conservation are most limited and knowledge of lotic ecosystems most incomplete; damage will center on lowland rivers, which are also relatively poorly studied.

Cosgrove (2002) described the approach used in New Jersey to characterize the relative contribution of point and nonpoint sources of pollutants in the Raritan River Basin. The "screening level" methodology uses only existing data and does not require advanced modeling techniques. Maimone (2002) presented the overall approach that was used to screen and evaluate the thousands of potential sources within the Schuylkill River watershed as part of the Schuylkill River Source Water Assessment Partnership. EVAMIX is the decision support software used for the assessments. The greatest benefit of EVAMIX, compared to other software, is that it allows mixed criteria evaluation – qualitative and quantitative – to be considered concurrently. The assessment included both point sources and run-off, and evaluations were performed for an overall priority of potential sources, as well as for priority lists for ten different contaminant categories of concern in drinking water treatment. Kim et al. (2002) investigated the impacts of land-use changes on runoff in the Indian River Lagoon watershed. The study demonstrated that land-use change could have a dramatic impact on runoff volume (increase of nearly 113% between 1920 and 1990).

Jia et al. (2002) coupled simulations of water and energy budgets for complex land covers to determine the impact of urbanization on land surfaces/canopies, soil moisture content, land surface temperature, groundwater level and river water stage. Wotling and Bouvier (2002) performed an initial characterization of pollution associated with stormwater runoff in Tahiti. Organic pollution appeared to be related closely to sediment, thus TSS could be used as a global indicator. Next, regression models between an event's TSS load and its hydrological characteristics were used to obtain annual load estimates. Great interannual variability was found to be strongly influenced by the few major floods that occur during the rainy season. The results also emphasized the importance of the impact of urbanization on solid catchment exportation: from 60 TSS t/km<sup>2</sup>/year in a natural forested catchment, fluxes reached more than 700 TSS t/km<sup>2</sup>/year during preparatory urbanization earthworks before stabilizing at 140 TSS t/km<sup>2</sup>/year in a consolidated urbanized area.

The pollutant export from various land uses (single-family residential, golf course, industrial, dairy cow pasture, construction site and wooded site) was investigated for at least 20 storm events in the upper Neuse River Basin by Line et al. (2002). Annual total nitrogen export was greatest for the construction land use during the house-building phase, followed closely by the residential and golf course land uses. Total phosphorus export was greatest for the golf course site followed by the pasture and residential land uses. Sediment export was greatest for the construction site during the rough grading phase, which averaged more than 10 times more sediment export than any of the other sites. To estimate export from a multiuse urban watershed, total nitrogen, phosphorus, and sediment export from the residential, golf course, and construction sites were averaged. The average total nitrogen, phosphorus, and sediment export from the three land uses (average of residential, golf course and construction site) was, respectively, 269, 302, and 256% greater than the corresponding exports from the wooded site, which was considered similar to the predevelopment land use. Lee et al. (2002) analyzed the first flush of urban stormwater runoff. The magnitude of the first flush phenomenon was found to be greater for some pollutants (e.g. suspended solids from residential areas) and less for others (e.g. chemical oxygen demand from industrial areas). No correlation was observed between the first flush phenomenon and the antecedent dry weather period, however, the first flush phenomenon was greater for smaller watershed areas.

The movement of water and particulate matter through a simulated coal pile using a rainfall-coal-pile simulator was investigated by Curran et al. (2002). Results demonstrated the need to determine the optimal coal-pile slope that minimizes water contact time, but at the same time minimizes the potential for mass wasting and rill erosion. Promotion of a compacted surface is beneficial for the minimization of solids loss.

Pritts et al. (2002) reviewed the EPA's assessment methodology for measuring the potential benefits of effluent guidelines, including reductions in pollutant loadings, habitat/biological impacts, and impacts on floodplain size. This was related to an environmental assessment of construction and land development. Stiles (2002) discussed incorporating hydrology into determining TMDL endpoints and allocations. The endpoints to be achieved by TMDLs utilizing analysis of hydrology would be a more accurate assessment of the level of water quality to be attained upon implementation of the load allocations. The implications to point sources would reflect a more direct linkage of their impacts to the stream and the desired goals of the TMDLs under flow conditions which are a subset of the total flow regime occurring on the river.

Richards (2002) reviewed the EPA's study of the water quality impacts of alternative development patterns and locations. Preliminary results indicate that low-density, dispersed development located in metropolitan edge areas transforms a large area that was previously undeveloped, resulting in far more runoff. Conversely, redeveloping a centrally located brownfield site with compact, mixed uses converts a relatively small area of one form of developed land into another form of developed land, resulting in far less impact to runoff quantity and quality. The runoff characteristics when looking at post-development pollutant loads such as sediments and nutrients were far more impacted at the greenfield site than at the brownfield site.

Gippel et al. (2002) described four key aspects of the process being undertaken to meet the flow and water quality objectives, and to design the flow options to meet the objectives, for the River Murray: establishing an appropriate technical, advisory and administrative framework; establishing clear evidence for regulation impacts; undergoing an assessment of environmental flow needs; and filling the knowledge gaps. The paper described two important investigations: how to enhance flows to wetlands of national and international significance, and how to physically alter or change the operation of structures (including a dam, weir, lock, regulator, barrage or causeway), to provide significant environmental benefits.

Hale et al. (2000) investigated the occurrence of nonylphenols (an endocrine disruptor often from laundry products) from a variety of outfalls, and found that the highest concentrations in the sediment (14,100 ug/kg) was detected near a federal

facility's stormwater outfall. Sediment samples taken below an out-of-service sewage treatment plant indicated that nonylphenol persisted in the sediment. Hartmann et al. (2000) investigated the application of linear alkylbenzenes (LABs) as a molecular marker in marine sediments in Narragansett Bay. In the urban rivers at the head of the bay, the Providence River, Seekonk River, and Taunton River concentrations were locally high with a few values exceeding 2000 ng/g total LABs. The I/E (internal/ external C-12 isomers) ratio, a measure of the degree of degradation, indicated that treated sources (i.e. sewage effluents) and local fresh sources (e.g. combined sewer overflows and boat cleaning detergents) were major contributors of LABs to the rivers. The observed decrease in LAB concentration with distance downbay suggested that most of the LABs were deposited within a few kilometers of their source.

Storm runoff from the log handling area at the Port of Tauranga, North Island, N.Z., showed that the runoff may contain significant concentrations of resin acids, e.g., dehydroabietic acid (Tian et al., 1998). Seabed sediment samples were collected adjacent to the log handling area and analyzed to determine the extent of the resin acid deposition. The concentrations of conventional parameters, i.e., biochemical oxygen demand (BOD), chemical oxygen demand (COD) and SS, and 123 priority pollutants of stormwater runoff samples from a log storage and handling facility in La. were determined and no significant levels of priority pollutants were found. Only about 1—13% of COD was biodegradable and similar to SS concentrations, suggesting that effective control of SS will control COD as well (De Hoop et al., 1998b).

Hydrologists have known for some time that runoff can occur as the result of both saturation and infiltration excesses in soil containing nonpoint source (NPS) contaminants. Watershed areas that generated NPS polluted runoff needed to be identified prior to the design of basin-wide water quality projects (Endreny and Wood, 1999).

Hydrologic runoff was one of the main processes in which radionuclides deposited in the surface environment migrate widely in both particulate and dissolved forms. Amano et al. (1999) concentrated on the transfer capability of long lived Chernobyl radionuclides from surface soil to river water in dissolved forms.

Zaman (1999) found that the catchments with high intensities of development in close proximity to stormwater systems were found to be transporting more pollutants to receiving waters than other catchments. Dry-weather water quality monitoring was used to identify the most polluted areas of the catchment. Nirel and Revaclier (1999) used the ratio of dissolved Rb to Sr to identify and quantify the impact of sewage effluents on river quality in Geneva, Switzerland. Rubidium was present in larger quantities than strontium in feces and urine, making the ratio of these two elements represents an effective tracer. This was especially true in regions where the natural Rb/Sr ratio was low (calcareous regions).

Gromaire-Mertz et al. (1999) collected stormwater runoff from 4 roofs, 3 courtyards and 6 streets on an experimental catchment in central Paris, France, and analyzed the samples for SS, VSS, COD, BOD<sub>5</sub>, hydrocarbons, and heavy metals both in dissolved and particulate fractions. The street runoff showed large SS, COD and hydrocarbon loads, but the roof runoff had high concentrations of heavy metals. Wiese and Scmitt (1999) described urban stormwater contributions into large river systems. Their purpose was to develop a mass balance model for many stormwater pollutants, stressing nitrogen and phosphorus, the oxygen depleting substances and some heavy metals.

Iatrou *et al.* (1996) described the results of stormwater samples collected from the New Orleans drainage system. The sampling locations chosen represented residential, commercial, and industrial areas. Sakai *et al.* (1996) measured characteristics of storm runoff from road and roof surfaces and found the ratio of COD<sub>MN</sub>: T-N to be in the range of 3:1 for roof-storm runoff and in the range of 7:1 for road-surface-storm runoff. They found the ratio of COD<sub>MN</sub>:T-P to be 160:1. Most of the organic components and T-P in road-surface-storm runoff are insoluble, and road-surface-storm runoff contained soluble nitrogen (N), which could have been contributed from air pollutants.

Nowakowska-Blaszczyk *et al.* (1996) studied the sources of wet-weather pollutants in Poland. It was found that storm runoff from parking areas and streets had the greatest concentrations of suspended solids (SS), chemical oxygen demand (COD), five-day biochemical oxygen demand (BOD<sub>5</sub>), and Pb, while phosphorus was mostly contributed from landscaped-area storm runoff. Storm runoff from roofs covered with roofing paper was also a significant contributor of many pollutants.

### ***Atmospheric***

Radke (2005) found that the aeration of wastewater was a continuous local source for organic compounds. The aerosols

were minor sources of sterols and anionic surfactants. Toombes and Chanson (2005) investigated the air-water mass transfer on a stepped waterway. Stepped waterways have been incorporated in storm water systems to improve the oxygen aeration efficiency. Van Der Velde et al. (2005) discussed the benefits of air pollution control on improving the water supply in the Netherlands. The primary benefit was the reduction of acidification of the water.

Sabin et al. (2005) studied the contribution from atmospheric deposition to the trace metal loadings in stormwater runoff in an impervious urban catchment. Atmospheric deposition accounted for over half, up to almost all, of the total trace metal loads in the runoff. Local anthropogenic sources were found to be substantial contributors to wet deposition of mercury in southern Florida (Dvovich et al. 2005). Higher concentrations were also found during the spring and summer compared to winter. Wang et al. (2005a) investigated the exchange flux of mercury from coal-burning power plants in China. Mercury accumulation was measurable in waters, soils and plants.

Rossini et al. (2005) investigated the atmospheric fall-out of persistent organic pollutants in an industrial district in Italy. The results showed that the atmospheric input was the same order of magnitude as that due to watershed runoff and approximately half of the direct industrial discharge.

Schiff and Stolzenbach (2003) investigated the heavy-metal contribution of atmospheric deposition to Santa Monica Bay and compared the atmospheric deposition loading to the loading from other sources. The annual atmospheric deposition of chromium, copper, lead, nickel and zinc exceeded the estimated annual effluent loads from industrial and power generating stations to Santa Monica Bay.

Yunker et al. (2002) investigated the sources of PAHs in the Fraser River Basin (British Columbia). PAH ratios and total concentration data revealed a basin lightly impacted by a variety of sources in its remote regions, especially near roads, but heavily impacted in urban areas, particularly near Vancouver. Contamination sources shift from biomass (e.g. wood and grass) burning to vehicle emissions between remote and urban locations. Stormwater and wastewater discharges appeared to collect PAH from urban areas and release them as point sources. In all cases the examination of a variety of PAH indicator ratios that encompass a range of masses is necessary for a robust interpretation.

Ahn and James (2001) report that atmospheric deposition is a substantial source of phosphorus to the Florida Everglades. Phosphorus has been measured on a weekly basis since 1974, but the results were highly variable: the average mean and standard deviation of the calculated P deposition rates for 13 sites were  $41 \pm 33 \text{ mg P m}^{-2} \text{ yr}^{-1}$ . They found that the atmospheric P deposition load showed high spatial and temporal variability, with no consistent long-term trend. Because of the random nature of P deposition, the estimated P deposition loads have a significant amount of uncertainty, no matter what type of collection instrument is used, and replicate sampling is highly recommended. Atasi et al. (2001b) conducted source monitoring using specialized sampling equipment and ultra-clean analytical methodology to quantify the concentrations and fluxes of mercury, cadmium, and polychlorinated biphenyl in ambient air, precipitation, runoff, sanitary sewer, and wastewater treatment plant influent. The relationships between the atmospheric deposition and runoff on controlled surfaces were also examined. Atmospheric deposition was found to be the primary source of these pollutants in runoff. They concluded that wet weather flows, not atmospheric deposition, contributed the main portion of these pollutants to the Detroit Wastewater Treatment Plant. Atasi et al. (2001a) also pointed out that most water resources regulations (especially TMDL procedures) do not normally account for atmospheric deposition sources. Tsai et al. (2001) described their pilot study, conducted from August 1999 through August 2000, that estimated the loading of heavy metals from the atmosphere to San Francisco Bay. Dry deposition flux of copper, nickel, cadmium, and chromium was approximately  $1100 \pm 73$ ,  $600 \pm 35$ ,  $22 \pm 15$ , and  $1300 \pm 90 \text{ } \mu\text{g/m}^2/\text{year}$ , respectively. The volume-weighted average concentrations of these trace metals in the rain water were 1.2, 0.4, 0.1, and 0.2  $\mu\text{g/L}$ , respectively. Direct atmospheric deposition onto Bay waters, from both dry deposition and rainfall, contributed approximately 1900, 930, 93 and 1600 kg/yr of copper, nickel, cadmium and chromium, respectively. Stormwater runoff contributed approximately twice as much as the loading from direct atmospheric deposition. Direct atmospheric deposition was therefore found to be a minor contributor to the total load of these pollutants to the Bay.

In a study on the influence of atmospheric deposition on the concentrations of mercury, cadmium and PCBs in urban runoff, Atasi et al. (2000) found that atmospheric deposition was the primary source of these compounds in runoff from controlled surfaces. The authors argued that the contribution of atmospheric deposition must be accounted for both in modeling of pollutant sources, but also in planning for pollution prevention.

Atmospheric deposition, often contaminated to varying degrees, can be a significant source of phosphorus to South

Florida's aquatic system. Outliers were detected by field notes, derived from visual inspection of the samples, and statistics, based on simple linear regression used for additional screening. Based on detected outliers in the data from 115 monitoring sites, a lumped cutoff value, used for further quality control, of 130 Fg/L was determined (Ahn, 1999).

Garnaud et al. (1999) studied heavy metal concentrations in dry and wet atmospheric deposits in Paris, France, for comparison with urban runoff. Samples were continuously collected for 2 to 13 months at each of four test sites. Comparisons of median values of metal concentrations showed that rainwater contamination with heavy metals was only slightly higher in the center of Paris than at Fontainebleau (48 km SE of the city) which illustrates the medium range transport of atmospheric contamination.

Atasi et al. (1999) used specialized sampling equipment and ultra-clean analytical methodology to quantify the concentrations or fluxes of mercury, cadmium, and polychlorinated biphenyl in ambient air, precipitation, runoff, sanitary sewage, and treated sewage in Detroit, Michigan. Atmospheric deposition was found to be the primary source of the mass of Cd, Hg, and PCB, in runoff from the controlled surfaces. Shiba et al. (1999) also investigated the role of atmospheric deposition as a source of urban runoff contaminants. They found that the chemical substances in rainwater were an important pollution source.

Detailed characterization of 71 individual polychlorinated biphenyl (PCB) congeners in the waste streams at the 26 New York City (NYC) and N. J. water pollution control plants (WPCP) showed that of the estimated 88 kg of PCB released annually by the WPCP, roughly 3% was contributed by CSO due to heavy precipitation (Durell and Lizotte, 1998). Atasi et al. (1998) analyzed atmospheric and runoff samples to determine wet and dry deposition and the relative contribution of deposition to runoff pollutant mass. Ahn (1998) recorded the total phosphorus (P) concentrations in south Fla. rainfall at weekly intervals with a detection limit of 3.5  $\mu\text{g/L}$ . Air deposition was found to be the primary source of Cd, Hg, and PCB mass in runoff at the controlled sites in the study. Phenols were present at high concentrations in urban rainwater and ambient air (Allen and Allen, 1997).

Results from ten watersheds indicated organic P and carbon (C) correlated with the concentration of suspended particles, which differed among the watersheds. Recent estimates also suggest that 40% of the nitrogen (N) loading to the Chesapeake Bay watershed comes from atmospheric deposition, 33% from livestock waste, and 27% from fertilizer (Jordan *et al.*, 1997).

Pankow *et al.* (1997) proposed that frequent observations of the fuel additive methyl-tert-butyl ether (MTBE) in shallow urban groundwater may be due to atmospheric deposition accumulated during precipitation events and subsequent infiltration of stormwater. A one-dimensional mathematical model simulated five scenarios with varying conditions of precipitation, transport, source concentrations, and evapotranspiration and indicated that significant contributions of the compound may be coming from the atmosphere.

### **Roof Runoff**

Sandburg et al. (2006) examined the corrosion-induced copper runoff from naturally and pre-patinated copper in a marine environment. The runoff rate of copper was significantly lower compared to the corrosion rate throughout the exposure period. The bioavailable concentration of released copper was significantly lower compared to the total copper concentration.

Residential runoff and roof runoff were sampled and analyzed for a variety of pollutants in Genoa, Italy: total suspended solids, COD, ammonia, pH, and dissolved heavy metals. The first flush of roof runoff of heavy metals was related to rainfall intensity and depth and to antecedent environmental conditions. For general urban runoff, correlation was seen between total suspended solids and maximum rainfall intensity.

Murakami et al. (2004) modeled road and roof dust in Japan. The model was able to explain the suspended solids and particulate-bound PAHs well. Runoff rates of Cu, Ni, Sn and Zn were investigated in a French industrial area by Jouen et al. (2004). Depending on the solubility of corrosion products, the runoff rates appear to be different for these metals in the following order: zinc > copper > nickel > tin. The results revealed the runoff amount of copper, zinc and nickel released mainly from the dissolution of soluble sulfate compounds present in the corrosion layers.

Rocher et al. (2004c) investigated the contributions of atmospheric deposition and roof runoff to the hydrocarbon and metal composition of runoff in central Paris (France). Results showed that the roofs (metallic and slate) were not

significant contributors of metals to runoff, although Zn-covered roofs released Zn and Ti, while Slate roofs mainly released Pb, Ti and Cu. Near chimney stacks, Ni and V concentrations were elevated. Liu et al. (2004) proposed a new coating of Zn-Ca phosphating/acrylic resin-SiO<sub>2</sub> which can stabilize the rusting of steel.

Clark et al. (2003) studied the potential pollutant contributions from commonly-used building materials (roofing, siding, wood) using a modified Toxicity Characteristic Leaching Procedure (TCLP) test. Results of particular interest included evidence of elevated levels of phosphate, nitrate and ammonia in the leachant following exposure of common roofing and siding materials to simulated acid rain.

Polkowska et al. (2002) presented the results of testing roof runoff waters from buildings in Gdansk, Poland. More than half of the samples (25) were found to be toxic, with inhibition exceeding 20%. The toxicity was weakly correlated to the levels of organonitrogen and organophosphorus pesticides in runoff waters. It was established that at least in some cases the roofing material affected the levels of the pollutants found in the samples. Heijerick et al. (2002) investigated the bioavailability of zinc in runoff from roofing materials in Stockholm, Sweden. Chemical speciation modeling revealed that most zinc (94.3-99.9%) was present as the free Zn ion, the most bioavailable speciation form. These findings were confirmed by the results of the biosensor test (Biomet<sup>TM</sup>), which indicated that all zinc was indeed bioavailable. Analysis of the ecotoxicity data also suggested that the observed toxic effects were due to the presence of Zn<sup>2+</sup> ions. Gromaire et al. (2002) investigated the impact of zinc roofing on urban pollutant loads in Paris. On an annual basis, runoff from Parisian zinc roofs would produce around 34 to 64 metric tons of zinc and 15 to 25 kg of cadmium, which is approximately half the load generated by runoff from all of Paris.

Karlen et al. (2002) investigated runoff rates, chemical speciation and bioavailability of copper released from naturally patinated copper roofs in Stockholm, Sweden. The results show annual runoff rates between 1.0 and 1.5 g/m<sup>2</sup> year for naturally patinated copper of varying age with rates increasing slightly with patina age. The total copper concentration in investigated runoff samplings ranged from 0.9 to 9.7 mg/l. The majority (60 – 100%) of the released copper was present as the free hydrated cupric ion, Cu(H<sub>2</sub>O)<sub>6</sub><sup>2+</sup>, the most bioavailable copper species. The copper-containing runoff water, sampled directly after release from the roof, caused significant reduction in growth rate of the green alga. Wallinder et al. (2002) studied the atmospheric corrosion of naturally and pre-patinated copper roofs in Singapore and Stockholm. Measured annual runoff rates from fresh and brown prepatinated were 1.1-1.6 g/m<sup>2</sup> and 5.5-5.7 g/m<sup>2</sup>, in Stockholm and Singapore, respectively. Naturally aged copper sheet (130 years old) and green pre-patinated copper sheet showed slightly higher (1.6-2.3 g/m<sup>2</sup>), but comparable runoff rates in Stockholm. In Singapore, runoff rates from green pre-patinated copper sheet were 8.4-8.8 g/m<sup>2</sup>. Comparable runoff rates between fresh and brown-patinated copper sheet and between green naturally patinated and green pre-patinated copper sheet at each site were related to similarities in patina morphology and composition.

Wallinder and Laygraf (2001) studied the seasonal variations in the corrosion and runoff rates from copper roofs. Their experiments lasted for two years, at one urban and one rural location. Seasonal variations in corrosion rates were observed at the rural site, likely associated with variations in humidity, while no seasonal variations were observed at the urban site. The corrosion rates continually decreased with time. The yearly copper runoff rates ranged from 1.1 to 1.7 g m<sup>-2</sup>y<sup>-1</sup> for the urban site, and from 0.6 to 1.0 g m<sup>-2</sup>y<sup>-1</sup> for the rural site. The runoff rates were significantly lower than the measured corrosion rates as long as the adhering copper patina was increasing with exposure time. From 70 to 90% of the copper in the runoff (collected immediately after leaving the surface) was present in the most bioavailable form, the hydrated cupric ion, Cu(H<sub>2</sub>O)<sub>6</sub><sup>2+</sup>.

Zobrist et al. (2000) examined the potential effects of roof runoff on urban stormwater drainage from three different types of roofs: an inclined tile roof, an inclined polyester roof and a flat gravel roof. Runoff from the two inclined roofs showed initially high (“first flush”) concentrations of the pollutants with a rapid decline to lower levels. The flat gravel roof showed lower concentrations of most of the pollutants because of the ponding of the water on the roof surface acting like a detention pond. Pollutant loadings was similar to atmospheric deposition, with the exception of copper from drain corrosion (rate about 5 g/m<sup>2</sup>/yr).

Tobiason and Logan (2000) used the whole effluent toxicity (WET) to characterize stormwater runoff samples from four outfalls at Sea-Tac International Airport. Three of the four outfalls met standards; the source of the toxicity at the fourth outfall was found to be zinc-galvanized metal rooftops. Typically, more than 50% of the total zinc in the runoff was in dissolved form and likely bioavailable.

Foerster (1999) and Foerster et al. (1999) reported on studies investigating roof runoff as stormwater pollutant sources. Runoff samples were taken from an experimental roof system containing five different roofing materials and from house roofs at five different locations in Bayreuth, Germany. It was found that local sources (e.g. PAH from heating systems), dissolution of the roof systems' metal components, and background air pollution were the main sources of the roof-runoff pollution. They found that the first flush from the roofs often was heavily polluted and should be specially treated. They concluded that roofs having metal surfaces should not be connected to infiltration facilities as concentrations of copper and zinc far exceed various toxicity threshold values. They also examined a green (vegetated) roof for comparison. These roofs were found to act as a source of heavy metals which were found to be in complexes with dissolved organic material. Leaching from unprotected zinc sheet surfaces on the green roofs resulted in extremely high zinc concentrations in the runoff. In contrast, the green roofs were a trap for PAH.

Sakakibara (1996) investigated roof-runoff quality in Ibaraki prefecture, Japan, in order to determine the feasibility of using roof runoff in urban areas for various beneficial uses. Eighty three samples were collected during one year and analyzed for pH (averaged 6.1), BOD<sub>5</sub> (averaged 1.6 mg/L), COD (averaged 3.2 mg/L), and SS (averaged 12 mg/L). It was concluded that roof-runoff could be used for toilet flushing and landscaping watering with minimal treatment or problems. Heavy metals and major ions in roof-runoff were investigated by Förster (1996) in Bayreuth, Germany. It was found that the major ions were from the rain, while very high Cu and Zn concentrations were from metal flashings used on the roofs. It was concluded that the best option would be to abandon the use of exposed metal surfaces on roofs and walls of buildings.

### ***Highway and other Roadway Runoff***

Kim et al. (2006b) estimated pollutant mass accumulations and loading rates for highways during dry periods in southern California. Walch (2006) monitored contaminants in Delaware street dirt samples. Major contaminants detected were heavy metals, petroleum hydrocarbons, PAHs and phthalates. Bacteria and nutrient levels also were high in some of the street dirt samples.

Barrett et al. (2006) presented the stormwater quality benefits of a porous friction course overlay on a highway. The porous course reduced suspended solids and particulate-associated pollutant discharges. The relative contributions of sediment and runoff from a road right-of-way from unsealed road segments was described by Croke et al. (2006). The road surface produced the most runoff at each site investigated, and sediment generation varied significantly with road usage and traffic intensity. Sheridan et al. (2006) analyzed the effects of truck traffic and road water content on sediment delivery from unpaved roads. This study showed that, for a good quality well-maintained gravel road, the level of truck traffic affected the sediment concentration of water discharging from the road, whereas the road's water content at the time of that traffic does not.

In a four-year study of highway stormwater runoff in California, Han et al. (2006a) found poor correlations between total suspended solids and most other pollutants. The strongest correlation between pollutants and storm characteristics was for antecedent dry days. Han et al. (2006b) found that for total metals, COD and DOC, a first flush occurred, indicating that stormwater controls that treat the first-flush mass will be effective for those pollutants. In contrast, the quality of runoff from paved surfaces at two automotive-related industrial sites was investigated by Gnecco et al. (2006). First flushes were observed for total suspended solids and hydrocarbons, but not for heavy metals.

Khan et al. (2006b) measured oil and grease (O&G) in highway runoff in California and found correlations between O&G event mean concentrations (EMCs), antecedent dry days and total rainfall.

In road traffic areas, Hjortenkrans et al. (2006) saw elevated levels of copper and Sb in roadside soils compared to background levels near deceleration areas. The authors stated that understanding these patterns will assist in placement of appropriate stormwater controls. Qiu et al. (2006) determined the lead content in urban road surface runoff in China using microwave digestion to prepare the samples. Sabin et al. (2006a) examined the dry deposition and resuspension of particle-associated metals near a freeway in Los Angeles, California. Compared with urban background conditions, atmospheric particle size distributions indicated the freeway was a significant source of these metals on large particles >6 µm in diameter. Preciado and Li (2006) evaluated metal loadings and bioavailability in air, water and soil along two British Columbia highways. Metals showed increasing bioavailability with decreasing particle size in all samples. Thus, bioavailability was low in road dust and roadside soils, intermediate in dustfall, and highest in atmospheric suspended particulates and runoff.

Particle-associated PAHs in the first-flush runoff from a highway were investigated by Aryal et al. (2006). In general, the fine-particulate fraction was greater in the runoff, although the coarse fraction increased as the runoff volume increase. In addition, PAH loadings to the fine particulates was less variable than the loadings to the coarse particulates. Motelay-Massei et al. (2006) applied a mass balance to PAHs in an watershed in France. A comparison of atmospheric deposition and runoff output showed the importance of street deposits as a source in urban areas. Simon and Sobieraj (2006) reviewed the potential contributions of common sources of PAHs to soil contamination. Concerns were raised about asphalt pavements and sealers that produce particulate matter that can contain concentrations of PAHs in the sub-percent range (100s to 1,000s mg/kg total PAHs) that would be transported in stormwater runoff.

Gilbert and Clausen (2006) compared runoff quality and quantity from a variety of driveway materials in Connecticut. The results showed that runoff from crushed stone driveways was similar to runoff from asphalt driveways, with the except of lower TP concentrations.

Westerlund and Viklander (2006) described the particles and associated metals found in road runoff during snowmelt and rainfall. Important factors influencing the concentrations and loads were the availability of material, the intensity of the lateral flow, and, additionally, the antecedent dry period. During the melt period, particle sizes and TSS were highly correlated with total concentrations of Cd, Cu, Ni, Pb, and Zn. During the rain period, the correlations between total metal concentrations and the different particle sizes were not as significant.

Sansalone et al. (2005) investigated event-based stormwater quality and quantity loadings from elevated transportation structures. The results demonstrated that the transport and loads in runoff as a function of hydrology was necessary when considering treatability and/or pollutant trading. Kayhanian and Stenstrom (2005) investigated the mass loading of first flush pollutants from a highway in Los Angeles, California. Mass first flush ratios were developed and used to describe the ability of stormwater treatment practices to treat highway runoff.

Whiteley and Murray (2005) investigated whether automobile-catalyst-derived platinum, palladium and rhodium were found in the sediments of infiltration basins and wetland sediments receiving urban runoff. The concentrations were strongly correlated to the amount of road surface drained and the traffic volume.

Street dust particles collected by a vacuum cleaner were partitioned into six size fractions by Lau and Stenstrom (2005). Relative PAH concentrations were higher on small particles than were metal concentrations. The lowest concentrations were found in single-family residential areas. The size- and density-distribution and sources of PAHs in urban road dust were investigated by Murakami et al. (2005). The statistical analysis showed that there were significant differences in PAH profiles related to the sampling location, rather than between size or density fractions. Asphalt/pavement were the major source of road dust on a residential street, and tire and diesel vehicle exhaust were the major sources of finer and coarser fractions, respectively, on a heavy-trafficked street.

Li et al. (2005) evaluated the particle size distribution of highway runoff in west Los Angeles (California). The results showed that particle concentration decreased as the storm progressed with the larger particle concentrations decreasing more rapidly than the overall concentration. Zanders et al. (2005) characterized road sediment and assessed the implications of the results on the performance of vegetated filter strips to treat the sediment-laden runoff. Particles less than 250  $\mu\text{m}$  had the highest metal contents. Smaller particles also were found to have lower densities, which affects their ability to settle out.

The potential of parking lot sealcoat to contribute to urban runoff pollution was investigated by Mahler et al. (2005). Those sealcoats made from coal-tar emulsions were found to be a potentially substantial contributor of PAHs to urban runoff.

Total captured gross pollutants in Southern California highway runoff were monitored by Kim et al. (2004). Approximately 90% of these pollutants were vegetation and 10% litter. Bridge runoff was found to contribute metals (especially copper and zinc) above background levels to receiving waters in the Seattle area (Colich 2004). During high-volume traffic times, these concentrations were up to three times higher than at the low-traffic-volume times.

Glanville et al. (2004) investigated the effects of using composted organics on highway embankments to prevent erosion.



The applied composts generally contained much greater pollutant concentrations than the conventional treatments for soluble and adsorbed Zn, P, and K, and adsorbed Cr and Cu. However, when comparing mass loads, compost performed as well as the two conventional soils used for highway embankments.

Kayhanian et al. (2003) investigated the relationships between annual average daily traffic (AADT) numbers and highway runoff pollutant concentrations from California Department of Transportation highway sites. No direct linear correlation was found between highway runoff pollutant event mean concentrations (EMCs) and AADT, but multiple linear regression showed that AADT, as well as antecedent dry period (ADP), drainage area, maximum rain intensity and land use, influenced most highway runoff constituent concentrations.

Mishra et al. (2003) developed hysteresis and normal mass rating curves were developed for runoff rate and mass of 12 dissolved and particulate-bound metal elements from Cincinnati, OH. Zinc was found to increase with antecedent dry period (ADP). Shinya et al. (2003) evaluated the factors influencing diffusion of highway pollutant loads in urban highway runoff. Particulates (suspended solids, iron and TP) were inclined to be washed off in heavier rainfall; event mean runoff intensity and cumulative runoff height were correlated with cumulative runoff load of the constituents except TN. ADP and traffic flow volume were not correlated with cumulative runoff load (except TN).

Sutherland (2003) investigated the lead in six grain-size fractions of road-deposited sediment from Oahu, HI. Significant Pb concentration was seen in all samples and the median labile Pb concentration was 170 mg/kg (4 to 1750 mg/kg), with the silt plus clay fraction containing 38% of the total sediment in this fraction. Westerlund et al. (2003) reviewed the seasonal variations in road runoff quality in Lulea, Sweden. The results showed that the concentrations of suspended solids, lead, copper and cadmium were higher for the melt period, compared to rain generated runoff on the catchment without snow, and the highest concentrations were found during the rain-on-snow events. Metal elements during melt period were more particulate bound as compared to the rain period characterized by a higher percentage of the dissolved fraction.

Zakaria et al. (2002) reviewed the distribution of PAHs in rivers and estuaries in Malaysia. Total PAHs concentrations in the sediment ranged from 4 to 924 ng/g. Alkylated homologues were abundant for all sediment samples. The ratio of the sum of methylphenanthrenes to phenanthrene (MP/P), an index of petrogenic PAHs contribution, was more than unity for 26 sediment samples and more than 3 for seven samples for urban rivers covering a broad range of locations. PAHs and hopanes fingerprints indicated that used crankcase oil is one of the major contributors of the sedimentary PAHs. Two major routes of inputs to aquatic environments have been identified: (1) spillage and dumping of waste crankcase oil and (2) leakage of crankcase oils from vehicles onto road surfaces, with the subsequent washout by street runoff. N-Cyclohexyl-2-benzothiazolamine (NCBA), a molecular marker of street dust, was detected in the polluted sediments.

Neary et al. (2002) studied the pollutant washoff and loadings from parking lots in Cookeville, Tennessee. The monitoring results indicated that the washoff response from small parking lot catchments was also affected by other factors that included antecedent dry conditions and rainfall intensity. Ma et al. (2002) investigated the first-flush phenomenon for highways. Most pollutants showed median mass first flushes where 30 percent of the mass is released in the first 20% of the runoff. Pollutants representing organic contaminants had the highest first flush ratios.

Rood and Lackey (2002) investigated the impacts of new highway construction on the Ocmulgee Old Fields Reserve near Macon, Georgia, by studying the impacts of the earlier interstate (I-16) construction in the same area. A general survey indicated that the minimal bridging on I-16 prevents surface waters from their natural flow toward the river. The crossing of the I-16 roadbed with a pre-existing railroad bed has impounded waters on the southeastern border of the Ocmulgee National Monument. Impoundment has transformed this zone from a forested wetland plant community with rich organic soils to an open aquatic wetland with emergent and floating vegetation. The findings indicated that between the highway and the river that any random or non-random event that removed forest canopy had a more significant impact on wetland community structure and function than did proximity to the highway.

Lau et al. (2002b) studied whether a first flush of organics (COD, oil and grease, and PAHs) would be seen in highway runoff. The three highway sites exhibited a first flush in most cases for most parameters. The mass first flush ratio (the ratio of the normalized transported mass of pollutant to the normalized runoff volume) generally was above 1.8 for the first 25% of the runoff volume, and in some cases as high as 2.8.

Glenn et al. (2001a and 2001b) described their research at highway test sites in Cincinnati, Ohio investigating the effects

of traffic activities and winter maintenance on the behavior of particulates in the runoff. They found that urban snow has a much greater capacity to accumulate traffic-related pollutants, as compared to stormwater, due to longer residence times before melting, and the snow's porous matrix. Parameters such as residence time, solids loadings, alkalinity, hardness and pH influence the heavy metal partitioning in the snow. They found that Pb, Cu, Cd, Zn, Al, Mg, and Fe were mostly particulate bound, while Na and Ca were mostly dissolved. Partition coefficients for most heavy metals in snowmelt water ranged from 103 to 106 L/kg. Stenstrom et al. (2001) studied freeway runoff from three sites in the west Los Angeles area. Each site was sampled for 14 storms during the 1999-2000 rainy season. Samples were collected very early in the storm in order to compare water quality from the first runoff to water quality from the middle of the storm. A large range of water quality parameters and metals were analyzed. The data showed large first flushes in concentration and moderate first flushes in mass emission rates. Zhou et al. (2001) studied accumulations of heavy metals in roadside soils. Heavy metal accretion in the surficial soils was a function of depth, surface drainage patterns, distance from the pavement edge and soil indices. Rapid decreases in heavy metal accumulations were found as the distance from the pavement increased. Plasticity and organic matter content were important soil characteristics affecting the observed heavy metal concentrations.

Fifteen highway construction sites were monitored by the California Department of Transportation (Caltrans) to assess the runoff quality from the sites (Kayhanian et al., 2001a). The results indicated the following: (a) construction-site runoff constituent concentrations were less than typical Caltrans and non-Caltrans highway runoff constituent concentrations, with the exception of total chromium, total nickel, total phosphorus, total suspended solids (TSS), and turbidity. (b) The concentrations of TSS and turbidity likely resulted from soil disturbance. (c) The origins of the total chromium, total nickel, and total phosphorus concentrations are unknown. (d) A correlation was observed between TSS and particulate runoff concentrations of chromium, copper, and zinc, indicating that solids removal may reduce total metals concentrations. The Solids Transport and Deposition Study (STDS) characterized the rates and patterns of solids transfer to, and the collection within, storm water drain inlets located along Caltrans highway facilities (Quasebarth et al., 2001). The primary objective was to determine if certain distinguishable site characteristics controlled the transport and deposition of sediment, metals, vegetation, litter, and petroleum hydrocarbons to highway drain inlets. The ANOVA results indicated that the four primary factors (erosion control/sediment loading [vegetation factor], litter management [litter factor], toxic pollutant generation potential [adjacent land use factor], and roadway design [design factor]) likely had little overall control on solids accumulation or metals mass accumulation, although roadway design and litter management were possibly important in some cases.

Since urban roads are typically directly connected to the drainage system and therefore respond quickly to storm events, the quality of urban road runoff in the Sydney, Australia, region was investigated by Ball (2000a). This paper also proposed guidelines for estimating the transportable trace-metal loading from road surfaces. Ball et al. (2000) showed that the quality of the runoff resulting from the construction of a new highway intersection in Australia could be improved by using treatment devices such as detention ponds and sand filters. Hirsch (2000) reported on the development of a TMDL for Straight Creek in Colorado due to the sediment and pollutant loads contributed to the stream by Interstate 70 runoff. The interstate construction increased erosion in the stream due to the significant cut-and-fill, as did the snowy winter road conditions which required extensive sand applications. An investigation by Drapper et al. (2000) showed that the pollutant concentrations (heavy metals, hydrocarbons, pesticides, and physical characteristics) in 'first flush' road runoff in Brisbane in southeast Queensland, Australia was within the ranges reported internationally for highways. Traffic volumes were the best indicator of road runoff pollutant concentrations, with interevent duration also being statistically significant factor. Exit-lane sites were found to have higher concentrations of acid-extractable copper and zinc, likely due to brake pad and tire wear caused by rapid deceleration, and laser particle sizing showed that a significant proportion of the sediment in runoff was less than 100  $\mu\text{m}$ . Krein and Schorer (2000) investigated heavy metals and PAHs in road runoff and found that, as expected, an inverse relationship existed between particle size and particle-bound heavy metals concentration existed. However, particulate-bound PAHs were found to be bimodally distributed. Three-ring PAHs were mostly found in the fine sand fraction, while six-ring PAHs were mostly concentrated in the fine silt fraction. Sutherland et al. (2000) investigated the potential for road-deposited sediments in Oahu, Hawaii, to bind contaminants, and thus transporting these bound contaminants to the receiving water as part of the runoff. In the sediment fractions less than 2 mm in diameter, the origins of the aluminum, cobalt, iron, manganese and nickel were determined to be geologic. Three of the metals concentrations, copper, lead and zinc, were found to be enhanced by anthropogenic activities. Sequential extraction of the sediment determined the associations of the metals with the following fractions: acid extractable, reducible, oxidizable, and residual).

An overview of the National Cooperative Highway Research Program (NCHRP) upcoming work was presented by Stein

et al. (2000). This presentation included an evaluation of past work on stormwater runoff from transportation facilities and a prioritization of future research in this area.

Walker et al. (2000a) reviewed the on-going water quality assessment program implemented by the San Diego region of the California Department of Transportation (Caltrans). Constituents of concerns were being targeted for monitoring and potential remediation. The thermal enhancement of stormwater runoff by paved surfaces was investigated by Van Buren et al. (2000a and 2000b). The results from the test-plot studies were used to help develop, calibrate and verify the wet-weather model TRMPAVE, a mathematical model that uses an energy balance to predict the temperature of the runoff. Glenn et al. (2000) found that the snow residuals along highways had high levels of particulate and solid matter, likely from nearby vehicular traffic. Snow also accumulated traffic-based pollutants to a greater degree.

In the Kerault Region of France, the effects of pollution were studied using solid matter from a section of the A9 motorway. This study analyzed both settled sediments from collecting basin and characteristics of sediments in the water column during and after eight storm events between October 12, 1993, and February 6, 1994. Settled sediments were used to measure particle sizes, mineral content, and related characteristics, whereas water samples were used to document total suspended solids, mineral content, and heavy metals (Andral et al., 1999).

Runoff from highways contains significant loads of heavy metals and hydrocarbons, according to German regulations it should be infiltrated over embankments to support groundwater recharge. To investigate the decontaminating effect of greened embankments, soil-monoliths from highways with high traffic densities were taken. Soils were analyzed to characterize the contamination in relation to distance and depth for lead, zinc, copper, cadmium, PAH and MOTH (Dierkes and Geiger, 1999).

The quality of highway runoff monitored in the Austin, Tex. area at three locations on the MoPac Expressway were similar in constituent concentration to median values compiled in a nationwide study of highway runoff quality (Barrett et al., 1998a). A grassy swale at one site which had a lower runoff coefficient due to infiltration reduced concentrations of most constituents in runoff. The pollutants available for transport during storm events of a suburban road in the eastern suburbs of Sydney, Aust. were significantly different from published data for North Am. (Ball et al., 1998). Both rain and wind events lowered the available pollutant constituent mass on the road surface. Fourteen composite samples of Marinette, Wis. stormwater, as well as baseflow samples, were analyzed to determine requirements for a National Pollutant Discharge Elimination System (NPDES) permit and the results indicated similarity to stormwater found in other communities (Scholl and Lauffer, 1998). Measurements of conductivity and turbidity taken in a study of the Crum Creek which runs through the suburbs of Philadelphia, Pa. indicated two stages during the first three hours of wet weather runoff: a dissolved solids flush followed by a suspended solids (SS) flush (Downing and McGarity, 1998).

In San Francisco, Calif., vehicle emissions of both ultrafine ( $< 0.12 \mu\text{m}$ ) and accumulation mode ( $0.12 - 2 \mu\text{m}$ ) particulate polycyclic aromatic hydrocarbons (PAH) are derived from diesel vehicles while gasoline vehicles emit higher molecular weight PAH primarily in the ultrafine mode. Heavy duty diesel vehicles were found to be important sources of fine black carbon particles (Miguel et al., 1998). In a European study, 90% of the particles from a contaminated highway runoff catchment were smaller than  $100 \mu\text{m}$ . The constituents of the contaminants smaller than  $50 \mu\text{m}$  were further analyzed by X-ray diffraction, thermogravimetry and specific mass and contained 56% clay, 15% quartz, 12% chalk, 9% organic matter, 5% feldspars, and 2% dolomite (Roger et al., 1998).

Several researchers investigated roadway storm runoff as a nonpoint pollution source and reported their results at the 7th International Conference on Urban Storm Drainage in Hannover (Sieker and Verworn, 1996). Wada and Miura (1996) examined storm runoff from a heavily traveled highway in Osaka, Japan. A significant "first-flush" for COD was found and the amount of small rubber pieces from tire wear in the highway storm runoff was more than 20 times greater than for an "ordinary" road. The primary factors affecting storm runoff concentrations were the amount of traffic (and related exhaust emissions and tire wear) and the fraction of the total traffic that was comprised of trucks and buses. Montrejaud-Vignoles *et al.* (1996) collected storm runoff from a heavily used six-lane motorway in the Mediterranean area of France. The very irregular rainfall in this area and associated very-long dry periods can result in storm runoff that is much more polluted than elsewhere in France. As an example, during the one-year study, a single rain of only 10 mm but having an antecedent-dry period of 35 days, produced more than 12% of the annual COD discharges. Ball *et al.* (1996) examined roadway pollutant accumulations in a suburb of Sydney, Australia. It was concluded that the local heavy winds have a significant effect on pollutant accumulations that commonly available stormwater models do not consider, and that historical United States' data on roadway-pollutant accumulations are much greater than found in their area. Sansalone

and Buchberger (1996) studied metal distributions in stormwater and snowmelt from a major highway in Cincinnati, OH. Zn and Cd were mostly in filterable (dissolved solids) forms in the storm runoff, while lead was mostly associated with particulates.

### ***Deicing Discharges and other Cold Weather Sources***

Reinosdotter and Viklander (2006) discussed the handling of urban snow in Sweden with regards to water quality. The results showed the importance of both the location and time of the snow, i.e., what happens to the snow while it stays on the ground. Richardson and Tripp (2006) studied the boundary shear stresses and pollutant detachment mechanisms of four chloride salts from impervious surfaces during simulation urban runoff. In general, higher overland flow rates produced lower boundary shear and lower washoff coefficients. Corsi et al. (2006) characterized aircraft deicer in airport snowbanks and snowmelt runoff. The results showed that glycol was not a good tracer to predict fate and transport of the de-icing and anti-icing products.

Mericas (2005) reviewed recent advances in airport stormwater management and in particular, how this relates to deicing of aircraft and surfaces. Research is ongoing into alternatives to glycol-based deicing fluids. Dillon and Merritt (2005) modeled the influence of reducing wetland environments and increasing the use of de-icing chemicals on the surface-ground water system in a semi-urban watershed. Pavement density affected the concentration of the deicing chemicals in the surface waters.

Marsalek et al. (2003) reviewed the cold-weather operation of urban drainage systems. Due to the increased pollutant loadings in cold-weather runoff due to the extended storage of pollutants in the snowpack, snowmelt and winter runoff discharged from urban drainage have been found to be toxic.

Deicing salt (NaCl) fate was determined from retention and loss in snow cover adjacent to a 14 km section of the highway in southern Ontario during the 1994-1995 winter. Almost all applied NaCl reached the soil surface via direct runoff and infiltration of saline water from the road into the shoulder and right-of-way, and transfer of salt to snow cover adjacent to the highway and release during snow melt (Buttle and Labadia, 1999).

Paschka et al. (1999) studied the water-quality effects associated with the extensive use of water-soluble iron cyanide compounds used as anticaking agents in road salt. Although available information did not indicate a widespread problem, it was also clear that the water-quality effects of cyanide in road salt had not been adequately examined.

During the winter of 1995-1996, deicing chemicals (approximately  $3 \times 10^6$  L of ethylene glycol,  $0.5 \times 10^6$  kg of urea, and  $23 \times 10^3$  kg of potassium acetate) were spread on the Pittsburgh (Pa.) International Airport and presumably drained into Montour Run, a nearby stream. The metabolism of glycols and urea exerted a strong BOD in receiving water and elevated concentrations of ammonia ( $\text{NH}_3$ ) (Koryak et al., 1998).

Complex ferrocyanide compounds, which can break down into free, toxic, cyanide compounds, are added to salt to prevent caking (Novotny et al., 1998a). Salt also decreased partitioning between adsorbed and dissolved metals which increased dissolved metals in snowmelt. A dynamic model was developed and calibrated to calculate daily loads and concentrations from snowpiles of three northern cities using salt for deicing (Novotny et al., 1998b). Snowmelt runoff from an urban watershed can produce density current intrusions in a lake (Ellis et al., 1997). Snowmelt runoff entering Ryan Lake in Minneapolis, Minn. increased electrical conductivity, salinity and density with salt spread on urban streets as the source of the salinity.

### ***Treated Wood***

Treated wood has periodically been identified as a potential source of toxicants in stormwater but few studies have specifically examined its role. Khan et al. (2006a) examined the release of arsenic to the environment from chromated-copper-arsenate-preserved wood currently in service. Arsenic levels in the runoff from the treated wood was 200 times greater than the levels found in runoff from untreated wood. Weis and Weis (1996) examined the leaching potential of Cu-Cr-As (arsenic) mixture (CCA) treated wood in Chesapeake Bay. Sediment and benthos samples were analyzed for Cu, Cr, and As at varying distances from treated-wood bulkheads at test and control sites. In general, sediment metal concentrations decreased with distance from the treated-wood bulkheads but not at the control stations. The species diversity and the number of individual species were also less at the treated-wood site at the poorly flushed location but not at the control area having similar flushing conditions.

### ***Wastewater, Combined Sewer Overflows (CSOs), and Sanitary Sewer Overflow (SSO) Sources***

Pollutant associations in stormwater in combined sewers were investigated by Anta et al. (2006) in Galicia (Spain). Measurements of pollutants in the combined sewage were correlated with event parameters and were compared with measurements in other catchments. Li and Li (2006) studied the characteristics of high-density residential CSOs in Shanghai. BOD was lognormally distributed, and correlations between EMCs of COD, suspended solids and the ratio of antecedent dry weather to rain duration were good.

Lawler et al. (2006a) examined the dynamics of suspended sediment for storm events in an urbanized river in the United Kingdom. In this catchment, first flushes of sediment from the combined sewers were not seen, with turbidity peaks lagging the flow maximum. This result was likely influenced by CSOs or wastewater treatment works, which discharge high flows late in the storms.

Arnone and Walling (2006) studied *Cryptosporidium* and *Giardia* concentrations, as well as more traditional indicator organisms, in combined sewer overflows (CSOs). CSOs were not found to be a significant contributor of *Cryptosporidium*, but were a *Giardia* source. Bai et al. (2006) modeling enterococci in the tidal area of the Christina River. The model results revealed that the enterococci concentrations were due to wash off of manure from agricultural lands in the watershed during storms and direct deposits of animals into the waterway. CSOs only affected limited areas around the outfalls since the dilution is strong in the tidal Christina River.

Hochedlinger et al. (2006) used UV/VIS-spectroscopy to correlate absorbance and CSO pollutant load concentrations. The correlations/regressions were incorporated into a model, with the model results showing that the complexity of the model did not affect the quality of the results. Gasperi et al. (2006) examined the spatial variability of PAH loads in CSOs. The runoff contribution to the PAH load was constant, while the dry weather flow load increased with increasing drainage area, while the sewer erosion contribution rate decreased with increasing catchment area. Caffeine was evaluated as a marker for CSOs by Buerge et al. (2006). It was shown to be a suitable marker for CSO flows, but its sensitivity depended on regional conditions and decreased to near inefficient levels when applied close to wastewater treatment plants.

Pollution load balances were used to compare the benefits of a separate versus a combined sewer system based on available database values (Brombach et al. 2005). For nutrients, the separate system produced lower loads, whereas for metals and COD, the combined sewer system yielded lesser loads. The Thames Tideway Study, including the effect of CSOs, was reviewed by Anonymous (2005a).

Langeveld et al. (2005) used turbidity measurements and an event-based hydrodynamic model to simulate suspended solids transport in combined sewers. The authors were unable to find a clear relationship between shear stress or flow velocity and solids transport. Biggs et al. (2005) investigated the effect of storm events on the particle size distribution of sediments in combined sewers. As the shear stress increased, a broad unimodal distribution developed. The type of sediment in the flume greatly affected the size of the eroded particles. Frehmann et al. (2005) modeled the sedimentation and remobilization of solids in in-line storage sewers as a means to predict stormwater treatment.

McIlhatton et al. (2005) investigated the potential for sediment resuspension in sewers under high flow conditions. Resuspension is considered a substantial source of solids discharged from sewers. The paper described some of the methods used to investigate solids resuspension. The influence of biodegradability of sewer solids on the management of CSOs was examined by Sakrabani et al. (2005). A new prediction method based on the Oxygen Utilization Rate and an Erosionmeter was proposed to evaluate trends in biodegradability during in-sewer sediment erosion in wet-weather conditions.

The spatial characteristics and origins of pollutants in combined sewers were examined by Kafi-Benyahia et al. (2005). Suspended solids were found to be relatively homogeneous spatially along the pipes. The heavy metals, except for copper, were more associated with wet-weather flow than dry-weather flow. Sewer deposit erosion also was an important source of wet-weather pollution. Rutsch et al. (2005) investigated the effects of compounds transported in sewers on CSO discharges and on the loading to the wastewater treatment plant using hydrodynamic simulations. Rain-induced pollutographs were evaluated based on the dynamic loadings. Suarez and Puertas (2005) determined the COD, BOD and suspended solids loading during CSO events in Spain. The existence of, or lack thereof, a first flush was also examined. Hydraulic parameters and pollutant amounts were measured in both dry and wet weather conditions.

Woodward et al. (2004) reviewed the water-quality monitoring portion of the Overflow Abatement Program in Nashville, Tennessee. The purpose of the program was to understand the relationship between potential pollutants and receiving streams, so that money is spent effectively to improve water quality and reduce overflows.

Curling et al. (2003) reported on the Thames Tideway strategy and sewer flow survey. The Thames Water Utility surveyed the system to obtain continuous flow data at specific sites. The data would be incorporated into models to assess storage and screening options for controlling CSOs discharging to the River Thames. Fonda et al. (2003) evaluated the impact of fats, oil and grease (FOG) in sewer systems and their effects on SSOs in the sewer system of Orange County (CA). The authors concluded on-site treatment of FOG using a dedicated anaerobic digester would reduce the impact of FOG. Newton (2003) reviewed the Kent County (DE) DPW's plan for FOG. The control strategies included education and regulation, the results of which appear to be an improvement in SSOs. Oros et al. (2003) monitored for previously-unmonitored synthetic organic chemicals (SOCs) in the San Francisco estuary. The major contaminant classes identified in the samples were fire retardants, pesticides, personal care product ingredients, and plasticizers with the major sources being the discharge of municipal and industrial wastewater effluents, urban stormwater, and agricultural runoff.

Heijs et al. (2002) reviewed Project CARE in North Shore City (New Zealand), which is a program that planned improvements to wastewater and stormwater systems in order to protect the streams and beaches. Hydrological and hydraulic models were both constructed to represent the sanitary and storm sewer systems and were coupled with a receiving water model to simulate the impact on beaches. Ferreira et al. (2002) investigated the performance of partially separate sewer systems in Oeiras, Portugal, and their impact on receiving waters. The volume and characteristics (COD loads) were estimated and used to evaluate the potential contamination of swimming/beach areas by bacterial loads, especially due to first-flush effects.

The Massachusetts Water Resources Authority (MWRA) completed its Long-Term Control Plan for CSO control in 1997. The plan used a watershed approach to assess the impacts of CSOs in relation to other sources of pollution in the watershed, including stormwater and upstream flows. The EPA and the Massachusetts Department of Environmental Protection agreed to revise the water quality standards for certain waters within Boston Harbor. For the Charles River, a two-year water quality variance was granted to allow further study of the impacts of non-CSO sources of pollution, as well as for additional CSO control alternatives. Important current activities described by Walker et al. (2001) include an assessment of additional CSO storage; performance evaluations of the MWRA's Cottage Farm CSO facility; development of a more detailed stormwater runoff model for areas tributary to the Charles River; and upgrading the receiving water model for the Charles River.

Lessard and Michels (2000) examined the effects of CSO basin discharge on the water quality in the Menominee River in 1997. Based on the data collected, the overflow from the CSO retention basin does meet the Michigan Water Quality Standards during the overflow discharge events, with the basin providing the equivalent of primary treatment plus disinfection. The loadings of most of the pollutants, including nutrients, metals and suspended solids, were insignificant compared to background. The CSO basin effluent also did not appear to impact the dissolved oxygen in the river to the point where the DO fell below standards.

CSO and urban streams receiving CSO in the Pittsburgh, Pa. area were tested for *cryptosporidium* and *giardia*. Data suggested CSO are a significant source in small streams (Stadterman et al., 1998).

The EPA (1996f) conducted case studies to examine the effects of CSOs on the biological integrity of some example streams in Ohio and New York using rapid-bioassessment protocols. Results were compared with historical assessments of the same streams. Drinnan *et al.* (1996) presented data that showed the application of rating systems developed to identify discharges that have public-health or environmental concerns and provide a protocol for initiating mitigative measures in Victoria, BC, Canada. The number of discharges designated as high priority because of their effects on public health has decreased steadily between 1992 and 1995 and the number of bathing beaches posted with a health advisory has decreased from 28 in 1969 to none in 1995. *Water Environ. & Technol.* (1996b) reported that the fecal coliform counts decreased from about 500/100 mL to about 150/100 mL in the Mississippi River after the sewer-separation program in the Minneapolis and St. Paul, MN area. Combined sewers in 8,500 ha were separated during this 10-year, \$332 million program.

Results from sediment samples collected adjacent to each of four CSO along the lower Passaic River of New Jersey

indicated that sediments proximate to the CSO outfalls were contaminated with a range of chemicals including toxic metals, PAH, PCB, pesticides, and other organic chemicals. The spatial distribution of these contaminants strongly suggested that the CSO were the primary source of contamination in sediments near these outfalls (Iannuzzi *et al.*, 1997).

### ***Inappropriate Discharges***

Pitt *et al.* (2004) revised an earlier flow-chart method for detecting illicit discharges into the storm sewer system. The revised flow chart includes fewer chemical tracers and helps differentiate between the two major source sub-groups: clean water (tap water, spring water, irrigation runoff) and dirty water (carwash, laundry, sewage, industrial sources).

The techniques, experiences, and lessons learned by the Village of Romeo (outside Detroit, Michigan) in eliminating illicit discharges into the storm sewer system were reported by McLaughlin *et al.* (2002). This work was performed in response to local health department reports of high bacteria levels and sanitary debris in East Pond Creek.

McGee *et al.* (2000) investigated the potential sources of indicator bacteria that closed a portion of Huntington State Beach in Orange County, California. The approach used was termed a “risk-based sanitary survey,” and the investigation used both state-of-the-art technologies (radar, sonar, and infrared imaging) and conventional techniques (geo-probes, television inspection of the sewers, and monitoring wells). White *et al.* (2000) investigated the effects of land use change and resulting bacterial concentrations on shellfish closures in Jump Run Creek in North Carolina. The results of this project showed that the likely sources of the elevated bacterial concentrations (high during wet weather, moderate during dry weather) was the area draining an older, medium density residential neighborhood (single family homes, trailer park with two malfunctioning septic tanks and more than 100 pets, plus wildlife). Dye studies in the area indicated that flow through area was too small for bacterial mortality to occur.

The combined use of sterol biomarkers and bacterial indicators showed that during wet weather, all sites sampled in the storm drainage system of Geelong, Victoria, Aust. were subject to human fecal contamination. Ratios of coprostanol to bacterial indicators were similar to those for samples collected from nearby sewer mains (Leeming *et al.*, 1998).

Sangal *et al.* (1996) conducted a feasibility study for the Rouge River National Wet Weather Demonstration Project to evaluate the applicability of the stable-isotope approach to identify illicit connections in three mini-watersheds in or near Wayne County, MI. The results indicated that the isotopic technique is extremely cost-effective and robust for distinguishing between local groundwater and water derived from domestic and industrial or commercial sources.

Baltimore, MD as part of their NPDES permit, examined their storm-drainage system for sources of illicit entries (Stack and Belt, 1996). About one third of the 344 small subwatersheds in the city have been targeted as potential sources of toxicants from illicit entries, based on analyses of surfactants, phenols, ammonia, Cu, Pb, Zn, and total petroleum hydrocarbons, with eight sources specifically identified.

### ***Industrial and Other Sources***

Golf courses have long been a concern in terms of runoff quality. Parsons *et al.* (2006) described the engineering of golf courses in terms of environmental aspects, such as stormwater runoff. The paper promoted the use integrated pest management techniques to limit fertilizer and pesticide use, plus maintaining buffer areas to treat chemical-laden runoff. Another source of nutrient and pesticide concerns were nurseries and aquaculture. Lu *et al.* (2006) examined the sorption and degradation of pesticides in nursery runoff recycling ponds. These ponds retained chlorpyrifos and pendimethalin, but their persistence/lack of degradation in the sediment may cause problems if the pond overflows. De Lacerda *et al.* (2006) investigated the importance of nitrogen and phosphorus emissions from aquaculture and other anthropogenic sources. Aquaculture was the most important source, followed by streamside agriculture, which is then trailed substantially by urban runoff.

Several other industries raised runoff pollution concerns. Bartlett (2006) review the performance and cost of stormwater treatment options at composting facilities in Washington state. The recommendation was to separate the actual activity areas from the areas that receive rainfall. Doig *et al.* (2006) characterized the particles in fresh and primary-treated log-sort yard runoff. Fresh runoff had higher concentrations of organics; however, even after primary treatment, substantial quantities of organics remained and could not be reduced by settling and biodegradation. Fernandez (2006) reviewed the concerns faced by the scrap recycling industry to monitor and control stormwater runoff. Mrozek *et al.* (2006) described landscaping rock as a source of heavy metal contamination in Nevada. The research supports the regulation of sulfide-bearing rocks in future landscaping applications.

Diez et al. (2006) reported on the occurrence and degradation of butyltins and other wastewater markers in Barcelona Harbor sediments. Stormwater runoff and CSOs were likely the most probably sources of surfactant intermediates (linear alkylbenzenes and nonylphenols). Luo et al. (2006) examined the PAHs in suspended particulate matter from Chinese coastal areas. Biomass and coal production was the primary source of PAHs in these areas, while gasoline and its combustion products contributed to the PAHs associated with suspended particulates.

Evaluation of dry and wet-weather flow nutrient loads in the semi-arid Ballona Creek Watershed (Southern California) was performed by McPherson et al. (2005a). Wet-weather flow was considered the source of the majority of nutrient loads on an annual basis; however, during the dry season, dry weather flow contributions were substantial comparatively. McPherson (2005b) performed the same analysis on the trace metal pollutant loads and found similar conclusions for copper, lead, nickel and chromium. Harrison et al. (2005) modeled the fate and persistence of diazinon and chlorpyrifos in the Newport Bay Watershed (California). Their modeling showed that certain land uses contributed these pesticides to runoff and that diazinon concentrations were not reduced below the aquatic toxicity levels even after the pesticide was phased out. Infiltration was suggested at the source sites as a means of controlling release into surface waters.

The paint used on depleted uranium hexafluoride samples was found to be toxic to *Ceriodaphnia* (Kszos et al. 2004). The zinc in the paint was found to be the culprit of the toxicity with runoff concentrations of zinc up to 13 mg Zn/L. The pollutant contributions from runoff from Superfund and hazardous chemical sites was raised by Lee and Jones-Lee (2004). Concerns also include the infiltration of runoff on the site, which might lead to groundwater contamination. Lewis et al. (2004) evaluated the bioavailable pollutant contributions from a Florida coastal golf complex. Concentrations of chlorinated pesticides and PCB congeners were usually below detection in the biota, while eight trace metals were commonly detected. Concentrations were not usually significantly different for biota collected from reference and non-reference coastal areas, indicating the golf course is not a significant contributor.

Myungi et al. (2003) reviewed the impact of home-based industries on the water quality of a tributary of the Marimba River, Harare. Pollution loads for certain parameters (TP, TKN, NH<sub>3</sub>, Fe and Pb) averaged four times higher in the sub-catchment containing home industries than in the sub-catchment containing residential areas only, likely due to higher runoff volumes from the area containing the home industries. The pollution concentrations in the two basins were not statistically different. Kszos et al. (2003) investigated the pollutant contributions of zinc from paint commonly used on cylinders of depleted uranium hexafluoride since the cylinders were determined to be the source of toxicity in stormwater runoff from the cylinder's storage facility. Rainwater collected directly from the painted cylinders contained up to 13 mg/L Zn.

Choe et al. (2002) characterized the surface runoff in urban (residential and industrial zones) areas. The event mean concentrations (EMCs) of COD, SS, TKN and TP in the residential zone were 313 mg/L, 279 mg/L, 8.45 mg/L, 1.98 mg/L, and those in the industrial zone were 80 mg/L, 106 mg/L, 5.07 mg/L, and 1.93 mg/L, respectively. No general relationship between the cumulative load and runoff could be established. The degree of first-flushing effect by constituents was in the following order: TKN > COD > SS > HEM > TP > PO<sub>4</sub>-P. Based on the correlation of constituents with SS, high treatment efficiency of SS, heavy metals, organic matter, and TP was expected. The unit pollutant loading rates of COD, SS, TKN, TP, Cr and Pb in the residential zone were 2,392, 2, 130, 64.6, 15.1, 0.31, and 1.83 kg/ha/yr, and those in the industrial zone were 612, 812, 38.7, 14.8, 0.51 and 0.82 kg/ha/yr, respectively.

Chang and Duke (2001b) summarized their research that examined stormwater quality from eight auto dismantling facilities in Los Angeles, CA, over a three year period. The majority of the samples had constituents exceeding stormwater discharge guidelines, but were highly variable. Talbot (2001) discussed some of the stormwater management challenges and solutions for power generation facilities.

Stormwater from a modern waste disposal site was characterized by Marques and Hogland (2001). They examined 22 different constituents and found that suspended solids, COD, BOD, total nitrogen and total phosphorus, exceeded discharge standards. Some of the runoff constituents were greater than found in the leachate from covered landfill sites. Copper, zinc and nickel were the most commonly detected heavy metals, being found in every sample. Surprisingly, the concentrations of zinc, nickel, cobalt, iron and cadmium found in runoff from composting areas were greater than the metal concentrations found in the runoff from areas having stored and exposed scrap metal. They concluded the presence of large amounts of organic compounds, plus site specific drainage pathways, were responsible for these findings.



Akan et al. (2000) noted that a significant pollutant loading to the adjacent receiving water can occur due to runoff from marine drydocks. The authors modeled the quantity and quality of marine drydock runoff by combining the two-dimensional kinematic wave and convective transport equations with an empirical formula for washoff. Lewis et al. (2000) reviewed stormwater-runoff monitoring data from industrial facilities discharging into the upper San Gabriel watershed in the Los Angeles region. The results of this review showed that while industrial facilities occupy less than 1% of the watershed area, they contribute between 10% and 70% of the total copper and between 15% and 60% of the total zinc loads. Moreno-Grau et al. (2000) investigated the heavy metal content of atmospheric aerosols and suspended particulate matter from industrial areas in Cartagena. The industries contributing to the atmospheric metals contamination included power plants, oil refineries, non-ferrous metals, fertilizer plants and a shipyard.

Samples of stormwater runoff from three sawmills on Vancouver Island, British Columbia, Canada, were tested for acute toxicity with juvenile rainbow trout. Causes of toxicity were investigated using toxicity identification evaluation techniques; specifically, treatment with the chelating agent EDTA (Bailey et al., 1999a). Samples of stormwater runoff from nine sawmills in British Columbia, Canada, were also tested for acute toxicity with juvenile rainbow trout over a 23-month period. Toxicity was attributed to divalent cations, particularly zinc, in 32 of the samples. Toxicity in the remaining samples was largely attributed to tannins and lignins and was associated with areas of bulk log handling (Bailey et al., 1999b).

The EPA has released NPDES stormwater-monitoring data from industries using agricultural products (Amick, 1996). Data from facilities representing the food, tobacco, textile mill, apparel, and other industries and appropriate best management practices for reducing or eliminating the pollutants are presented. Su and Christensen (1996) developed a chemical-mass-balance model to identify sources of polychlorinated dibenzo-p-dioxin (PCDD) and dibenzofuran (PCDF) in a sediment core from the Baltic Sea that spanned the time period from 1882-1985. The results indicate that coal-fired-power plants, municipal incinerators, and pentachlorophenol-containing matter contribute significantly to the measured PCDD and PCDF.

Hall (1996) collected samples from two estuarine wetlands in highly urbanized areas to determine if chromite ore processing residue surrounding one site contributes to significantly higher chromium (Cr) concentrations in biotic and abiotic media relative to those at a reference site. Although concentrations of Cr, Cu, and Pb were significantly higher in sediment samples from the study site compared to the reference site, no pattern of higher metals concentrations in biotic samples from the study site was found.

Line *et al.* (1996) examined stormwater from ten industrial sites in North Carolina for a broad list of conventional- and metal- and organic-toxic-substance-pollutant parameters. Automobile-salvage-yard runoff had the highest metal concentrations except for the wood-preserving sites which had the highest chromium concentrations. Other pollutants did not vary significantly between different types of industrial operations.

### ***Specific Pollutant Sources***

#### **Litter**

Williams and Simmons (1999) investigated the sources of litter in and along the river Taff, South Wales, UK. The greatest inputs of sewage-derived solids were introduced to the river by malfunctioning CSO. While sewage-derived material constituted approximately 23% of all items on the river Taff, large quantities of waste, especially plastic sheeting, originated from fly tipping sites (illegally dumped rubbish in public places).

#### **Sediment**

Rossi et al. (2005) performed stochastic modeling of TSS in urban areas during rain events. The model predicted the probability of TSS loads arising from CSOs as well as from stormwater in separate sewer systems. The different washoff behaviors of coarse versus fine suspended solids was observed in highway runoff by Aryal et al. (2005a). The concentration of the fines was steadier compared to the coarse fraction, as was the PAH content measured in the fine fraction.

The effect of applying composted organics to new highway embankments was investigated by Persyn et al. (2005). The results showed that, when evaluating the potential for erosion, the shear stress model was not well suited. Detachment caused by flotation of low-density particles, as well as bridging by coarse particles, were proposed as the two rill erosion mechanisms.

Fan et al. (2003) reviewed the sewer sediment control projects conducted by the Wet-Weather Research Program of the US EPA. The projects focused on the relationship between wastewater characteristics and flow-carrying velocity, on the abatement of solids deposition and solids resuspension in sewers, and on the sewerline flushing systems for removal of sewer sediment.

Goodwin et al. (2003) investigated the temporal and spatial variability of sediment transport and yields in the Bradford Beck catchment (UK). The results demonstrated that for individual storms the sediment yields from the urban sub-catchment were generally higher than those from the rural system although the annual yields were comparable. For large events, urban sediment transport was dominated by the impact of CSO discharges. Cristina et al. (2003) defined “first-flush” criteria for solids from small impervious watersheds, dividing the category into two types. They were a concentration-based first flush and a mass-based first flush, and the operational definition should define treatment design and operational efficiency.

Paul et al. (2002) evaluated the quantitative relationships that had been previously developed between landscape metrics and sediment contamination in 75 small estuarine systems across the mid-Atlantic and southern New England regions of the U.S. The landscape metrics important for explaining the variation in sediment metals levels ( $R^2 = 0.72$ ) were the percent area of nonforested wetlands (negative contribution), percent area of urban land, and point source effluent volume and metals input (positive contributions). The metrics important for sediment organics levels ( $R^2 = 0.5$ ) and total PAHs ( $R^2 = 0.46$ ) were percent area of urban land (positive contribution) and percent area of nonforested wetlands (negative contribution).

Nelson and Booth (2002) reported on sediment sources in the Issaquah Creek watershed, an urbanizing, mixed-land use watershed. Human activity in the watershed, particularly urban development, has caused an increase of nearly 50% in the annual sediment yield, now estimated to be  $44 \text{ tons km}^{-2} \text{ yr}^{-1}$ . The main sources of sediment in the watershed are landslides (50%), channel-bank erosion (20%), and road-surface erosion (15%).

Benoit et al. (1999a) studied sources of sediment entering Jordan Cove, Connecticut. Recent sediment accumulation rates were found to be decreasing (from  $0.84 \text{ cm/yr}$  to  $0.40 \text{ cm/yr}$ ) but were slightly faster than relative sea-level rise at this site ( $0.3 \text{ cm/yr}$ ). Long Island Sound was found to be an important source of sediment to the cove; a minor part of total sediment was supplied from the local watershed. Benoit et al. (1999b) also studied sources and the history of heavy metal contamination and sediment deposition in Tivoli South Bay, Hudson River, New York. The measured sedimentation rate ranged from  $0.59$  to  $2.9 \text{ cm/yr}$  suggesting that rapid accumulation occurred during the time period represented by the length of the cores (approximately the past 50 yrs). The sources of this material were expected to be upland streams, or the Hudson River, during storm events. Concentrations of Pb, Cu and Zn correlated with each other within individual cores at five of the six sites tested, suggesting a common proximate source. Nelson (1999) described the sediment budget of Issaquah Creek, a  $144 \text{ km}^2$  mixed-use, urbanizing watershed near Seattle, WA. The water quality of Lake Sammamish, located at the outlet of the basin, was degrading with time, and fine sediment entering the lake from the watershed was a likely source of phosphorus during periods of lakeanoxia. Another potential in-channel concern was the effect of fine sediment on spawning gravel for the salmon species that occupy Issaquah Creek. The sediment balance was being used to identify the major sources of sediment, and thus guide the most effective remedial measures.

## **Nutrients**

Lunetta et al. (2005) investigated the land-use contributions to nonpoint source nitrogen pollution in the Neuse River Basin (North Carolina). High and medium densities of imperviousness in urban areas were the greatest contributors of nitrogen on a unit area basis. Nitrogen was characterized in urban runoff in Melbourne, Australia, during baseflows and storm event (Taylor et al. 2005). Concentrations of nitrogen species did not vary significantly between baseflows and storms, although there was a slightly higher fraction of particulate nitrogen in the storm runoff. Robinson et al. (2005b) found that an increase in impervious surfaces resulted in an increase in low-nitrate runoff, which resulted in lessening of nitrate concentrations in receiving waters. Torreceilla et al. (2005) investigated nutrient dynamics and sources in Spain. Agricultural nonpoint source pollution accounts for most of the nitrate loads in the study area while urban and industrial sources account for most of the phosphate and COD loads. Biological reactions were the key factor in nutrient content and dynamics. The role of exchangeable phosphorus on nutrient dynamics and eutrophication control in the Marne River (tributary to the Seine River) was examined and modeled by Garnier et al. (2005). Phytoplankton abatement could be reduced slightly by reducing wastewater treatment plant phosphorus discharges by 85%. Further decreases in eutrophication would require control of nonpoint sources.

Kirchoff et al. (2004) investigated the use of composted animal manures and biosolids for erosion control and found that compost-amended soils leached nutrients (but decreasing concentrations over time) and metals in direct relation to the amounts in the compost. These amended soils also delayed the peak of the hydrograph due to the water-holding capacity of the compost. Critical conditions for inorganic nitrogen in dry, semi-urbanized watersheds were determined by Keller et al. (2004). The higher inorganic nitrogen concentrations occurred in low-flow times, but concentration peaks occurred during the first storms.

Emerson (2003) discussed Plymouth, MN restrictions on the use of lawn fertilizers containing phosphorus. The result of the program has been an improvement in water quality due to reducing phosphorus in the runoff. Strynchuk et al. (2003) studied the decomposition of grass and leaves and the subsequent input of nutrients to receiving waters in Brevard County, FL. Release rates for these nutrients have been calculated, which can then be used to select and determine maintenance frequencies of stormwater treatment practices that treat nutrients.

Nhapi et al. (2002) performed an assessment of the major water and nutrient flows in the Chivero catchment area, Zimbabwe. The results showed that urban water demand would exceed available treatment capacity by the year 2003. Sewage effluent presently is the major source of nutrients in the rivers. It was concluded that the current situation is not sustainable.

The research conducted by Sonoda et al. (2000) investigated the impact of land use on streamwater nutrient concentrations in an urbanizing watershed in Oregon. During the dry season, soluble reactive phosphorus (SRP) was correlated with light industry land use, while during the wet season, SRP was correlated with light industry, single family residential and mixed residential land uses. During the dry season, nitrate-plus-nitrite was correlated with rural, and heavy and light industry land uses, while during the wet season,  $\text{NO}_3 + \text{NO}_2\text{-N}$  was correlated with rural and heavy industry land uses.

Basnyat et al. (1999) described a methodology to assess the relationships between land use and nitrate and sediment concentrations in streams in the Fish River, Alabama watershed. Residential and other developed urban areas were identified as the largest contributors of nitrate in the area, while active agriculture was identified as the second largest contributor.

Waschbusch et al. (1999) investigated sources of phosphorus in stormwater and street dirt from two urban residential basins in Madison, Wisconsin. They collected numerous sheetflow runoff samples from throughout the test watersheds and used SLAMM, an urban stormwater quality model, to quantify the significance of the different phosphorus sources. Lawns and streets were found to be the most significant sources of phosphorus in the test basins, contributing about 80% of the total annual loading. Peters and Donohue (1999) examined nutrient concentrations and fluxes in tributaries to the Swan-Canning estuary, Western Australia. In addition to the rapid mobility of nutrients in stream water from agricultural areas during the wet season, urban area storm drains typically had high nutrient concentrations, and were also an important source of nutrients to the estuary. Sonoda et al. (1999) described correlations between land use and nutrient inputs to an urbanizing Oregon stream. In the urbanizing areas, possible nutrient sources included fertilizer applied to yards, in addition to roof runoff, various household chemicals, and street runoff.

Manure or compost from beef cattle feedlots can be an excellent source of nutrients and organic matter when added to soils, but they can also pollute runoff. Eghball and Gilley (1999) determined the effects of simulated rainfall on runoff losses of P and N, and EC and pH following application of manure and compost to a Sharpsburg silty clay loam (fine smectitic, mesic Typic Argiudoll) soil having grain sorghum [*Sorghum bicolor* (L.) Moench] and winter wheat (*Triticum aestivum* L.) residues.

A study has been conducted on a 4% slope during 1991 to 1993 at Belie Mina, Alabama, on a Decatur silty clay (clayey, kaolinitic, thermic Rhode Paleudult) to determine effects of broiler litter CBL on seasonal transport losses of nutrients and heavy metals in surface water (Wood et al., 1999). Rainfall, slopewash (the erosion of soil particles), surface runoff and fine-litter transport at humid-tropical steep land sites in the Luquillo Experimental Forest, Puerto Rico (18 degrees 20' N, 65 degrees 45' W) were measured from 1991 to 1995 (Larsen et al., 1999). To identify critical sources of P, Sharpley et al. (1999) investigated chemical and hydrologic factors controlling P export from a mixed land use (30% wooded, 40% cultivated, 30% pasture) 39.5 ha watershed in east-central Pennsylvania.

Sauer et al. (1999) reported that grazing animal excretions were not as significant a source of nutrients to runoff water as was poultry litter; such treatments receiving poultry litter had significantly higher losses of nutrients, including those most commonly associated with surface water indices.

Mass balance calculations for a treated and untreated watershed at the BBWM in Maine showed that annual and cumulative retention of experimental N amendments has leveled off at about 80% after nine years of treatment. The annual retention of treatment S has declined to less than 34% after nine years, with the cumulative retention below 60% over the course of the experiment (Kahl et al., 1999). Soils that contained high P levels could become a primary source of dissolved reactive P (DRP) in runoff, and thus contribute to acceleration eutrophication of surface waters. Because results might differ on other soils, runoff studies were conducted on three additional Ultisols to identify the most consistent STP method for predicting runoff DRP levels, and determine effects of site hydrology on correlations between STP and runoff DRP concentrations (Pote et al., 1999).

An investigation of nonpoint sources (NPS) of P loads to Lake Champlain (Vt./N.Y.) revealed that 18% of the P load came from urban sources which only represented 3% of the contributing Lake Champlain Basin (Meals and Budd, 1998). Other sources included agricultural (66%) making up 28% of the basin, and forest (16%) making up 62% of the basin. An analysis of the Middle Huron River Watershed concluded that the highest concentration of P in runoff came from urban residential areas (Brenner and Rentschler, 1998). A watershed for a small lake in suburban Boston, Mass., supplied over 90% of the P in the lake during a year with normal precipitation and only 15% of the P during a dry year. The P not supplied by the watershed was supplied by a large population of Canada Geese directly to the lake (Moore et al., 1998a).

Choi and Blood (1999) reported the increase of urban growth along coastal states, resulting in the growth of urban non-point source nitrogen runoff to be a major contributor to coastal and estuarine enrichment.

Sediments in the rivers and basins around Washington, D.C. have high concentrations of phosphorus (P) and based on geographic distributions are largely derived from urban stormwater runoff and municipal wastewater (Huanxin *et al.*, 1997). Concentrations of total sedimentary P ranged from 24  $\mu\text{m}$  — 56  $\mu\text{m}$  P/g-dry weight and were highest near combined sewer outfalls and suggested that P from natural sources is small compared to anthropogenic inputs.

Herrmann and Klaus (1996) examined nutrient discharges to rivers in Germany from urban-area-drainage systems. Groundwater was the single largest source of nitrogen, while municipal wastewater was next. Other sources (runoff, drainage water, erosion, stormwater, and industrial waters) were all much smaller. Municipal wastewater was the largest source of phosphorus, while erosion sources was next, with the other sources much smaller.

### **Bacteria**

Kim et al. (2005a) related indicator organisms in a Korean river with land use. The area with the combined sewer overflow impacts had the largest concentration of fecal coliforms. Coliforms were most strongly correlated with suspended sediment. The spatial and temporal nature of point and nonpoint bacterial load contributions was studied by Petersen et al. (2005) in Houston, Texas. The nonpoint source loads were relatively constant from the stream headwaters to the mouth of the bayou; however, the point source loads exhibited greater spatial variability.

Jones et al. (2004) reviewed the need for and development of a bacterial TMDL for the 44 beaches along Santa Monica Bay, California. An innovative Implementation Plan was prepared and included all the municipalities affecting the Santa Monica Bay.

Le Fevre and Lewis (2003) studied the role of resuspension in enterococci distribution at an urban beach. Stream and storm water contributed the greatest numbers of enterococci and, consequently, high numbers of enterococci were found in both water and sediments surrounding discharge points for these sources. Bacterial resuspension under waves was directly related to weather and wave conditions. Scott et al. (2003) used multiple antibiotic resistance (MAR) and land use characteristics to determine the sources of fecal coliform bacteria in a small, urbanized estuary between Myrtle Beach and Georgetown, SC. The MAR results suggest that the majority of the fecal pollution may be from non-human sources, including fecal coliforms isolated from areas in close proximity to high densities of active septic tanks. McLellan and Salmore (2003) concluded that localized bacterial loadings (nearshore) were responsible for the chronic beach closings in a freshwater marina on Lake Michigan. Locally high *E. coli* levels coincided with bird presence and stormwater at the swimming beach located within the marina, and were unrelated to *E. coli* levels in connecting harbor waters. Selvakumar and Borst (2003) showed that land use and season affected microorganism concentrations in stormwater runoff. Organism

concentrations from high-density residential areas were higher than those associated with low-density residential and landscaped commercial areas. Concentrations of organisms were significantly affected by the season during which the samples were collected.

Tobiason et al. (2002) performed stormwater bacteria source tracing at Seattle-Tacoma International Airport using the microbial source tracking (MST) technique. The results showed that more than 90% of the fecal contamination in runoff was attributable to animals. More than 60% of the “fingerprints” matched bird sources and 30% matched small mammals and domestic pets. Pigeons accounted for 20 to 25% of the bird sources for two outfalls in particular, and were most likely linked with a pigeon colony found on the terminal rooftop. Overall, less than 10% of the isolates matched human sources, and these were limited to certain sampling stations and events. Overall, the MST study showed that human sources were present sporadically for two airport outfalls and two stream locations, but occurred in small numbers relative to animal sources.

Griesel and Jagals (2002) investigated the impact of a variety of urban discharges from Bloemfontain on the numbers of microbiological fecal indicator organisms in the water of the Renoster Spruit subcatchment. The results indicated that the fecally polluted urban runoff, combined with inadequately treated wastewater effluent, exceeded the assimilation capacity of the Renoster Spruit in the immediate vicinity of the city to the extent that it posed a possible risk of infection to potential water users for a considerable distances downstream from the urban area. The high levels of fecal indicators in the Renoster Spruit diminished downstream sufficiently that the receiving Modder River, directly downstream from the confluence with the Renoster Spruit, posed an infection risk for domestic users only but not for recreational users of the water.

Heath et al. (2002b) investigated the impacts and control of wet weather pollutant sources on the Ohio River. Key findings of the study included: 1) bacteria were the only pollutant of concern; 2) the project framework could be successfully transferred to other projects; 3) Ohio River bacteria levels exceeded criteria for contact recreation; 4) Ohio River bacteria criteria violations significantly increased during and after wet weather events (typically two-plus days); 5) CSOs collectively accounted for approximately 75 percent of the total annual fecal coliform load; 6) modeling results showed the Ohio River exceeded contact recreation criteria approximately fifteen percent of the time along the center channel and as much as eighty percent of the time along its banks; 7) the greatest benefit to water quality from CSO reductions occurred for “average” storm events; 8) Even with 100 percent control of bacteria loads from CSOs, contact recreation criteria would be exceeded on occasion. 9) a survey of *Giardia* and *Cryptosporidium* identified both pathogens in the Ohio River – no consistent relationship with the occurrence of wet weather was identified.

Rifai et al. (2002) reviewed the development of the urban indicator bacteria TMDL for Buffalo and Whiteoak Bayous in Houston, Texas. The paper presented the results of efforts aimed at quantifying the relative contribution of these sources to the observed fecal levels in the bayous. The paper also presented modeling results aimed at developing TMDLs and load allocation scenarios for the two watersheds. Results from summer 2001 monitoring for two storm events showed a direct correlation between in-stream bayou flow and *Escherichia coli* concentrations. In-situ studies conducted to assess the rates of bacterial regrowth in chlorinated wastewater effluent, sediment resupply and die-off as influenced by light intensity, sediment concentrations, organic strength and isolation from sediment indicated that sediment resupply may be a significant reservoir and source of bacteria to bayou waters.

The suspected source of the bacterial contamination that has affected Lake Pontchartrain, New Orleans, LA, is urban stormwater that is collected and pumped to the lake. Barbe' et al. (2001) concluded that the stormwater may be contaminated by sanitary sewage. Five monitoring stations were selected for study that had varying distances to stormwater drainage canals. Fecal coliform concentrations was found to be wet weather-dependent at all stations, except for one. They found that the water is generally unsuitable for primary contact recreation, especially close to urban drainage canals, for at least two to three days following a storm event. The study period was characterized by unusually low rainfall and lower than typical fecal coliform observations. They suspected that the lower bacteria concentrations may have been due to the drought conditions, rather than from decreased contamination. Brion et al. (2001) addressed sources of bacteria indicators. They found that first flush discharges contained high levels of pathogens, originating from storm sewers, overflowing domestic sewers, and surface scour. They present some new analytical tools (bacterial ratio that varies with age) and modeling tools (neural network) to help identify the predominant bacteria sources in stormwater.

De Luca-Abbott et al. (2000) used enterococci to trace the spatial and temporal impacts of stormwater discharges from an outfall in northeastern New Zealand. Both seasonal and temporal trends in *enterococci* concentrations were noted, with

the maximum contamination being found with the high winter rainfalls and near the outfalls. The occurrence and possible sources of *Giardia* and *Cryptosporidium* in Paris rivers were investigated by Rouquet et al. (2000). The results showed that non-point sources likely influenced parasite concentrations in the rivers. Parasite sedimentation was high, as was the potential for resuspension by urban runoff. Ramirez Toro et al. (2000) presented the study design for investigating water quality in La Parguera in relation to onshore development, stormwater outfalls, and mangroves and sewage treatment plants in the vicinity. Samples were analyzed for the following constituents: bacteriological indicators (total and fecal coliforms, *Escherichia coli*, *enterococcus*), total suspended solids, chlorophyll, light attenuation (light reaching the bottom compared to surface) and nutrients ( $\text{NH}_3$ ,  $\text{NO}_3$ ,  $\text{NO}_2$  and  $\text{PO}_4$ ).

Young and Thackston (1999) studied fecal bacteria in urban tributaries in Nashville, Tennessee. The urban streams (unaffected by sewage discharges) were much higher in sewered basins than in nonsewered basins and the fecal bacteria densities were related to the density of housing, population, development, percent impervious area, and apparent domestic animal density. Preliminary fecal bacteria data collected for surface runoff samples in these urban neighborhoods indicated that a relationship existed between various urban land uses and bacterial loading.

Rainfall increased levels of both *giardia* cysts and *cryptosporidium* oocysts in the Delaware River through its influence on turbidity, flow volume, and possibly other unidentified factors (Atherholt et al., 1998). The sources included river bottom sediments, stormwater runoff, direct inputs from domestic or wild animals and possibly WPCP. Samples of point and nonpoint discharges in a creek in Nashville, Tenn. were analyzed for fecal coliforms during four wet-weather events. Modeling showed that bacterial contamination originated minimally (14%) from SSO and mostly from other sources including urban runoff, and upstream agricultural, wildlife and septic tank sources (Goffinet et al, 1998). Duke and Kihara (1998) report that available information supports an improved regulatory approach to nonstorm discharges to storm drains. Some discharge types, including condensate from machinery and firefighting equipment discharges, are believed to represent minimal threats to receiving-water quality while runoff from landscape irrigation is an unregulated discharge that may represent a threat to receiving-water quality and is fairly widespread. During an investigation to identify major sources of bacteria that were keeping the town of Greenwich, Conn. beaches closed, the primary identified WWF sources were an outdoor sewage sludge composting facility and a regional municipal solid waste transfer station (Audet, 1998).

Gibson *et al.* (1996) reported an overall increase in fecal coliform densities during wet-weather compared with dry weather for the Ohio River and the physical parameters (temperature, pH, and conductivity) do not correspond to CSO discharges into this large river. Lyons *et al.* (1996) reported that the intensive monitoring conducted could not support the hypothesis that depressed levels of dissolved oxygen found during the low-flow, summer months are associated with discharges from CSOs in the Cincinnati, OH area. Van Der Tak *et al.* (1996) presented the results of New Jersey's Tri-City Sewerage Authority's monitoring program of CSOs for Hg, SS,  $\text{BOD}_5$ , and fecal coliform. Clean-sampling techniques were used in order to detect mercury at extremely low levels.

### **Toxicants**

Duke and Erickson (2003) determined critical flow conditions for chloride impairment in a western US stream dominated by effluents from agricultural and urban growth. Impairment was greatest not during lowest flows, which are dominated by wastewater treatment plant effluent, but when groundwater and other nonpoint sources are highest, thereby contributing chloride load disproportionately to their flow.

Mumley and Abu-Saba (2002) investigated the sources of mercury in San Francisco Bay as part of the TMDL development for mercury. Half of the contemporary excess mercury concentration in Bay sediments is accounted for by background processes, including shifts in the mineralogy of watershed source sediments and atmospheric deposition of global air sources. The other half of the excess mercury in Bay sediments is mostly attributed to mining legacy sources, with lesser fractions attributed to wastewater discharge (1-3%) and urban runoff (3-10%). Water column mercury concentrations in the turbid Bay waters are directly proportional to mercury concentrations of suspended sediments.

An investigation of natural and anthropogenic sources of  $\text{SO}_4$  in the Arno River catchment, northern Tuscany, Italy was conducted by Cortecchi et al. (2002). The river solutes consisted mainly of  $\text{Ca}^{2+}$  and  $\text{HCO}_3^-$ , but the proportions of  $\text{Na}^+$ ,  $\text{Cl}^-$  and  $\text{SO}_4^{2-}$  increase downstream, in keeping with the basically anthropogenic origin of the latter. The  $\delta^{34}\text{S}(\text{SO}_4^{2-})$  signature also increases downstream toward the urban areas.

Toxicity testing was performed by de Vlaming et al. (2000) in order to identify chemical causes and sources of contamination. Urban runoff was found to be toxic to *Selenastrum*. The overall results indicated that the whole-effluent

toxicity (WET) tests, when combined with traditional chemical analyses, were beneficial in locating sources of toxicity within a watershed.

Pitt et al. (1999) investigated typical toxicant concentrations in stormwater, the origins of these toxicants, and storm and landuse factors that influenced these toxicant concentrations. Nine percent of the 87 stormwater source area samples analyzed were considered extremely toxic (using the Microtox toxicity screening procedure). Thirty-two percent of the samples exhibited moderate toxicity, while fifty-nine percent of the samples had no evidence of toxicity. Vehicle service and parking area runoff samples had many of the highest observed concentrations of organic toxicants. All metallic toxicants analyzed were found in the analyzed samples. Marsalek and Rochfort (1999) also investigated the toxicity of urban stormwater and CSO. Acute toxicity, chronic toxicity and genotoxicity of stormwater and CSO were studied at 19 urban sampling sites in Ontario, Canada, using a battery of seven bioassays. Most frequent responses of severe toxicity were found in stormwater samples (in 14% of all samples), particularly those collected on freeways during the winter months. Compared to stormwater, CSO displayed lower acute toxicity (7% of the samples were moderately toxic, and none of the samples was severely toxic).

Huber and Quigley (1999) studied highway construction and repair materials (e.g. deck sealers, wood preservatives, waste-amended pavement, etc.) for their chemical and toxicological properties and leaching characteristics. *Daphnia magna* (a water flea) and the algae *Selenastrum capricornutum* were used for the toxicity tests. Leaching was evaluated as a function of time using batch tests, flat plate tests and column tests, as appropriate for the end-use of the highway material.

Malmquist et al. (1999) investigated the sources of pollutants discharging to Lake Trekanten, Stockholm, which receives stormwater from residential and traffic areas. Lead, cadmium, copper, zinc, phosphorus, and PAH in the stormwater from the catchment area were quantified by a source model. It was concluded that building materials were the dominant sources for copper and important sources for zinc. Source control measures, including covering copper-plated roofs, decreasing traffic, and changes of vehicle materials, were expected to reduce discharges of copper to less than a third of current levels.

Potential contributions of urban runoff pollutants to surface sediments of the Passaic River in New Jersey were investigated by Walker et al. (1999). Mass loading calculations demonstrated that urban runoff was a significant source of the metals observed in the sediments, and that PAH and DDT sediment loadings could, in some cases, be accounted for by urban runoff. Observed sediment loads for PCB, however, were significantly higher than were estimated from urban runoff.

### **Heavy metals**

The sources of heavy metals and PAHs in urban runoff were investigated by Brown and Peake in New Zealand (2006). Observed elevated lead and copper levels likely originated from industrial land uses, while zinc was attributed to residential galvanized roofing. The PAH observations suggested that an idle gasworks plant was contributing PAHs to runoff. Tucillo et al. (2006) investigated the size fractionation of metals in runoff from residential and highway storm sewers. Pb and Cr were associated exclusively with particles > 5 µm in size. Fe, Al, and Si were found mostly in larger size fractions (> 70%), with smaller amounts in the smaller particles (0.45-5 µm in size).

Ramessur (2004) quantified Cr, Zn and Pb in rural and urban estuarine sediments in Mauritius and found that Zn and Pb were significantly higher in urban sediments. Sources were thought to be road runoff.

Michels et al. (2003) investigated the environmental impact of stormwater runoff from a copper roof. It was shown that the runoff became less toxic as it passed through the drainage system. Lebow et al. (2003) investigated the release of preservatives, primarily arsenic, from CCA-treated wood under simulated rainfall and the ability of wood finishes to prevent/reduce the release. Water repellent significantly decreased the amounts of these elements in the runoff, while UV exposure increased the leaching of preservatives from the wood. Sansalone and Dean (2003) studied the metal and particulate relationships at the upper end of an urban watershed in Baton Rouge, LA. Results indicated that mass-limited events generally exhibited similar but temporally disproportionate mass deliveries for Cd, Cu, Pb and Zn and an initial rapidly declining concentration profile. In contrast, flow-limited events produced mass deliveries that were strongly proportional to the hydrograph. Partitioning of Cd, Cu, Pb and Zn in runoff was predominately to the particulate fraction.

Sorme and Lagerkvist (2002) investigated the sources of heavy metals in urban wastewater in Stockholm, Sweden.

Results showed that it was possible to track the sources of heavy metals for some metals such as Cu and Zn (110 and 100% found, respectively) as well as Ni and Hg (70% found). Other metals sources are still poorly understood or underestimated (Cd 60%, Pb 50%, Cr 20% known). The largest sources of Cu were tap water and roofs. For Zn the largest sources were galvanized material and car washes. For Pb, Cr and Cd, where sources were more poorly understood, the largest contributors for all were car washes. Vink and Behrendt (2002) investigated the heavy metal emissions, loads and transport in the Rhine and Elbe river basins. In most cases the measured heavy metal loads at monitoring stations were lower than the sum of the heavy metal emissions. This behavior in large river systems could largely be explained by retention processes (e.g. sedimentation) and was dependent on the specific runoff of a catchment. Between 51% (for Hg) and 74% (for Pb) of the total transport in the Elbe basin was supplied by inputs from diffuse sources. In the Rhine basin diffuse source inputs dominated the total transport and deliver more than 70% of the total transport. The diffuse hydrological pathways with the highest share were erosion and urban areas. Boller and Steiner (2002) investigated the emission and control of copper from roofs and roads in urban surface runoff. A large copper façade was used to investigate the concentrations of copper emitted. The concentrations ranged from 1 – 10 mg/L.

Notgrass (2002) performed an analysis of the effect of precipitation on metals loading in Boulder Creek (Arizona). The sources of pollutants (arsenic, beryllium, copper, lead, manganese and zinc) are three tailings piles, the upper, middle, and lower tailings piles, and an adit discharge from the abandoned Hillside Mine. The critical condition of Boulder Creek occurs during low flow (0.75 cfs). Flow ranges from spatially interrupted, independent pools in the summer to raging floods in response to large winter storms. The winter storms have a larger areal extent, contribute higher overall flows to Boulder Creek, but bring rain mainly to the higher elevations of the headwaters. Metals flushed into the system during these types of precipitation events are diluted due to the high flows in the creek. The monsoon storm driven flows are highly variable, dependent upon location and storm intensity. Monsoon storms also have a dramatic effect on metals loading in Boulder Creek. By providing brief, but intense, precipitation, monsoon storms flush large amounts of metals into the creek without greatly increasing the overall flow.

De Vos et al. (2002) performed a survey of the distribution and origin of platinum group elements in contemporary fluvial sediments in the Kentish Stour, England. The main factor responsible for the dispersion of these elements is their extensive anthropogenic use, and significant quantities enter fluvial systems via road runoff, storm drains, and wastewater and sewage treatment systems. The highest element abundances occur in the motorway-runoff sediments (maximum total PGE content of 55 ng/g), whilst the lowest values were recorded in the sedimentary rocks, where some samples contain PGE at concentrations below the limit of detection. The total PGE content of the river sediments ranged from 0.4 to 10.8 ng/g. The distribution and variation in concentrations and ratios of the PGE in the contemporary fluvial sediments correspond strongly with land-use changes (urban versus rural) and with points of discharge from sewage works. In-stream metal loadings in the Tijuana River watershed were characterized by Gersberg et al. (2002). In general, metal-loading trends could be ascertained from the shape of the storm hydrographs. Elevated metal concentrations existed in base and storm flow conditions.

Nonpoint sources of heavy metals (Hg, Cd, Cu, Zn, Pb, Ni) in the Rhine River watershed were investigated by Mohaupt et al. (2001). They found that urban stormwater was the most important source for these metals in the Dutch portion of the watershed. Erosion was of lesser importance, while atmospheric deposition onto open water was a much less important source. Anthropogenic nonpoint sources accounted for 40 to 80% of the total sources for some metals. They recommended further studies of urban nonpoint sources of heavy metals and on ways to improve urban stormwater management. A mass balance of all known sources and sinks for heavy metals (Ag, Cd, Cu, and Pb) in New Haven Harbor, CT, was conducted by Rozan and Benoit (2001). Sources included direct atmospheric deposition, rivers, treated sewage effluent, combined sewer overflows, and permitted industrial discharges. All of the fluxes were directly measured, and the uncertainties were quantified. River inputs accounted for most of the total yearly metal discharges, while the salt marshes removed about 20 to 30% of the metals from the rivers before reaching the harbor. Atmospheric deposition is of minor importance, and is comparable to sewage effluent discharges. Davis et al. (2001a) presented loading estimates of lead, copper, cadmium, and zinc in stormwater from different sources. They reviewed available data from the literature, and conducted controlled experiments and other sampling. Specific sources that they examined included building siding and roofs; automobile brakes, tires, and oil leakage; and wet and dry atmospheric deposition. The most important sources they identified were building siding for all four metals, vehicle brake emissions for copper, and tire wear for zinc. Atmospheric deposition was an important source for cadmium, copper, and lead.

A study of heavy metal concentrations in sediments from Australian estuaries and the continental shelf by Birch (2000) showed that the concentration of metals was significantly higher in the estuaries than along the continental shelf. Also, the



estuaries were found to have sediment metals concentrations that were related to the degree of urbanization/industrialization in the watershed. High metals concentrations, including Pb and Zn in Port Jackson (Sydney, New South Wales) which were at levels expected to have adverse environmental/biological effects, were found in the fluvial sediments, indicating that metals are still being added to the estuaries, potentially through stormwater runoff (including land reclamation leachate). Webster et al. (2000) analyzed the sources and transport of trace metals in the Hatea River catchment and estuary in New Zealand. They found that the recently deposited estuarine sediment has elevated levels of Cu, Pb, and Zn from the more densely-populated areas, city stormwater drains and the Cu-containing antifoulants used in the marina. All metals were transported in both dissolved and particulate form in the tributaries, with lead being shown to bind most effectively to the sediment. Levesque and De Boer (2000) investigated the impact of a large urban center on the trace metal chemistry of a surficial fine-grained sediment in the South Saskatchewan River, Canada. No effect from the urban center on the metals content of the sediment was seen - with the exception of uranium, whose concentration was measurably greater below the urban center. Smith and Swanger (2000) investigated the impact of leaching of lead-free solders in construction waste and found that alloys containing antimony had leachate concentrations above regulatory limits. Alloys containing silver also potentially could impact the environment if entrained in stormwater runoff.

Birch et al. (1999) investigated the sources of heavy metals in stormwater draining into Port Jackson, Sydney, Australia. Road dust from streets with different traffic densities in the catchment were highly enriched with Cu, Pb, and Zn. Soils also contained high concentrations of these metals over extensive areas of the catchment. Preliminary data suggests that roads and soils were probably important in supplying heavy metals to the estuary but the contributions of atmospheric deposition and contaminated sites had not yet been evaluated.

Land applications of organic soil amendments can increase runoff concentrations of metals such as Fe and Zn, metalloids such as B and As, and non-metals such as P and S that have the potential for causing adverse environmental impacts. Aluminum sulfate, or alum ( $\text{Al}_2(\text{SO}_4)_3 \cdot 14\text{H}_2\text{O}$ ), can reduce concentrations of some materials in runoff from sites treated with organic amendments (Edwards et al., 1999).

Sanudo-Wilhelmy and Gill (1999) examined dissolved ( $< 0.45 \mu\text{m}$ ) trace metals and phosphate concentrations in surface waters collected along the Hudson River estuary, New York, between 1995 and 1997 and compared them with samples collected in the mid-1970s. They concluded that the release of Pb and Hg from watershed soils, and Ni and Cu from estuarine sediments, may represent the primary contemporary sources of these metals to the estuary.

Concentrations of copper (Cu), zinc (Zn), lead (Pb), cadmium (Cd) and nickel (Ni) measured in the headwaters of the Hawkesbury-Nepean River, Aust. were amongst the lowest reported in the literature for freshwater systems, and will be used as a benchmark for assessing the effects of increasing urbanization in the catchment (Markich and Brown, 1998). Davis et al. (1998a) studied the levels of chloride and bromide and the ratio between them in the groundwater of Yucca Mountain, Nev. Atmospheric precipitation generally has a mass ratio between 50 and 150 and summer runoff in urban streets, between 10 and 100. Samples of mercury (Hg) and methyl-mercury (MMHg) were collected during baseflow and storm flow from the Anacostia River, an urban, impacted river of greater Washington, D.C. (Mason and Sullivan, 1998). Total concentrations of Hg during the storm flow measured 3—5 times that of the baseflow indicating storm flow is the major vector for Hg in the Anacostia.

Birch *et al.* (1997) reported that point sources (waste dumps, sewage overflows, and discharge from a polluted river) were responsible for elevating sediment heavy-metal concentrations up to 50 times above background while NPS contributed in raising baseline levels to four times background. High trace-element concentrations in the Piedmont province streambed sediments were related to land use (O'Brien, 1997).

Solo-Gabriele and Perkins (1997) quantified metal transport (i.e. Fe, Cu, chromium [Cr] and arsenic [As]) for the Aberjona-River watershed and proposed storm-sewer overflows and direct urban stormwater runoff as mechanisms of metal transport. The runoff from roofs and streets contributed 50% — 80% of heavy metals, i.e., Cd, Cu, Pb and Zn, to the total mass flow in domestic wastewater (Boller 1997).

Schueler (1996b) summarized the effort to characterize metal and organic toxicants in stormwater discharges in the 700  $\text{mi}^2$  Santa Clara Valley, CA watershed. The highest Zn, Cd, Ni (nickel), Pb, and Cu concentrations were associated with industrial-land uses and all of the heavy industrial-area samples were found to be extremely toxic; probably from the dissolved metal fractions. Pesticides and other nonpolar hydrocarbons were probably responsible for the moderate to toxic

samples obtained from the mixed-land-use areas.

**Cadmium.** van Geen and Luoma (1999) conducted a five-year study of dissolved Cd in San Francisco Bay, California and adjacent coastal waters. They showed that the composition of surface waters towards the mouth of the estuary was determined largely by the effect of coastal upwelling. However, surface samples collected throughout San Francisco Bay confirmed an internal Cd source unrelated to river discharge. The Cd content of a benthic foraminifer (*Elphidiella hannai*) in a dated sediment core from San Francisco Bay was measured to determine if the water column Cd enrichments in San Francisco Bay could be related to the rapid development of the watershed.

**Copper.** Copper mine spoil from Touro, A Coruna, Sp. was used in the construction of rural roads and tracks in the surrounding area. Roadside soils, sediment in drainage ditches, and water from first-order streams were analyzed to determine both total Cu content and the Cu fraction susceptible to uptake by plants. Despite some high soil concentrations of total Cu, Cu fraction susceptible to uptake was low in most samples, and no water samples were found to exceed European Community legislation thresholds for drinking water and for supporting fish (Arias et al., 1998).

**Lead.** Davis and Burns (1999) examined lead concentrations in runoff from painted surfaces. In many tests, high lead concentrations were found (using 100 mL of wash water over 1600 cm<sup>2</sup> of surface). Lead concentrations from 169 different structures followed the following order (median concentrations in the wash water): wood (49 µg/L) > brick (16 µg/L) > block (8.0 µg/L). Lead concentration depended strongly on paint age and condition, with the lead levels from washes of older paints being much higher than from freshly painted surfaces. Lead from surface washes were found to be 70%, or greater, in particulate lead form, suggesting the release of lead pigments from the weathered paints.

**Mercury.** Bonzongo et al. (1999) studied the impacts of land use and physicochemical settings on methyl mercury levels in the Mobile-Alabama River system. In the Coastal Plain portion of the state, Hg concentrations above the FDA's safe limit have been found in tissues of some fish species in both Fish River and Mobile Bay, Alabama. These rivers/streams receive most of their Hg from NPS (e.g. atmospheric deposition and inputs related to land use within the watersheds). They reported results of detailed investigations aimed to study the biogeochemistry of Hg and other trace metals, specifically the impact of different land-use types within the watersheds on Hg speciation. Glass and Sorensen (1999) examined a six-year trend (1990-1995) of wet mercury deposition in the Upper Midwest of the United States. The annual wet mercury deposition averaged 7.4 µg Hg/m<sup>2</sup>-yr and showed significant variations between sites and illustrated significant increasing trends over the monitoring period. Warm (rain) season wet mercury deposition was found to average 77% of total annual wet deposition.

**Platinum.** Schaefer et al. (1999) studied the increasing concentrations of Pt, Rh, and Pd in urban areas associated with increased use of catalytic converters on automobiles. At a typical urban site, the daily deposition rate of Pt in airborne dust was up to 23 ng/m<sup>2</sup>.

### **Organic toxicants**

Pedersen et al. (2006) investigated the presence of organophosphorus pesticides in agricultural and residential runoff. On an area basis, the loads from residential areas may exceed those from row crop sites, and no first flush effects were detected.

The presence of diazinon in rural and urban streams before and after its ban was investigated by Banks et al. (2005). The ban has resulted in substantial reductions in surface water concentrations of diazinon.

Schiff and Sutula (2004) characterized the diazinon and chlorpyrifos concentrations from different land uses in urban Southern California. Mixed agricultural, followed by commercial and residential (at an order of magnitude less) was the greatest source of diazinon, while chlorpyrifos was not consistently detected in samples from any land use.

Litten et al. (2003) investigated the accumulation of various chlorinated biphenyls in water, sediment and sewage sludge after the destruction of the World Trade Center. Increased concentrations were seen in the ash-laden runoff from the site although no increase in sediment concentrations was seen in the sampling post-9/11 and to date. Walters et al. (2003) monitored carbaryl applied in urban California areas. The urban runoff had a maximum concentration of 1737 ppb in a sample collected from a drain adjacent to a sprayed site.

Watcher and Herrmann (2002) measured the concentrations of PAHs, polynuclear aromatic sulfur heterocycles (PASH)

and polynuclear aromatic ketones (PAK) in stormwater runoff from roofs and roads in Dresden, Germany. The selected classes of trace organic pollutants are mainly released during incomplete combustion and are emitted by traffic, industry and residential-heating. The pollutographs of the particle-bound fraction showed a "first-flush"-effect. Rain contributed about half of the load of pollutants in the runoff of roof sites. Its contribution to the load at the street sites was far less important. Specific concentrations of pollutants sorbed on to particles as well as the concentrations in the aqueous phase were smaller in street runoff than in roof runoff. Gryniewicz et al. (2002) traced 16 selected compounds from the PAH group at 10 precipitation and 5 runoff sampling sites located across the "Threecity" (Gdansk-Sopot-Gdynia). Naphthalene, phenanthrene+anthracene, fluoranthene and pyrene were found most frequently and at top concentrations (from few ng L<sup>-1</sup> up to several hundred ng L<sup>-1</sup>), while dibenzo(a,h)anthracene, indeno(1,2,3-c,d)pyrene, benzo(a)pyrene, and benzo(g,h,i)perylene were present at concentrations close to the detection limit only. Correlations of PAH concentration with the percentage of coal stoves in the area gave coefficient of correlation (R<sup>2</sup>) equal to 0.85 and 0.78, for rainwater and runoff, respectively, while PAHs concentration vs. traffic intensity correlation yielded the respective values of 0.40 and 0.54.

Muller et al. (2002) studied the point and nonpoint sources of pesticides in surface waters and their transport pathways. The contribution by the WWTPs to the pesticide load was defined as point-source pollution (PSP). The load was dominated by PSP with at least 77% of the total pollution. No significant interdependencies between intrinsic properties of the pesticides, hydrometeorological factors, and the loads occurring in the stream could be found. Kay (2002) studied organophosphate pesticides and metals in the Chollas Creek watershed from 1999 to 2001. The first four storm events monitored from 2000-2001 resulted in no definitive linkage between diazinon and toxicity. There were no observed relationships between dissolved metals and toxicity to either *Ceriodaphnia dubia* or *Hyaella azteca*. Further, there was no specific area or watershed reach that definitively demonstrated greater contaminant contribution during storm events. Only after analyzing the data resulting from the first flush event was a correlation between diazinon and bioassay organism toxicity evident, but no specific area or watershed reach demonstrated greater concentrations of contaminants.

Ellis and Chatfield (2001) reported that nonpoint discharges of oil and hydrocarbons to urban receiving waters constitutes a major pollution source, being responsible for up to 30% of all reported water pollution incidents in the UK. Commercial and industrial areas, along with heavily used highways, are the major sources of these pollutants, with about 20,000 to 24,000 tonnes of oil per year being discharged to urban receiving waters from these sources. Blanchard et al. (2001) investigated PAHs and PCBs in the combined urban flows to the Acheres wastewater treatment plant in Paris, France, under different meteorological conditions. The PAH concentrations were found to increase much more than the PCB concentrations during wet weather. They concluded that atmospheric wet deposition was the most important source for the PCBs, while urban stormwater was the most important source for the PAHs.

Ashley and Baker (1999) developed inventories and identified sources for hydrophobic organic contaminants (HOC) in the surficial sediments of Baltimore Harbor, Maryland. There was enormous spatial variability in the concentrations of HOC at the 80 sampling sites which was not well correlated to grain size or organic carbon content, suggesting that nonequilibrium partitioning and/or proximity to sources were important factors. High concentrations of HOC were localized around major urban stormwater outfalls. Lower molecular weight PAH, having lower affinity for particles, may travel further from the sources. Ollivon et al. (1999) studied the PAH fluctuations in rivers near Paris (France). During storm events, the atmospheric contributions of PAH were negligible, compared to stormwater discharges. During heavy rains affecting the river Seine, high first flush PAH concentrations were observed, and about 25% of the PAH came from the rain and about 75% came from the stormwater. During light rains, atmospheric contributions only accounted for about 2% of the total PAH to the river.

Air-water exchange fluxes of 13 polycyclic aromatic hydrocarbons (PAH) were determined along a transect in the Patapsco River from the Inner Harbor of Baltimore, Maryland, to the mainstream of the northern Chesapeake Bay. The direction and magnitude of the daily fluxes of individual PAH were strongly influenced by the wind speed and direction, by the air temperature, and by the highly variable PAH concentrations in the gas and dissolved phases. The largest PAH volatilization fluxes occurred adjacent to the stormwater discharges, driven by elevated dissolved PAH concentrations in surface waters (Bamford, 1999).

Urban runoff samples were collected in a 1- year period in the Santa Monica Bay Watershed during both dry and storm periods and analyzed for polychlorinated dioxins, polychlorinated furans, and polychlorinated naphthalenes (Fisher et al., 1999).

A study of methyl tert-butyl ether (MTBE) in an alpine lake in the Sierra Nevada, Calif. suggested that neither highway runoff nor snowmelt runoff is a significant source of MTBE to the lake. Most MTBE is introduced to the lake from motorized watercraft operating on the lake during the summer (Reuter et al, 1998). Hydrocarbon pollution in lake core sediments, streambed sediments, stormwater and street surface sediments were investigated in the Brunette River watershed in Burnaby, British Columbia, Can. Hydrocarbon concentrations in streambed sediments corresponded to the land use indices of impermeable area and traffic density and road washoff of nonparticulate oil appeared to be an important source of hydrocarbons to stormwater solids, and ultimately streambed and lake core sediments (Larkin and Hall 1998). A thorough review of previous studies analyzing the contribution of highway runoff and urban stormwater to source loadings of semivolatile organic compounds (SVOC) and volatile organic compounds (VOC) showed that SVOC, primarily PAH, have been extensively studied, and are correlated with SS concentration. VOC have been studied to a lesser extent, and result primarily from urban land surfaces, but also from atmospheric washout (Lopes and Dionne, 1998). PCB found in street dust in Buffalo, N.Y. were redistributed by natural and vehicle-generated wind. More frequent street cleaning was suggested to reduce CSO and stormwater contamination of the Buffalo River (Irvine and Loganathan, 1998).

While spills may not be important in terms of the average annual loading of petroleum hydrocarbons in a watershed, large and medium size spills pose a significant risk to the aquatic resources in urban areas (Zandbergen and Hall, 1998).

Particle scavenging was the dominant contributor of PCB and PAH to falling snow in Minn., but less important in rain (Franz and Eisenreich, 1998). Gas scavenging was important only for low molecular weight PCB congeners and PAH which exceeded levels as predicted by Henry's Law constants for both snow and rain.

The concentration levels of phenol found in Terre Haute, Indiana were high enough to cause eye irritation and skin disorders in humans according to the U.S. Environmental Protection Agency (U.S. EPA) standards. The Environment Protection Department of Hong Kong identified stormwater as one of the likely sources of pollutants to Victoria Harbor, Hong Kong. Chlorohydrocarbons; PCB (as Aroclor 1254); total 2,2-bis (p-chlorophenyl)-1,1,1-trichloroethane (DDT); and total hexachlorocyclohexane (HCH) pose a significant risk, and probably have caused damage to the marine ecosystem as well as posing a hazard to seafood consumers (Connell et al., 1998). Enhanced concentrations of dissolved methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) were observed only in the western Oder Estuary of the Baltic Sea near the mouth of the Peene River. The distributions of CH<sub>4</sub> and N<sub>2</sub>O in the investigated Boddem waters are, directly or indirectly, linked to the Peene River runoff (Bange et al., 1998).

A receptor-source model was used to apportion source contributions for PAH in street and creek sediments. The model showed that vehicles along with the coke ovens, are the major contributors to PAH in street sediments (Sharma *et al.*, 1997). The spatial distribution and fingerprint patterns of PCB and polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/F) strongly indicated that CSO was a source of contamination in sediments near these outfalls. Evaluation of the industries operating within the CSO districts provides a link between tile facilities that discharge wastes to the combined sewer system (CSS) and PCB and PCDD/F found in the sediments (Huntley *et al.*, 1997). Concentrations of 18 hydrophobic chlorinated-organic compounds in streambed sediments from 100 sites throughout New Jersey were examined (Stackleberg, 1997). The highest median normal concentrations were found in samples from the most heavily urbanized and populated areas, with the lowest concentrations in the least developed, most heavily forested areas.

Trihalomethane (THM) formation potential at different stations of the Kurose River and the contribution from point and NPS within the river basin were determined. THM precursors in the river could be attributed mainly to industrial effluents, domestic wastewater, and agricultural drains with stormwater runoff contributing significant amounts of THM precursors to the river during storm events (Galapate *et al.*, 1997).

The source and fate of benzothiazoles leached from crumb rubber material (CRM) and asphalt containing 1% — 3% CRM were investigated (Reddy and Quinn, 1997). The environmental chemistry suggests that benzothiazoles from CRM should not be harmful. Measurements of aliphatic hydrocarbons in the Point Loma Wastewater Treatment Plant (PLWTP) effluents were mainly petroleum derived and were generally consistent with those of PAH. (Tran *et al.*, 1997). The PLWTP discharged approximately 3.85 metric tons of n-alkanes (C-10 — C-35) in 1994, well below the level (136 metric tons) estimated in 1979.

Steuer *et al.* (1996) reported on a two-year study that monitored stormwater from eight cities in the Lake Superior basin. Four to five storms were sampled at each station, for a broad list of conventional and toxic- substance-pollutant

parameters, with fluoranthene and pyrene having the highest concentrations for any of the organic toxicants (site-median concentrations were about 5 µg/L).

Results reported by Shepp (1996) suggested that storm-runoff concentrations of petroleum hydrocarbons from automotive-intensive land uses typically range from 0.7-6.6 mg/L. Evaluation of these observations and their respective catchments suggested that the degree of automotive exposure (a combination of duration of exposure and volume of exposure) is the primary factor in the generation of petroleum hydrocarbons in storm runoff from automotive-intensive land uses. Delzer *et al.*, (1996) reported that in the most comprehensive evaluation of stormwater volatile organic compounds (VOCs) ever conducted, the USGS analyzed 592 stormwater samples collected from 16 United States cities for 62 VOC compounds, including methyl tert-butyl ether (MTBE). Stormwater was thought to be a potential source of MTBE in urban groundwaters. Four of the VOCs were detected in more than 10% of the samples (toluene, xylene, chloroform, and trimethylbenzene); MTBE was found in about 7% of the samples at a median concentration of 1.5 µg/L.

Revitt *et al.* (1996) identified the sources of hydrocarbons in urban storm runoff through an extensive monitoring program and the use of principal component statistical analyses. It was found that anthropogenic organics were invariably associated with the greatest concentrations of hydrocarbons in aquatic organism tissue. Automobile-exhaust-related hydrocarbons (especially fluoranthene and pyrene) and lubricating oil components (methylated homologues), along with biogenic hydrocarbons (high-molecular-weight odd-numbered carbon-chain alkanes, with  $>C_{25}$ ) were most closely related to bioassay-mortality rates.

Using site-specific nonpoint and point source PAH-concentration data from waterborne sources, PAH loadings in the near-shore regions of Massachusetts Bay were estimated to be  $1.4 \times 10^4$  kg/yr (Cura and Studer, 1996). The greatest loadings of low-molecular-weight and total-PAH compounds were from POTW while the greatest sources of high-molecular-weight and carcinogenic compounds were nonpoint sources including rivers. Urban stormwaters and CSOs were found to have the highest PAH concentrations of the various source types.

**Pesticides and herbicides.** Lee *et al.* (2000) found that stormwater runoff in San Diego Creek was toxic to *Ceriodaphnia* and *Mysidopsis*. About half of this toxicity was found to be attributable to the use of the organophosphate pesticides diazinon and chlorpyrifos used in the urban areas for structural termite and ant control and for lawn and garden pest control. Lutes *et al.* (2000) investigated an eleven-acre lake on a golf course at NAS Jacksonville in terms of potential ecological and health risks posed by sediments and fish in the lake. The identified contaminants of interest at the site; PCBs in fish, metals in sediments, pesticides in sediments, and PAHs in sediments, are most likely attributable to storm water impacts. The identified exposure pathways to the contaminants are through recreational fishing and the use of the lake by wildlife.

Temporal trends of three phenoxyacid herbicides: 2, 4-D, dichlorprop and MCPA and the phenolic herbicide (bromoxynil), were determined in ambient air and precipitation over a 4-yr period within a well-defined watershed in southern Manitoba. Elevated levels of these herbicides in creek water samples were observed during period of high concentration in both atmospheric compartments, despite the lack of surface runoff events within the watershed over that period (Rawn *et al.*, 1999).

Farrugia *et al.* (1999) studied household herbicide use. They found that typical urban uses of herbicides exceeded agricultural uses, and the transfer coefficients (amount of the herbicide in the runoff compared to the amount applied) was also higher in urban areas. The highest measured diuron concentration was 20 µg/L, while the average was 5 µg/L. Compared to EEC standards for drinking water protection (0.1 µg/L), they concluded that suburban uses of herbicides may severely endanger drinking water supplies.

A study that examined surface waters adjacent to golf courses in N.C. showed that levels of pesticides and nutrients were generally below U.S. EPA health advisory levels in water bodies on the course, and always below detection levels at the outflows from the courses (Ryals *et al.*, 1998). An analysis of water samples from 64 rivers and streams in New York showed that pesticide concentrations were dependent on upstream land use and pesticide application patterns (Phillips *et al.*, 1998). Specific pesticides are correlated with each land use type.

Pesticides present in rainwater do not pose a greater groundwater contamination problem during artificial roof runoff infiltration (a practice in Switz. to reduce runoff) than does the direct application in agriculture (Bucheli *et al.*, 1998a); however, the herbicide (R,S)-mecoprop, a root protection agent in Preventol B 2 commonly applied to roofs, is of the

same order of magnitude as loads from agricultural applications (Bucheli et al., 1998b).

### **Monitoring and Sampling**

Xiao et al. (2006a) investigated the effects of the experimental design program (the number of samples and replicates) on the detection of *Cryptosporidium* oocysts in stormwater. Horowitz et al. (2005) presented an overview of the USGS water-quality monitoring program being implemented by the City of Atlanta (Georgia). The purpose of the program is to monitor whether planned infrastructure improvements affect the suspended sediment concentration and the chemical and biological quality of the receiving waters. Prasad et al. (2005) studied the effect of the growing Indian population on a vegetation index, soil moisture, aerosol optical depth and rainfall. Over the five-year study period, the aerosol optical density increased substantially. Luke (2005) described transportable refrigerated samples as a means of preserving field samples until they can reach the laboratory for analysis.

Atlanta's extensive water-quality and quantity monitoring system was reviewed by LaFontaine and Hillick (2004). The monitoring network consists of 20 long-term sites, 12 of which record continuous data on selected water-quality parameters and stream stage, and are supplemented by high- and low-flow sampling at specific locations. Yaros et al. (2004) presented the monitoring and modeling network used to address the sources of water quality degradation in Rock Slough and Contra Costa Canal.

Graettinger et al. (2003) used uncertainty analysis to determine where and what to sample in environmental receiving waters and urban water systems. The Quantitatively Directed Exploration (QDE) approach was demonstrated on a water quality model where non-point source loading, stream characteristics, and contaminant behavior were the uncertain input parameters and concentration was the uncertain model result. Taube et al. (2003) reviewed the long-term watershed monitoring approach for the City of Atlanta. The program collected the data needed to assess stream improvements and identify any pollution reduction that can be attributed to the Clean Water Atlanta (CWA) program implementation.

Davenport et al. (2002) reviewed the EPA National Nonpoint Source Monitoring Program (NMP), whose purposes are to provide credible documentation of the feasibility of controlling nonpoint sources and to improve the technical understanding of nonpoint source pollution and the effectiveness of controlling nonpoint source control technologies and approaches. Maglione et al. (2002) reviewed the data collection plan for non-point and point source determination for the Upper Ashley River system. This new data collection was needed because the TMDL was based on data that was almost 10 years old and significant changes had occurred in the watershed within the past decade. Wilson (2002) reviewed Pennsylvania's community-based water monitoring. The paper explored the makeup of these groups as well as the rationale behind their formation and sustained activity. The role of community based water monitoring in state assessments also was explored.

Leecaster et al. (2002) assessed sampling designs for urban stormwater monitoring for their efficiency. Flow and TSS information was collected every 15 minutes in the Santa Ana River in 1998. The data was used to calculate the "true load" and then three within-storm sampling designs (flow-interval, time-interval, and simple random) and five among-storm sampling designs (stratified by size, stratified by season, simple random, simple random of medium and large storms, and the first *m* storms of the season) were simulated. The evaluation included estimating three estimators for storm mass emissions (mean, volume-weighted, and ratio) and three estimators for annual mass emissions (median, ratio, and regular). Single storms were most efficiently characterized (small bias and standard error) by taking 12 samples following a flow-interval schedule and using a volume-weighted estimator of mass emissions. Sampling seven storms is the most efficient method for attaining small confidence interval width for annual concentration. Sampling three storms per year allows a 20% trend to be detected in mass emissions or concentration over five years. These results are decreased by 10% by sampling seven storms per year.

De Ridder et al. (2002) presented an overview of the influence of analytical method, data summarization method, and particle size on the total suspended solids removal. Based upon the data from three source studies, each of these variables were isolated, evaluated, and found to demonstrate the potential to influence the summary of TSS removal efficiency by a minimum of 7 to 10 percentage units. Compounding of these differences resulting from combinations of these variables could lead to a considerable range of possible results. It was found that a consistent analytical method, data summarization method, and particle size must be applied to systems under review in order to produce accurate, comparable data.

Pitt and Burton (2002) reviewed methods available for the assessment of urban wet-weather flow impacts. The data from the past decade has shown, during numerous receiving water assessment studies that no one single approach (e.g., chemical-specific criteria, benthic microorganisms, or habitat surveys) can routinely be used to accurately determine or predict ecosystem health and beneficial use impairment. Each assessment approach or component has associated strengths and weaknesses. The selection of specific assessment tools and goals would be highly dependent on local conditions and objectives.

Ruby and Brosseau (2002) reviewed the comprehensive long-term monitoring and assessment plan for the San Francisquito Creek watershed. The objectives were placed into the following general categories: Physical – activities related to the physical habitat of the watershed (erosion, sedimentation, barriers, etc.) and land use impacts Hydrological – flooding potential, surface/groundwater interactions, low flow conditions (re: aquatic habitat), etc. Chemical – sources, distribution and impact of known and potential (suspected) chemical pollutants Biological – biological habitat and processes, as well as biodiversity and special status species Social – community interests and concerns (aesthetics, uses, property and water rights), social aspects and resources (demographics, complementary facilities, access), and direct impacts of human activities (litter, recreation, etc.).

The Patrick Center for Environmental Research of The Academy of Natural Sciences in conjunction with the University of Delaware developed a method to assess streams based on geomorphic, habitat and riparian features (Cianfrani et al., 2001). An overall Stream Quality Index (SQI) was developed that could classify streams into four major categories: severely impaired, impaired, moderately impaired, and slightly or non-impaired. The SQI rating was used with other natural-resource inventory data in restoration planning and overall management of the Fairmount Park system.

Dwyer and Wissing (2000) described Waterwatch Australia, a national monitoring and environmental education program. The program has involved over 2000 groups monitoring approximately 5400 sites in 246 catchments, with most work done by volunteers and community groups.

Buried mineral soil-bags and natural solutions, studied as indicators of forest response to elevated N and S inputs at the BBWM, were reported by Fernandez et al. (1999) having continued utility in environmental monitoring and assessment research. In the Mediterranean region, climatological factors make CSO a major urban pollution problem that should be monitored and controlled. In comparing rainfall estimates from weather radar pictures to a rain-gauge network in terms of the ability to predict sewer flow in the urban basin in Barcelona, Spain, the results showed that the use of radar data enabled the combined sewer system model to improve the reproduction of the observed flows. Also indicating the spatial description of rainfall was a key problem in modeling the events giving rise to CSO (Sempre-Torres et al., 1999).

A receiving water quality monitoring program was developed to measure beneficial use impacts resulting from toxicity in stormwater runoff. The goals of the water quality monitoring program were to determine the persistence, fate and significance of the aquatic toxicity in the receiving water (Taylor, 1999).

Gracie (1999) presents a monitoring protocol and evaluates performance of several projects which have had varying degrees of success. Clar et al. (1999) described the current approach adopted by Baltimore County, Maryland to integrate stream stability assessment and water quality modeling for a comprehensive study of the Patapsco River Watershed in south-western Baltimore County.

The 1996 handbook *Environmental Indicators to Assess Stormwater Control Programs and Practices* described the use of 26 indicators within 6 general categories B water quality, physical/hydrological, biological, social, programmatic and site-specific B to measure the success of stormwater programs. The handbook also suggests a methodology for using the indicators to identify problems within local watersheds and for assessing, re-evaluating and improving stormwater management programs. With grant assistance from the Water Environment Research Foundation, the Santa Clara Valley Urban Runoff Pollution Prevention Program (SCVURPPP) was demonstrating this methodology at a watershed scale (Coyote Creek watershed, Santa Clara County, California) and at a smaller, more defined scale, that of a 28-acre industrial catchment in the City of Santa Clara, California (Cloak and Bicknell, 1999).

A new settling testing method was compared to a traditional test in a laboratory side-by-side evaluation. The comparison attempted to determine whether these tests can capture the rapidly settling particles in wet-weather flow. A summary of the performance, as measured by predicted percent removal of the columns for 15 laboratory bench-scale tests, and the limitations and advantages of each approach were presented and compared (O'Connor et al., 1999). Kuo et al. (1999)

presented results of field tests of pollutant removal efficiencies of grassed swales conducted in Taiwan and Virginia. The Virginia experiments tested a highway median swale, while the Taiwan experiments were conducted on an agricultural test farm.

The specific goals of the Small Business Innovation Research (SBIR) project, sponsored by the Federal Highway Administration (FHWA), was to develop a small, inexpensive, simple, effective sheetflow sampler to aid transportation officials in meeting their regulatory requirements. The field testing program includes the installation of approximately 18 samplers throughout varying highway environments in Virginia, Maryland, and California. Stormwater samples will be collected and analyzed for various highway pollutants over a period of 9 months (Graziano et al., 1999).

According to Klove and Bengtsson (1999) the hydrology of a cutover fen was studied from May to October in 1995 and 1996. Rainfall equivalent depths were measured every 15 min and stream runoff was continuously monitored. Storm runoff was separated into different components; rain falling directly into channels and rapid groundwater response based on a contributing area method and on different electrical conductivities of rain-, ground- and stream-water. The Ohio Environmental Protection Agency employed biological, chemical, and physical monitoring and assessment techniques to assess how effectively they were achieving their goals of the Clean Water Act, namely the maintenance and restoration of biological integrity and the basic intent of water quality standards (Yonder et al., 1999). Strecker (1999) described some of the problems with typical BMP monitoring and effectiveness reporting; and suggested the utilization of consistent stormwater monitoring techniques.

A method for quick, simple, and inexpensive analysis of CSO used a statistical approach for rainfall analysis and considered the preceding dry period, which has a significant affect on the pollutant loading of the overflow (Udale and Osborne, 1997). The Greater Houston Wastewater Program devised an innovative flow-remonitoring effort that allowed engineers to eliminate the construction of overflow-control facilities. The initiative integrated temporary- and permanent-meter-flow data that allowed for modifications in design to save 77-million dollars (Bagstad, 1997). MacDonald and Phillips (1997) discussed applications and configurations for multiple-path ultrasonic transit-time flowmeters under various hydraulic regimes commonly encountered in wastewater collection systems. A station was established to perform continuous high quality time-series flow, wastewater, and stormwater-runoff characteristics monitoring. Time-series research will be carried out in order to establish knowledge of dry-weather characteristics and rainfall-runoff relationships including the variability of relevant stormwater pollutants (Schaarup-Jensen *et al.*, 1997). An experimental urban catchment was created in the center of Paris for the purpose of obtaining a description of the pollution of urban WWF. Results revealed that a significant portion of pollution originates from inside the combined sewer and it is suspected that the pollution is probably due to resuspension of sewer sediments (Gromaire-Mertz *et al.*, 1997). Baloch (1997) observed large seasonal differences in river-mercury (Hg) concentrations and loadings showing dramatic increases in response to spring snowmelt and precipitation events. Results revealed total Hg concentrations were highly correlated with SS.

Dowling and Mar (1996) developed and tested a low-cost “culvert composite sampler” for obtaining flow-weighted stormwater samples. This sampler should enable much more cost-effective stormwater sampling for many purposes, including NPDES monitoring. Initial testing was performed for a sheetflow sampler to collect highway runoff using an acrylic prototype (Stein et al., 1998).

Lee and Jones-Lee (1996) stressed the need to focus receiving-water stormwater-monitoring activities on those pollutants causing the specific problems identified, instead of using very broad (and expensive) monitoring approaches. Highly focused site-specific studies are needed for each type of use impairment. The focus of the monitoring program should be devoted towards the suspected use impairments, such as, aquatic-life toxicity and bioaccumulation, closure of beaches and shellfish harvesting due to high bacteria concentrations, etc. When specific impairments are identified, then detailed chemical analyses may be justified in order to identify the specific compounds causing the observed problems.

Fuchs *et al.* (1996) investigated the use of biofilm samplers (six glass plates inside a 30 cm PVC pipe, initially coated with stearic acid and exposed for 14 days) to indicate heavy-metal variations in an urban area. The biofilm samplers were found to be very representative of more difficult to conduct sampling efforts, and are probably more representative of conditions affecting aquatic life.

### ***Rainfall and Flow Measurement***

A telemetric system for hydrology and water quality monitoring was used by Meyer and Huey (2006) in northern New



Mexico. Site selection was constrained by access, distance, technology and cost, but in spite of these limitations, the system performed well. Lei et al. (2006) presented a runoff-runon ponding method for measuring transient infiltration capability on sloped surfaces. This method overcomes the limitations of the traditional rain simulator and double-ring infiltrometer methods on sloped surfaces.

Panjan et al. (2005) reviewed the different procedures around the world to derive a statistical Equivalent Design Rainfall (design storm rainfall). A stochastic model for determining the Equivalent Design Rainfall was proposed. Smith et al. (2005a) presented the results of a study on a watershed experiencing land-use changes. It was shown that a strong correlation between measured and predicted rainfall did not always guarantee a strong relationship between measured and generated runoff. Smith et al. (2005b) examined the storm event hydrologic response in an urbanizing watershed. There was large storm-to-storm variation in the event water balance, and this variation was linked to antecedent soil moisture, rainfall variability and spatial heterogeneity of runoff production.

Grum et al. (2005) proposed a method to link point rain gauges, radar, and microwave measurements into a hydrologic model of a watershed. The paper reviewed the method's applicability, limitations and directions for future improvements. Mikkelsen et al. (2005) described the high-resolution rainfall gauge network installed in Denmark. Statistical regionalization procedures were developed from this long time series of data. It was recommended that hydrologic design be based on a historical rain series from an area with similar physiographic characteristics and a pre-specified level of safety. Runnels and Ward (2005) characterized higher frequency storm events in the Albuquerque (New Mexico) area. The purpose was to determine the precipitation amounts associated with frequent events. Petersen-Overleir and Reitan (2005) characterized the uncertainty in flood discharges from urban and rural catchments due to inaccurate head measurements associated with an instantaneous flood discharge. The results showed that variability in head determination had minimal impact for biasing the estimating instantaneous flood statistics.

The Michigan Department of Transportation supported the study by Trefry et al. (2005) to update the state's intensity-duration-frequency curves for the state. The study applied a regional frequency analysis approach based on L-moments. The characterization of the return period of rainfall events in Marseilles, France, was studied by Ramos et al. (2005). The degree of storm severity and its impacts on flooding was dependent on the extent of heavy rain areas.

Vaes et al. (2005) proposed areal rainfall correction coefficients to account for the spatial variability in rainfall. The spatial variability greatly affects the discharge from the watershed. Vieux and Vieux (2005a) discussed the considerations for rainfall accuracy when using radar and rain gauge networks. The influence of uncorrected radar measurements was greater than the random errors that remained after correction. The algorithm used to disaggregate hourly rainfall data to the 5-minute scale was examined by Onof et al. (2005). An alternative method that addressed the limitations of the current method was proposed. The impacts of rainfall data on modeling accuracy and refinement was presented for the Allegheny County (Pittsburgh, Pennsylvania) by Meenehan et al. (2005). The results showed that in an area such as Pittsburgh where there can be significant spatial and temporal differences in the rainfall distribution, there are substantial benefits to installing a regional gauge-adjusted regional radar rainfall system.

Russo et al. (2005) reviewed the rainfall monitoring system in Rome and compared two rainfall interpolation methods with radar rainfall measurements. Rain gauge fields were reconstructed after the errors were analyzed. Hergren et al. (2005) refined the rainfall simulators used in agricultural research for application to research on urban paved areas. They also proposed a simulant mix that mimics the chemical properties of natural rainfall in their study area.

Molini et al. (2005a) presented a methodology to infer the influence of rainfall measurement errors on the reliability of extreme rainfall statistics determined using tipping-bucket rain gauges. The procedure corrects the low resolution data series after disaggregation. The impacts of these measurements errors on urban stormwater depth-duration-frequency curves were discussed in Molini et al. (2005b). Spherical rain gauges were compared with traditional rain gauges to determine if spherical rain gauges provided a more accurate record of rainfall (Chang and Harrison 2005). The spherical gauges were effective at reducing the impacts of wind on rainfall measurement. Vasvari (2005) discussed the calibration of tipping bucket rain gauges in Graz (Austria). The calibration process is dynamic and uses a peristaltic pump to perform the calibration. Deviations in recording actual intensity are seen in both directions – positive and negative errors in measurement.

Sewage network monitoring to minimize sanitary sewer overflows was reviewed by Sier and Lansley (2005). Their methodology assisted in locating meters to maximize the likelihood of detecting system blockages and SSO disruptions.

The design of a system for managing rainfall information for sewer system management was described by Vieux and Vieux (2005). The design was highly dependent on the ability to accurately characterize rainfall in a watershed, including its temporal and spatial variation.

Valeo et al. (2005) estimated snow evaporation with GPS-derived precipitable water vapor. Evaporation rates for natural fresh snow, natural ripened snow and mechanically displaced snow were estimated and compared to the rates derived using the GPS.

Methods for quantifying inflow and infiltration (I&I) were presented by Dutt and Dent (2004). Several methods, including smoke testing and closed-circuit television, are reviewed and the difficulties of using only one method are highlighted.

Balion et al. (2004) described the site selection steps in the development of the flow monitoring program for Cincinnati, Ohio. The site selection of an appropriate sample station required the site to fulfill three components: met a modeling objective, data quality ensured and site conditions acceptable for a sampling station.

Fekete et al. (2004) reviewed the uncertainties in precipitation estimation and the resulting impact on runoff estimates. The comparisons of six monthly precipitation datasets on runoff estimation emphasized the need for accurate precipitation measurements, especially in arid and semi-arid areas. The temporal and spatial distribution of rainfall measurements required for urban hydrological applications was examined by Berne et al. (2004). The results showed that a temporal resolution of 5 min and spatial resolution of 2 – 3 km was adequate for modeling rainfall in Mediterranean regions.

Carlson (2004) reviewed how satellite image data, in conjunction with an urban growth model and runoff calculations, could be used to estimate future surface runoff. The use of this model was shown for Spring Creek Watershed in Central Pennsylvania. Blossom (2004) proposed using satellite imagery to update stormwater databases, to determine the quantity of runoff from different land uses and to more fairly distribute stormwater fees.

The use of radar rainfall data in urban drainage forecasting was highlighted by Einfalt et al. (2004). Evaluation and improvement of quantitative precipitation were reviewed, as were uncertainties and methods for obtaining accurate rainfall measurements at high resolution. Dual-frequency microwave links were proposed by Rahimi et al. (2004) as a way to compensate for the problems inherent in measuring rainfall in urban areas. This form of measurement was shown to complement well the more conventional measurements – gages and radar. Shutov (2004) reviewed the methods used to incorporate radar information into applied hydrology and estimation of runoff. Several different procedures are proposed to increase the accuracy of radar estimation use.

Monitoring/modeling the contribution of soil in generating runoff was studied by Berthier et al. (2004). Soil contribution was found to be particularly important in areas with a shallow groundwater table. The hydrological behavior of roads affects the quantity of runoff generated (Ramier et al. 2004). Runoff losses (infiltration and evaporation) in asphalt concrete surfaces were found to be measurable, especially for porous asphalts.

Isotopes were used to quantify flows in Miami-Dade County between those contributed by the Everglades and those contributed by urban-area runoff (Wilcox et al. 2004). The isotopes, oxygen-18 and deuterium, were capable of showing which contribution was greater – urban runoff in shallow groundwater.

St. Hilaire et al. (2003) assessed the impact of rainfall-gauge-network density on the estimation of basin precipitation and runoff using a case study in the Mauricie area of Quebec, Canada. High precipitation cells were better defined with the denser network, and decreases in the relative spatial variance were observed. Similarly, kriged daily precipitation better described the spatial distribution of rainfall during important rain events of 1999. Peak flows during important summer flood events were generally better simulated when a denser network was used to calculate the mean daily precipitation used as input.

Jacobs et al. (2003) used remotely-sensed soil moisture to improve rainfall/runoff estimates in Oklahoma by improving the selection of the curve number for SCS runoff prediction methods. Jeffrey (2003) reviewed the innovative technologies available for TMDL data acquisition, analysis and dissemination, including hand-held computers, remote sense and Internet mapping. Case studies were provided for several 303(d)-listed streams in MA.

Fogle and Taraba (2003) overviewed systematic sampling and storm chasing in karst basins. It was determined that storm sampling was not required because the flow-composited storm nitrate-N and total solute sample concentrations were comparable to the systematically collected grab sample concentrations both in value and trend.

Barton et al. (2003) reported on the data analysis tools used by the Metropolitan Sewer District of Greater Cincinnati for portable flow monitoring. Stevens et al. (2003) reviewed Atlanta's procedures for measuring sewage spills by identifying when flow is missing from a pipe. Using recent data, the system learns a rainfall-to-RDII (Rainfall Dependent Infiltration Inflow) relationship for each monitor basin and is able to predict what current flow should be. Hall (2003) analyzed flow monitoring data collected as part of an I/I study. One common problem was that many wastewater treatment plants did not have sufficient influent flow metering capacity to accurately measure significant wet weather flow events. Kurz et al. (2003) presented a proposal for an industry-wide standardization of I/I calculations. The proposal was based on work done by the Metro Nashville (TN) Department of Water and Sewerage Services and would set a criteria of "a projected I/I volume from a 5-year, 24-hour storm." Reid (2003) reviewed real-time wireless CSO monitoring equipment. The CSO monitors were integrated with wireless rain gauges to check rainfall and differentiate between wet and dry weather events.

Vallabhaneni et al. (2003) presented a case study in Cincinnati of site selection for flow monitoring. The case study focused on how to select appropriate flow monitoring sites and how the collected data was used in the development of the System-Wide Model for the sewer system.

Grottker et al. (2002) discussed limited flow reduction as a measure for reducing hydraulic stress from urban storm flows into rivers and creeks. Bowns et al. (2002) reviewed the use of a multiphase data collection and analysis program (inspection of plant headworks, system metering and pump stations; collection system flow metering with rainfall recording; groundwater level identification; structure inspections; flow isolation; and smoke test and CCTV inspections) in Sandy Hook, Kentucky to create digital aerial maps of the city's sewer system and to guide an upgrade of both the treatment plant and collection system. Cowger et al. (2002) reviewed the problems experienced by the Sanitary District of Decatur (Illinois) with its existing infrastructure telemetry system. An evaluation of alternatives demonstrated that Cellular Digital Packet Data (CDPD) provided for a more reliable system and one that could be polled for data more frequently.

Carlson (2002) reviewed the coupling of land surface classification and impervious surface cover derived from Landsat™ imagery with an urban growth model. The results have been used to predict future changes in surface runoff resulting from urbanization. An illustration was presented.

The Tropical Rainfall Measuring Mission (TRMM) is a United States-Japan joint project to measure rainfall from space (Ohsaki 2001). In this paper, rain/no-rain discrimination for the TRMM was validated through simulation and theory for the no-rain condition and by comparison with the ground-based radar data for rain conditions. The precipitation radar (PR) aboard the TRMM demonstrated the feasibility of measuring rainfall from space (Sadowy et al., 2001). The Second Generation Precipitation Radar (PR-2) has been developed. The PR-2 will improve capabilities and substantially reduce system mass compared to the TRMM PR. This paper surveyed the technologies for the PR-2.

A combined Microwave/Infrared Rain Rate Algorithm (MIRRA) was presented by Miller et al. (2001). MIRRA combined the strengths of these two broad approaches to rain rate measurement from space. The algorithm was tested using data from the TOGA-COARE campaign, with shipboard radar rain rate estimates used as truth. Results indicate enhanced performance in bias, correlation and rms error for MIRRA. Calibrated radar rainfall systems, often called 'virtual rain gauges,' have become popular due to the advantages they offer over conventional precipitation monitoring networks (Orie et al., 2001). The 3 Rivers (Allegheny County, Pennsylvania) Wet Weather Demonstration Program made virtual rain gauges available to the public by integrating the calibrated rainfall system with the Internet. A methodology was developed that matched coincident space-based radar (PR) and ground-based volume scanning weather radar observations in a parallel three-dimensional Cartesian grid (Anagnostou et al., 2001). The data matching was performed to minimize uncertainties associated with the type of weather seen by the radars, grid resolution, and differences in radar sensitivities, sampling volumes, viewing angles, and radar frequencies. The authors compared reflectivity observations from the PR and several U.S. weather surveillance Doppler radars (WSR-88D) as well as research radars from the TRMM field campaigns in Kwajalein Atoll and the Large Biosphere Atmospheric (LBA) Experiment. Correlation values above 0.8 were seen between PR and ground radar.

A daily rainfall disaggregation method that yields regional hourly rainfall estimates was presented in terms of application to continuous-simulation watershed models (Socolofsky et al., 2001). When compared with hourly data, the method reproduced well the variance, lag-1 autocovariance, and probability of zero rainfall. Application of the method in the upper Charles River watershed in eastern Massachusetts demonstrated that the method greatly improved the river flow simulation capability of the hydrologic model over alternate simulations using hourly rainfall from outside the watershed. An overview of weather radar-related developments in South Africa, as related to hydrological research and operations, was given by Terblanche et al. (2001). This program developed the necessary infrastructure, expertise and related hardware and software to collect and archive high-quality radar data. Shortcomings of weather radar data for hydrological applications were described and the ongoing research efforts to address these shortcomings were highlighted. Valeo and Tang (2001) developed a model for the second order process of rainfall in an area of southern Ontario. Hourly rainfall data collected from 17 gages over a period of five years were used to develop a correlation function for rainfall, with an exponential model for the correlation function being selected over a spherical and Gaussian model. A regional, index-storm approach based on L-moments was applied to estimate short duration (less than or equal 24 h) design rainfalls in South Africa (Smithers and Schulze 2001). The regionalization was performed using only site characteristics (latitude, longitude, altitude, concentration of precipitation, mean annual precipitation (MAP), rainfall seasonality and distance from sea). The index storm used was the mean of the annual maximum series and a relationship was derived between the index storm and MAP.

Rainfall simulation experiments were carried out on more than 40 1-m<sup>2</sup> plots to measure infiltration point-processes (Perrin et al., 2001b). The high density of measurement devices allowed identification of the origin and nature of the various contributions to runoff for the different physiographic units of the watershed: urban area, farmland, pasture, forested land, and paramo. Variations in the runoff coefficients were related first to the baseflow and second to the amount of rainfall in the previous 24 h. In the paper by Morin et al. (2001), high-resolution meteorological radar data are used for the determination of a characteristic temporal scale for the hydrological response of the basin – the ‘response time scale’ (T-s\*). The identification of the response time scale was carried out by analysis of observations only and without assuming a specific rainfall-runoff model. For all analyzed basins a stable response time scale was identified with relatively short time scales found for the urban and arid basins (15-30 min) and longer time scales for the rural basins (90-180 min). Habib and Krajewski (2001) reported on the application of a computational fluid dynamics-based method to improve the aerodynamic design of rainfall measurement devices, including a two-dimensional video disdrometer that provides information about raindrop size distribution. The distorted wind field around and inside the instrument's body was simulated using a three-dimensional numerical model. Raindrop trajectories were simulated to investigate the wind effect on the catchment efficiency of the instrument.

The study by Kurz and Qualls (2001) evaluated the EPA's PCS (Permit Compliance Study) database and determined the various parameters that may be useful in developing I/I control and sewer rehabilitation strategies on a state and regional level. The study summarized DMRs (monthly NPDES Discharge Monitoring Reports) for 1999 from 790 systems in Region 4 categorized as “major.” Maheepala et al. (2001) described the issues that need to be considered when conducting a successful and cost-effective hydrologic data monitoring program. It was found that that tipping bucket resolutions up to 0.5 mm would give reasonably accurate results in urban stormwater modeling, and two-minute data logging intervals were suitable for flow data monitoring. The results also suggested that combining low cost simple flow measurements and limited high cost sophisticated measurements could reduce the data acquisition cost without compromising the accuracy of flow hydrographs measured in stormwater conduits. Remote sensing was used as a source of data to address the spatial variability of hydrologic processes such as storm runoff (Melesse et al., 2001). Remote sensing provided quantitative land cover information of suitable spatial resolution for model inputs. The study area was the S-65A sub-basin of the Kissimmee River basin in south Florida, and results showed that the temporal and spatial variability of runoff volume resulting from changes in land cover could be determined from Landsat images.

The WERF research described by Schultz et al. (2001b) will assist municipal agencies to quantify and simulate rainfall-derived infiltration and inflow (RDII) that affects their sewer systems. Eight major categories of RDII analysis methods were tested in several diverse sewersheds and metrics suitable for objective comparison of the RDII analyses were identified. An accurate dye dilution testing protocol using Rhodamine WT was used to quantify flow meter accuracy in the Greater Detroit Regional Sewer System (Stonehouse et al., 2001). The seven technologies assessed were electromagnetic induction meters (magmeters); full-conduit, multiple-path, transit-time meters; full-conduit, open-channel, ultrasonic meters; flumes; and weirs. It was concluded that (i) there were observable accuracy differences between flow meter technologies, (ii) objective standards like dye dilution testing were critical, (iii) verifying installed accuracy was important, and (iv) the simplest technology that can be used often was the best. Swarner et al. (2001b)

reported on the effort by King County determine the wet weather performance and geographic distribution of I/I through its entire service area; conduct several pilot rehabilitation projects to evaluate rehabilitation effectiveness; develop and calibrate an accurate hydraulic model of the system; and implement a Regional I/I Control Program. The paper discussed the political and administrative actions to achieve consensus among the local agencies and analyzed the I/I results as a function of basin size.

Chao and Hegwald (2000) documented procedures for deploying flow meters and for data evaluation to ensure that a flow-monitoring program would be successful. Stonehouse et al. (2000) reported on the work of the Flow Metering Task Force (FMTF) in Detroit, whose purpose was to evaluate and improve the current flow metering occurring in the Detroit sewer system. The guidelines developed by this group included procedures for meter evaluation, data collection and review, and information sharing. This group also developed a dye dilution testing protocol that provided more accurate results than prior protocols. A specialized probe using time-domain reflectometry (TDR) was developed, calibrated and field tested for continuously measuring soil-water content and surface runoff during studies of water erosion and sediment transport (Thomsen et al. 2000). The laboratory investigation of this TDR probe showed that water levels could be measured with a standard deviation of less than 2 mm. Zandbergen and Schreier (2000) investigated the current methodologies used to assess the impervious cover in a watershed. These included ground surveys, stereo-photogrammetry, air photo interpretation, and satellite image analysis. The following factors were found to influence the accuracy of imperviousness measurements (in order of decreasing importance): selection of imperviousness factors; accuracy and scale of land use mapping; consideration of land cover in addition to land use; and watershed delineation.

Burrows et al. (1999) evaluated a flow stick with inclination transducer. The data from the flow stick, when combined with a depth measure, provided an accurate measure of the instantaneous flow rate in a storm, sanitary or combined sewer. Goyen and O'Loughlin (1999) described their project in which they used intra-catchment gauging stations in Canberra, Australia to collect data regarding rainfall and runoff. They determined that the spatial and temporal variability of rainfall and runoff even over a single catchment were great enough to ensure the single-parameter models cannot perform well consistently and so, they proposed a runoff simulation model that incorporates the intra-catchment elements needed to determine runoff from a larger watershed. Tilley et al. (1999) demonstrated the inadequacy of current stream-gauge height-measurement-averaging techniques combined with a rating curve to estimate flow at a site during flash flooding in urban areas. They recommended that the monitored gauge height be used for each subarea for each time increment in order to calculate the volume of flow during a flash flood. Steiner et al. (1999) demonstrated the necessity for having good quality rain gauge data if it will be used to adjust for biases in radar rainfall estimates of precipitation. They concluded that the differences resulting from radar data processing scenarios were small compared to the effects of rainfall data adjustment based on rain gauge information. Maheepala and Perera (1999) described the quality assurance checks program used during the collection of urban drainage hydrologic information for a flood-prediction model for Victoria, Australia. They discussed not on the quality of the data but also the occupational safety and health aspects of collecting it. Guitierrez (1999) reported on the development of regional regression equations for predicting flows at ungauged urban catchments in Mexico.

Riotte and Chabaux (1999) found that the ratio of U-234/U-238 could be used to investigate hydrological processes such as flooding events. Weiler et al. (1999) used natural tracers/isotopes with mass balance calculations to determine the fraction of surface flow and subsurface flow in the receiving water prior to a rain event. The isotopes were also used to demonstrate the importance of infiltration water to the quantity of subsurface runoff due to preferential flow. McDonnell et al. (1999) combined tracer studies (using  $^{18}\text{O}$ ) with measures of rainfall and runoff in four nested catchments on South Island, New Zealand. The results showed that water contributions from various source areas in a catchment was a complex function of the mixing of these contributions and of the contact time in the groundwater and drainage system. Mehlhorn and Liebundt (1999) determined that the modeling approaches for tracer hydrology and rainfall-runoff modeling were mathematically equivalent and therefore, tracer time parameters could be used to calibrate baseflow runoff models. Coupling the water age and turnover time of the mobile groundwater led to a more accurate determination of the baseflow in the stream.

Post et al. (1999) used hand-held radiometers to evaluate the ground cover of semiarid rangelands and to correlate the data collected with the hydrologic characteristics of the area. The results showed that vegetative cover and percent runoff were highly correlated with spectral reflectance, while soil-rock cover and eroded sediment were poorly correlated with the reflectance.

A method to adjust the daily precipitation measured by the U.S. National Weather Service (NWS) 20.3 cm (8 in.)

standard gauge for wind-induced undercatch, wetting loss, and trace amount of precipitation was tested at ten climate stations in Alaska during 1982-83. Results showed that daily adjustment increased the gauge-measured annual precipitation by up to 800 mm for the two years (Yang et al., 1998). An accuracy test conducted in the Stephen F. Austin Experimental Forest, Tex. revealed that a U.S. standard gauge, weighing-type recording gauge, a standard gauge fitted with an Alter windshield, and a pit gauge showed each gauge to have an average deficiency greater than 10% when compared to a recording anemometer (Chang and Flannery, 1998). Correction for wind effect on angle of raindrop reduced the deficiency from 11% to 6% leaving the remaining error to wind effects, nonrandom errors and other unknown sources. The procedures were presented for the collection and quality control of rain data from a network of tipping bucket rain gauges in Den. carried out by the Danish Meteorological Institute as input to software packages such as MOUSE and SAMBA for designing sewers and storage basins, and simulating overflows and flooding. Although it is possible to improve the efficiency of the quality control, long term corrections will always be necessary (Jorgensen et al., 1998).

Spatial and temporal variability in rainfall concentrations of several contaminants were monitored at seven locations in or near the Conodoguinet Creek watershed of south-central Pa. and compared precipitation quality in forested, agricultural and urban areas. The major ion concentrations were related more to regional influences than local while herbicides in precipitation may have had more local influences (Shertzer et al, 1998). Quality checks also indicated that trained volunteers were reliable in collecting data in a timely manner. The Residential Stormwater Monitoring Project, initiated by the Boston Water and Sewer Commission in March of 1997, characterized the seasonal variation in the quality of stormwater discharged from a low density residential area (Schofield and Eggleston, 1998). The project included precipitation monitoring, stormwater quality sampling and quantification of flows at a single manhole location for up to five storms per season for a period of one year, surface stormwater quality sampling at five gutter locations, and inspection and sampling of dry weather flows in storm drains.

Short-term flow monitoring programs such as those employed for SSO and CSO should focus on the anticipated use of collected data (Hollenbeck, 1998). Monitoring should start approximately two weeks prior to initiation of the normal "storm season" and a minimum of 90 days (ideally 120) of short-term monitoring are necessary to determine a reliable relationship between rainfall intensity and stormwater inflow. Flow monitoring devices at or upstream of sewer overflow structures for recurrent CSO and SSO in the Pittsburgh, Pa. were installed to determine the quantity of sewage which pass through selected regions. The monitors collected data until the selected study points stayed within specified limits for eight consecutive months (Patsey, 1998). In a Boston, Mass. sewer separation project, several flow meters recorded depths which differed significantly from wet and dry weather manual measurements. Analysis determined that the meters were most likely reading a constant fraction of the actual change in depth (DePasquale and Caulfield, 1998).

The U.S National Weather Service radar images have produced significantly greater resolution in the spatial distribution of rainfall in comparison to raingauges alone which can contribute to the accuracy of CSO modeling (Burgess *et al.*, 1997).

### ***Toxicity Testing***

Dupuis and Kreutzberger (2003) reviewed the use of time-variable toxicity testing for decision-making. The time-variable bioassay generally consisted of standard techniques, but with the key exception being that test organisms are exposed to a sequence of discrete wet weather samples collected over the duration of an event.

Palachek et al. (2002) reviewed recommended assessment protocols for use with ambient toxicity tests in the 305(b) and 303(d) listing process. Assessments were conducted in Texas based on 6 stream segments for sediment toxicity and 4 stream segments for water toxicity in order to provide a means to address observed impairments. The paper presented supporting evidence that the above criteria are reasonable, considering that toxicity test results are used to make regulatory "yes or no" decisions concerning ambient 303(d) listing. The supporting evidence included a summary of the controversy concerning ambient toxicity test variability and Type I errors.

Heijerick et al. (2002) correlated chemical speciation results for zinc from roofing materials with the biosensor test Biomet™. The regression analysis showed that, for this type of runoff samples, the rapid screening biosensor was capable of predicting (a) the total amount of zinc present in the runoff samples ( $R^2$  of 0.93-0.98;  $p$  less than or equal 0.05) and (b) the observed 72 h-EbC<sub>50S</sub> ( $R^2$  of 0.69-0.97;  $p$  less than or equal 0.05).

Hall and Lockwood (2002) reviewed methods for identifying fish pathogens in industrial effluents. The study resulted in a

very functional “weight of evidence” approach that provides three levels of certainty (symptomatic, preliminary identification, confirmation) regarding the causative role of fish pathogens. This would allow a cost-effective, phased approach in resolving WET permit compliance issues.

Schiff et al. (2002) discussed using Toxicity Identification Evaluations (TIE) to assist in developing the TMDL for aquatic toxicity in the Chollas Creek and San Diego Bay, California. The primary objective of this study was to identify the toxicants and determine the areal extent of impairment in the waterbody of concern. The stormwater plume emanating from Chollas Creek was dynamic, covering areas up to 2.25 km<sup>2</sup>. Approximately half of the plume was estimated to be toxic to marine life, based upon results of purple sea urchin (*Strongylocentrotus purpuratus*) fertilization tests. The area nearest the creek mouth was the most toxic (No Effect Concentration, NOEC = 3 to 12% plume sample), and the toxicity decreased with distance from the creek mouth.

Warren-Hicks et al. (2002) discussed the need to account for toxicity test variability when evaluating TIE test results. This research was designed to address the precision of WET test procedures, and to develop methods for incorporating variance estimators into EPA decision-making frameworks. In addition, a national data base of reference toxicity tests, a national data base of WET compliance test results, and a series of case studies were developed in support of the statistical analyses.

Bdour et al. (2001) examined the relationships between Index of Fish Density (IFD) and man-made disturbances, watershed parameters, habitat parameters, water quality parameter, and climate parameters for the 61 HUCs (Hydrological Unit Code) for the South Fork Clearwater River basin in Idaho and 15-20 reaches for Red River and Newsome Creek within the South Fork Clearwater River Basin. The results showed that incorporating both fine and coarse scale parameters in any assessment model will improve the correlations. Biomonitoring using juvenile giant clams (*Tridacna maxima*) was conducted in conjunction with sediment and stormwater sampling at U.S. Army Kwajalein Atoll. Elevated levels of metals, PAHs, pesticides, and PCBs were detected in clams from the sampling locations. Trends in clam tissue, sediment and stormwater data suggested that both sediment and stormwater are significant sources of the pollutants detected in clams.

Baker et al. (2000) reviewed a project undertaken as part of Mecklenberg County’s Surface Water Improvement and Management (SWIM) program, and which included restoration in the highly-urbanized Edwards Branch watershed. The project emphasized the importance of using a variety of monitoring techniques - EPA stream habitat assessment protocol, ambient water quality monitoring, fish and benthic macroinvertebrate surveys, and channel cross-section monitoring - to investigate the effectiveness of the installed stormwater treatment practices and other restoration techniques. The bioassessment approach used in the Camp Creek Watershed in Fulton County, Georgia was reviewed by Jones (2000a). By linking the biological results with the water quality monitoring data, management goals were set and improvements were focused on critical management areas. The paper by Rochfort et al. (2000) encouraged the use of benthic assessment techniques, in conjunction with toxicity testing and sediment and water chemistry analyses, to determine the impacts of stormwater and combined sewer overflows (CSOs) on receiving water and the biota. The results from all three analysis techniques showed that the sediment chemistry could not be correlated to either the toxicity testing or the benthic community impacts, and that a combination of techniques was necessary to show a complete picture of stream health.

Chappie and Burton (2000) described the application of in-situ aquatic sediment toxicity testing for stormwater runoff assessment. Burton et al. (2000) described the problems associated with using traditional toxicity testing methods for assessing the biological impacts of stormwater runoff. The problems noted include the inability to produce reliable conclusions when this technique was used to detect the adverse effects of fluctuating stressor exposures, nutrients, suspended solids, temperature, UV light, flow, mutagenicity, carcinogenicity, teratogenicity, endocrine disruption, or other important subcellular responses. In watersheds receiving multiple sources of stressors, accurate assessments should use a range of laboratory (such as whole effluent toxicity [WET] tests) and novel in situ toxicity and bioaccumulation assays, and should include a simultaneous characterizations of physicochemical conditions and indigenous communities. de Vlaming et al. (2000) used USEPA protocols for freshwater toxicity testing to evaluate ambient water quality in California. Testing since 1986 showed that the three WET tests, when performed along with toxicity identification evaluations (TIEs) and chemical analyses, were useful in identifying pollutant sources and identifying potential benefits of alternate land uses or best management practices. Tobiason and Logan (2000) reported on the benefits of using WET testing of stormwater at outfalls to trace sources of pollution at Sea-Tac International Airport. WET testing was found to be very effective in helping to identify a zinc-galvanized metal rooftop as the source of zinc contamination and therefore the source of the toxicity of the stormwater runoff. Ellis (2000a) reviewed using in-situ biomarker techniques to evaluate

the effects of transient pollution events, such as the inflow of stormwater runoff, in urban receiving waters. This paper also discussed the limitations of more traditional toxicity tests such as the Direct Toxicity Assessment (DTA) procedures for assessing transient events that leave sub-lethal stresses on the biota.

Several field and laboratory assays were employed below an urban storm sewer outfall to define the relationship between stormwater runoff and contaminant effects. Specifically, two bioassays that measure feeding rate as a toxicological endpoint were employed in the field and in the laboratory, along with bioassays measuring survival and growth of test organisms. The results of the study suggest significant toxicity at this site was due to accumulation of contaminants in the sediment and the mobilization of these contaminants during a storm event (Hatch and Burton, 1999).

Doherty et al. (1999) compared *Ceriodaphnia dubia* and the Microtox® inhibition tests with *Vibrio fischeri* on industrial and municipal wastewaters. For samples that were not toxic, the Microtox® method correlated well with the results with the *C. dubia* results. However, for samples that were toxic to *C. dubia* after 24 hours, the Microtox® detected toxicity in only two. For five other samples that the Microtox® found to be toxic, the *C. dubia* required a minimum of 48 hours of exposure before toxicity could be detected. Kosmala et al. (1999) used *C. dubia* in laboratory toxicity tests in combined with field analysis of the *Hydropsychid* life cycle to assess the impact of both the wastewater treatment plant effluent and the stormwater overflow on the receiving water. They found that the results seen in the laboratory toxicity tests and in the in-situ biological measurements were due to nutrient and micropollutant loadings. Marsalek et al. (1999) used several different toxicity tests to assess the various types of toxicity in typical urban runoff and in runoff from a multi-lane highway. The tests included traditional toxicity analysis using *Daphnia magna*, the Microtox® toxicity test, sub-mitochondrial particles and the SOS Chromotest for genotoxicity. Tucker and Burton (1999) compared in-situ versus laboratory conditions for toxicity testing of nonpoint-source runoff. They found that NPS runoff from urban areas was more toxic to the organisms in the laboratory while the agricultural runoff was more toxic to the organisms exposed in situ. The differences seen between the two types of toxicity tests demonstrated the importance of in-situ assays in assessing the effects of NPS runoff.

Brent and Herricks (1999) proposed a testing protocol for the toxicity assessment of wet weather events that includes an event-focused toxicity test method, a corresponding test metric that more accurately represents the toxicity of brief exposures, and an event-based index that described the acute toxicity of wet weather events. This testing protocol was designed to quantify toxic response produced by brief contaminant exposures (< 24 h), as well as time-varying contaminant exposures, which were typical of wet weather events. The protocol described the use of an event-focused toxicity test to determine a PELET50 (post-exposure lethal exposure time for 50% of the population) metric for individual event samples.

When considering urban runoff toxicity, it was necessary to carefully consider magnitude, duration, and frequency in any toxicity analysis. First, to measure this toxicity it was necessary to apply a new paradigm, the time-scale toxicity paradigm. The time-scale toxicity paradigm was reviewed, and data from storm events was provided to illustrate paradigm utility in assessing the toxicity of urban runoff and the related impact of urban runoff on receiving systems (Herricks, 1999).

Researchers in King County, Wash. used transplanted and wild mussels to monitor Cu, tributyltin and PCB. In the wet season, concentrations of Cu increased in wild mussels near CSO although the source of Cu was unclear (Munger et al., 1998b). Seidl et al. (1998a) found that CSO contributed toxicity to the River Seine, Fr. even after settleable solids were removed and effluent was diluted five-fold. The results of this study suggest that Zn may contribute significantly to phytoplankton toxicity of CSO effluent. A further CSO study in the Seine comparing biodegradable to residual dissolved organic carbon (BDOC to RDOC) showed that an additional source of carbon was contributing to the oxygen budget, possibly phytoplankton or degraded particulate organic matter (Seidl et al., 1998b). In Paris, Fr. further CSO studies showed a higher proportion of refractory organic carbon during rain events than during dry weather with a possible contribution of the in-sewer sediments to the bacterial wet weather flux (Seidl et al, 1998c). A multi-parameter continuous water quality monitor was examined for evaluating in-situ photosynthesis/respiration rates of microbes (Easton et al., 1998). The city of Indianapolis, Indiana completed a large instream sampling program directed at characterizing ambient bacteria levels in the White River and its tributaries. Analysis showed less wet weather influence on bacteria in the White River than in the tributaries (Burgess et al., 1998). Søballe (1998) illustrated the difficulties inherent in monitoring an ecosystem. Monitoring programs provide unbiased evaluation only for those phenomena whose temporal and spatial characteristics match those of the monitoring program.



Two years of sampling in San Francisco, Calif. revealed that only certain individual dioxins/furans and PAH were commonly detected in the city's collection system, and may be indicative of specific sources. PAH were also detected more frequently in catchbasin influent than effluent implying that particle deposition in catchbasins may be an effective removal mechanism for PAH (Moore et al., 1998b).

### ***Testing for Chemical Pollution and Pollution Tracers***

Sampling for volatile organic chemicals (VOCs) is challenging. Williams et al. (2006) described sampling strategies for VOCs at three karst springs in Tennessee. Results from the study indicated that sampling strategies for karst springs need to be developed on a site-specific basis. The use of fixed sampling intervals (as infrequently as quarterly or semiannually) produced accurate concentration and load estimates at one of the three springs. Marsalek et al. (2006a) described an elutriation apparatus for assessing settleability of CSO pollutants. Solids settling can be measured under dynamic conditions by flow through a series of settling chambers of various diameters.

A continuous fiber optic in-stream transmissometer was used to measure suspended solids concentration mobilized during peak flows in rivers and streams (Campbell et al. 2005). The particle size dependence on transmittance posed a problem for anything but site-specific calibration. The potential of using Sea-viewing Wide Field-of-View Sensor to assess the distribution of stormwater runoff plumes in coastal waters was investigated by Nezhin et al. (2005). The backscattering properties of surface waters were found to best characterize the runoff plume, and the resultant data showed that the primary factors regulating the relationship between rainstorm and plume were land-use characteristics, size and elevation.

Lacarra et al. (2004) presented San Diego County's water quality assessment process, which has been shown to be applicable to both wet weather and urban runoff monitoring needs. In addition, this tool is an iterative tool that can be used to evaluate watershed improvements.

Aichler et al. (2004) reviewed the testing performed to determine if CSOs were contributing to decreases in DO in the Detroit River. Water quality data was collected using sondes both in the CSO plume and outside, with turbidity being the greatest indicator of CSO water. Online techniques for quantifying CSO pollutant loads were examined by Gruber et al. (2004). The research team designed a modular online monitoring station that continuously monitored water quality in the sewer network. A monitoring station in an inline CSO tank was presented by Frehmann et al. (2004). The monitoring program was able to demonstrate the efficiency of the control system.

Fluorescence spectroscopy was proposed as a screening tool for identifying the presence of natural and anthropogenic organic compounds in urban runoff (Smart et al. 2004). The benefit to this tool is the ability to provide continuous monitoring of water quality, which is more likely to locate a problem. Tagert et al. (2004) examined the analytical techniques and monitoring program used to identify pesticide contamination in the Upper Pearl River Basin, Mississippi. The results will be linked to remotely-sensed land use in the basin to determine if 303(d) listed streams are truly "impaired" by pesticides. Zeng et al. (2004) proposed the use of dibenzothiophene and triphenylene as markers for urban stormwater runoff entering stormwater channels and wastewater treatment plants. While these compounds degraded in salt water and sunlight, they were present in sediments even after six months of sunlight exposure and source specificity was believed to exist.

Marias and Armitage (2004) examined the problems encountered when measuring urban litter entering stormwater sewer systems in Cape Town, South Africa. The study catchments, the litter-trapping devices, the implementation process for the monitoring and the installation of the trapping devices are all reviewed.

Grismer and Hogan (2004) proposed the use of a portable rainfall simulator to measure revegetation treatment efficiency on infiltration and erosion. Measured parameters included time to runoff, infiltration, runoff/infiltration rate, sediment discharge rate, sediment concentration, total Kjeldahl nitrogen (TKN), and total dissolved phosphorus.

Zuccarello et al. (2003) analyzed the concentration of the fuel additive methyl tert-butyl ether (MTBE) in a recreational harbor using solid-phase microextraction. The samples collected at the Marina del Rey harbor, a shallow recreational harbor near Los Angeles, CA, showed MTBE contamination in the low  $\mu\text{g/l}$  level. No evidence for MTBE contamination from the adjacent stormwater control channel was noted.

Barraud et al. (2002) discussed the implementation of a monitoring system to measure the impact of stormwater runoff infiltration. The main difficulty in monitoring is due to the complexity of the system and the need for multidisciplinary

approaches. A second difficulty is that the measurements must be carried out in situ, in an uncontrolled environment. The paper presented an experimental site, the project objectives and the way the monitoring has been built according to the various disciplines involved (biology, ecology, hydrology, chemistry and soil sciences) and to the will of assessing all the uncertainties in the measurement process.

Gruning and Orth (2002) investigated the dynamic behavior of the composition of combined sewage using on-line sensors – sensors for dissolved solids using UV absorption and sensors for particulates using scattered light measurement. A statistical relationship between these two parameters and the chemical oxygen demand was established. The analyzing methods presented permit the real-time control of sewer systems on the basis of the pollution carried in the combined sewage. Hack and Lorenz (2002) presented the use of an on-line wastewater organic load measurement in a combined sewer system as a technique to improve and integrate wastewater transportation and treatment. The paper reviewed the use of the spectral absorption coefficient at  $\lambda = 254 \text{ nm}$  (SAC), defined in DIN 38402 by the German Institute for Standardisation. As a purely physical parameter, the SAC shows a good correlation to organic sum parameters like COD and TOC, especially if municipal wastewater is considered.

Polls and Lanyon (2002) introduced the methodology used in a case study in Chicago for determining DO impairment. The methodology was the use of real-time, continuous water quality monitors (monitors). Beginning in August of 1998, DO was measured hourly at 20 stations on the deep-draft waterways using remote in-situ monitors. The paper reviewed the continuous DO monitoring approach used in urban deep-draft waterways in Chicago. Included were (1) the criteria used for selecting monitoring stations; (2) the features of the continuous monitors; (3) a description of the housing enclosures used to protect the monitors in the field; (4) the field and laboratory DO monitoring programs; (5) the quality control program and the data management system; and (6) examples of the continuous DO monitoring data showing the causes and sources of DO impairment in Chicago urban waterways.

O'Neill et al. (2002) investigated the determination of the method detection limit for methyl tert-butyl ether (MTBE) in water and discussed the application of a convenient headspace analysis method for MTBE. The MDL of the headspace method was calculated at  $2.0 \mu\text{g L}^{-1}$  by the EPA single-concentration design method<sup>1</sup> and  $1.2 \mu\text{g L}^{-1}$  by a calibration method developed by Hubaux and Vos (1970). The static headspace method was applied to analysis of a tap water sample and a monitoring well sample from a gasoline service station, a river sample, and aqueous extracts from soil excavated during removal of a leaking underground storage tank (LUST). The water samples examined in this study had MTBE concentrations ranging from 6 to  $19 \mu\text{g L}^{-1}$ . Aqueous extracts of a soil sample taken from the LUST site had  $8 \mu\text{g L}^{-1}$  MTBE.

Cristina et al. (2002) reviewed the use of a granulometry-based selection methodology for the separation of traffic-generated particles in urban highway snowmelt runoff by testing snow melt particles from 10 highway shoulder sites in Cincinnati. Each site was exposed to traffic and maintenance activities (plowing and de-icing salts only). Model results supported previous experimental data indicating the predominance of surface area and heavy metal mass was associated with the coarser fraction of particles. The methodology was in the form of a process selection diagram to evaluate mechanisms of particle separation.

Automated samplers were used to collect urban runoff in Pecan Creek, Denton, Texas (Appel and Hudak 2001). The results showed that concentrations of some heavy metals (cadmium and arsenic), as well as pesticides (atrazine and diazinon), were within ranges typical for urban runoff and first flush samples were more concentrated than composite samples for most of the constituents. Automated samplers were seen to be an effective way to sample urban runoff in Pecan Creek. Ruban et al. (2001) studied the SS and COD concentrations in combined sewers using in-line ultraviolet and visible absorbances. The optical measurement of SS and COD could then be used to determine average or long term pollution loads, for example the yearly impact of urban stormwater discharges. Continuous and on-line measurements would allow agencies to react with short delay to unexpected phenomena. A portable, field rugged, sampling and analysis system was developed for the rapid screening of aqueous samples during scoping and remediation studies (Beals et al., 2001). The equipment uses ion selective solid phase extraction (SPE) disks and counted for the radionuclide of interest in the field using portable detectors. The Savannah River Site H-area tank farm storm water runoff system was analyzed for Sr-90 and Cs-137.

The investigation by Moustafa and Havens (2001) determined the effect of sampling frequency and sampling type on estimates of monthly nutrient loads and flow-weighted nutrient concentrations in a constructed wetland. The results showed that bi-weekly composite sampling could be used to monitor nutrient concentrations and loads discharged from

larger-scale Everglades Stormwater Treatment Areas (STAs) now under construction. Compounds including coprostanol, epicoprostanol, cholesterol and dihydrocholesterol were quantified in CSO waters and their relative ratios calculated to investigate their potential application as source tracers (Marvin et al., 2001). A mean coprostanol:epicoprostanol ratio of approximately 70 was calculated for CSOs. When combined with physical measurements (e.g., current velocities) and meteorological data, these ratios may assist in determining the influence of shore-based activities, including sewage treatment and livestock operations, on aquatic systems. Indicators for assessing pathogen contamination and for distinguishing human origin and animal origin were investigated (Sankararamkrishnan and Guo (2001) with samples being taken from storm sewer outfalls to a coastal lake during wet weather as well as from the lake during the dry weather. The FC-to-FS ratio indicated the contribution of both human and animal wastes, with the presence of human wastes confirmed by increased concentrations of caffeine, fluorescence whitening agent, fluoride and anionic surfactant during wet weather.

Hartmann et al. (2000) investigated the usefulness of linear alkylbenzenes (LABs), a byproduct of LAS detergents, as a marker of sewage in the marine environment. Their usefulness was confirmed in Narragansett Bay where LABs were found in higher concentrations near the urban outfalls and in the upper layers of the sediment. Standley et al. (2000) investigated the potential for using molecular tracers of organic matter, such as fecal steroids, caffeine, consumer product fragrance materials, and petroleum and combustion byproducts to trace sources of organic matter in a watershed. The authors showed that molecular tracer content could be correlated with watershed-scale land uses and that wastewater treatment plant effluents were associated with caffeine and fragrance materials while urban runoff was associated with the PAHs. Allison et al. (2000) described two years of monitoring and characterization (litter material larger than 5 mm) of freeway runoff in California.

Maldonado et al. (1999) evaluated the use of trialkylamines and coprostanol as chemical tracers of pollution in the western Mediterranean and the northwestern Black Sea from urban areas. Trialkylamines were found to be the better marker of urban pollution in the water because they had higher concentrations in the water and were not as likely to associate with the particulate phases. Sidle and Lee (1999) used the deuterium isotope to determine the origin of the stormwater runoff from an urban watershed. Deuterium isotope concentrations were significantly different in the vadose and saturated zones between an area affected by a storm sewer leak and an area where a stream contributes to the groundwater. The measurements were useful in modeling leaks and seepages and in improving mass balances in urban watersheds.

Soerens et al. (1999) reported on the development of a sampling scheme to find the minimum required sampling interval during a storm that would be necessary to obtain realistic pollutant loadings for TMDLs. They found that the optimum sampling interval was dependent on the parameter measured and the stream order. Persson et al. (1999) developed and demonstrated a passive in-situ sampler for metals in stormwater runoff. The results indicated that the metals concentration in the passive sampler corresponded to the bioavailable fraction of the metals in the runoff. They also found that in-situ deployment of the passive sampler with direct analysis of the water by laser ablation-ICP/MS provided better accuracy than traditional bottle sampling, either a grab or a composite sample.

Instream water quality monitoring assessed CSO in the Rouge River, Mich. (Hufnagel et al., 1998). The primary CSO impacts on the river were bacteria and oxygen demand while solids and nutrients were not identified as a limitation of river viability.

A field program sampled conventional parameters, i.e., bacteria, trace metals and organic compounds, in the water column, sediments, CSO discharges and fish and invertebrate tissues in the Duwamish River and Elliott Bay, Seattle, Wash. (Mickelson, et al., 1998). Because concentrations were too low for conventional sampling methods, semi-permeable membrane devices were used to assess water column organic concentrations and low level mercury sampling techniques were used to estimate mercury concentrations. In order to optimize the design and management of sewer networks and settling tanks, there is a need to determine the settling velocity characteristics of sewage and stormwater solids (Lucas-Aiguier et al., 1998). Several methods to determine the settling velocity characteristics of sewage and stormwater solids were selected and compared and results indicated that there is a need to develop an international test procedure in order to be able to compare the results uniformly.

Chemical transfer from soil to surface runoff was simulated using a gypsum tracer under dry, wet, and water-table conditions. During the dry testing, no tracer was found in the stormwater runoff and tracer concentrations were found to decrease exponentially with time under wet and water-table conditions (Zhang, 1997). Observations of rainstorm and

sprinkling experiments were conducted to demonstrate stormwater runoff generation in colluvial soils is through near-surface bedrock (Montgomery *et al.*, 1997).

### **Biological and Microbiological Testing**

McDonald *et al.* (2006) identified sources of fecal contamination with targeted sampling and bacterial source tracking using inexpensive methods. The study combination was able to identify sources quickly, easily and cheaply. Nakajima *et al.* (2006) examined the transfer of hydrophobic contaminants to benthic organisms using an *in vitro* bioaccessibility test. The methodology was viable for assessing exposed contaminants compared to traditional methods.

Stormwater runoff samples from three New York watersheds were analyzed for *Cryptosporidium* genotypes by molecular techniques (Jiang *et al.* 2005). These results were compared to traditional analytical methods for *Cryptosporidium*, with the conclusions being that the molecular methods complement well the traditional methods of filtering and that the molecular methods are able to identify the source of several of the genotypes. The genetic markers for bacterial pollution were assessed for usefulness in evaluating the quality of Lake Michigan (Bower *et al.* (2005). These markers, which do not require culturing for detection, were found for several days after a sewer overflow event and up to 2 km offshore. Fuhrman *et al.* (2005) demonstrated a rapid method for the detection of enteroviruses in natural waters draining to Santa Monica Bay, California. The method, real-time filtration-quantitative reverse transcriptase PCR, was rapid, sensitive and cost efficient for measuring enteroviruses directly, rather than relying on surrogate indicators.

Pathogen indication using surrogate indicators such as particle size distributions in lakes and reservoirs was investigated in South Australia by Brookes *et al.* (2005). The differing settling rates of particles versus the surrogates made the surrogates of limited value for most pathogens.

Jin *et al.* (2004) compared the use of *E. coli*, enterococci and fecal coliforms to indicate the microbiological water quality of brackish water in Lake Pontchartrain. Attachment of microbial indicators to suspended matter and subsequent sedimentation appeared to be a significant fate mechanism and bottom sediment appeared to act as a reservoir for these indicator organisms. Enterococci appeared to be a more stable indicator than *E. coli* or fecal coliforms.

Noble *et al.* (2004) compared three methods of bacterial indicator analysis – membrane filtration, multiple tube fermentation, and chromogenic substrate – for measuring contamination of beach water. There was more than 90% agreement between three methods as to whether the State of California Beach Water Quality Standards were met or exceeded.

Choi *et al.* (2003) applied enterococci antibiotic resistance patterns to identify contamination sources at Huntington Beach, CA. When enterococci isolated from the seawater were classified using the known ARP database, it was evident that bird feces were the source of surf zone contamination on some days while the coastal salt marsh and sewage plumes may have impacted the surf zone water quality to various degrees during other times. Baumstark-Khan *et al.* (2003) used the Bacterial Lux-Fluoro test (a combination of two bioassays that simultaneously measure the genotoxicity (SOS-Lux test) and the cytotoxicity (LAC-Fluoro test)) to identify polluted water from samples of rural and urban sources and collected in the Punjab rivers' basin. Nieman and Brion (2003) used a novel bacterial ratio to predict fecal age. The ratio of atypical colonies to total coliforms (AC/TC) ratio was confirmed in the analysis of two years of Kentucky River water quality data where the average AC/TC ratio during months with high river flow (rain) was 3.37 and rose to an average of 27.58 during months with low flow. The average AC/TC ratio during high flow months compared to raw human sewage (3.9).

Rangarajan *et al.* (2002) reviewed a methodology for pathogen TMDL development for water bodies closed to shellfish harvesting in New York State. The study objectives included: • identification of water quality target(s) for pathogens based on the designated use of shellfish harvesting; • assessment of point and non-point sources of pollution that contribute pathogen load to the waterbody; • establishment of linkage between water quality target(s) and sources, thereby, the baseline scenario of pollution loading from point and non-point sources, and; • development of load allocations and implementation plans to achieve water quality target(s).

Ibekwe *et al.* (2002) used multiplex fluorogenic real-time PCR for detecting and quantifying *Escherichia coli* O157:H7. A direct correlation was determined between the fluorescence threshold cycle ( $C_T$ ) and the starting quantity of *E. coli* O157:H7 DNA. A similar correlation was observed between the  $C_T$  and number of CFU per milliliter used in the PCR assay. These results indicate that the developed PCR assay is suitable for quantitative determination of *E. coli* O157:H7 in

environmental samples and represents a considerable advancement in pathogen quantification in different ecosystems.

Chang and Hsieh (2002) compared the Colitag™ Method and the Standard Methods for the detection of fecal coliforms and *Escherichia coli* in urban creeks in Berkeley, California. The Colitag™ method was found to be as sensitive as the Standard Methods for detecting fecal coliforms; statistical analysis of parallel test results showed a strong linear correlation of 0.87 between the two methods, a relationship that held up well at both high and low fecal coliform counts. In addition, the Colitag™ method gave rapid and specific enumeration of *E. coli* and takes only 24 hours compared to up to 96 hours for the Standard Methods. Saving three days means that monitoring agencies could respond faster to sudden increases in *E. coli* and could therefore take immediate corrective action to ensure public safety.

Elevated bacteria levels indicated significant impairment to surface water quality in many urban areas within the Great Lakes watershed (Murray et al., 2001a). CSO outfalls were assumed to be the major source of bacteria to streams in many of these urban areas, including the Rouge River of southeastern Michigan. The data depicted a strong influence of upstream water and rural runoff on the water quality of the Rouge River, and FC to FS ratios suggested the primary source of bacteria throughout the watershed was from domesticated animals and wildlife and not from CSOs. Sources of the indicator bacteria total coliform, fecal coliform, and enterococcus were investigated in stormwater flows discharging to Mission Bay in San Diego, California (Schiff and Kinney 2001). Stormwater flows were targeted because long-term monitoring had indicated that wet weather discharges were the predominant source of bacterial contamination. Upstream tracking during multiple storm events on two watersheds showed that bacterial sources were diffuse and widespread. Two case studies were used to demonstrate how WERF's ecological risk assessment methods, Aquatic Ecological Risk Assessment: A Multi-Tiered Approach, could be used to improve the ecological- and cost-effectiveness of water quality management (WERF 2001b). The two cases (Salado Creek in the City of San Antonio, Texas, and the Jordan River in Utah) were explored in detail, including direct and indirect effects of changes in flow on fish and invertebrate aquatic life.

Quintero-Betancourt and Rose (2000) investigated the potential use of stormwater and/or reclaimed water to rehydrate wetlands in St. Petersburg, Florida. The adequacy of using these waters was assessed through microbial water quality testing using bacterial indicators, coliphages, *Cryptosporidium* and *Giardia*. Long et al. (2000) evaluated the potential of using three alternative (compared to traditional coliform testing) source-specific indicator organisms for determining the human health risks associated with a water source and for determining if the source of the bacterial contamination was human or grazing animal. These alternative organisms were sorbitol-fermenting *Bifidobacteria*, *Rhodococcus coprophilus*, and serogroups of F+ coliphages), and they were found to correlate well with predictions of land use contributions to a receiving water. Rex (2000) reported on the impacts of changing from coliforms to *enterococcus* as the indicator organism of water quality. The paper advocated that more studies need to be done to improve the understanding of *enterococcus* behavior during treatment so that its use can provide information about the quality of CSO control. Brion and Mao (2000) researched the use of atypical colonies found in the total coliform test as a part of watershed monitoring. The ratio of atypical colonies to coliphage concentrations correlated well with the degree of known fecal pollution. Meek et al. (2000) advocated the use of shellfish as indicators of bacterial pollution of water. When compared to coliforms, the shellfish gave a better representation of the pollution levels and the changes over time of bacterial concentrations in the water. An evaluation of the naturally-forming algal community in stormwater detention ponds by Olding (2000) showed that this algal community could be used to demonstrate the effectiveness of the detention pond as a treatment device. The taxonomic breakdown of the community also indirectly showed the pond influent water quality.

Myrmel et al. (1999) presented their work on using adsorptive filtration and PCR to detect small round-structured viruses in water and wastewater. The method detected virus concentrations of 0.5 – 5 virus particles per milliliter in a 500-mL sample. Abbaszadegan et al. (1999) compared PCR to cell culture testing for the detection of viruses in groundwater. They found that, with the improved sample-processing technique and large-volume amplification protocol, the PCR test was a rapid and effective tool for screening water for enteroviruses, hepatitis A virus, and rotavirus. Betts (1999) reported on the evaluation of “DNA chip” technology for the rapid, sensitive and inexpensive testing of water for bacteria, parasites and viruses. Zisette et al. (1999) used a genetic fingerprinting technique to assist in identifying source of microbial contamination to Drayton Harbor Watershed, Washington. The results from the bacterial tests were then to be used to determine which sources (municipal sewage discharge, failing septic systems, animal management practices, seafood processor discharges, and people who live aboard houseboats at the marina) were causing the shutdown of the oyster and shellfish harvest areas. Clancy and Hansen (1999) discussed the lack of use of protozoan monitoring data in public health decision-making. They found in their survey that the primary reason cited by water companies was unreliable data. However, the protozoan data has been used successfully in conjunction with other water quality results to assess treatment efficiency and support investment planning.

Matlock et al. (1999) used the Matlock Periphytometer to measure nutrient limitations and trophic status in situ in the Bosque River Watershed in Texas. The data was used to develop a lotic ecosystem trophic status index (LETSI), and through the use of LETSI, differences in nutrient limitations in tested streams were detected, including two streams which were co-limited by nitrogen and phosphorus. Toetz et al. (1999) related annual phosphorus loadings from eight subbasins in the Illinois River impacted by NPS runoff to the alkaline phosphatase activity (APA) in the water. The correlation between APA and soluble reactive phosphorus and between APA and the annual predicted phosphorus loading by the SIMPLE model allowed the researchers to demonstrate which of the eight subbasins did not require pollution abatement and were not in jeopardy of becoming eutrophied.

Fry (1999) measured the concentration of stable C and N isotopes in the clam *Potamocorbula amurensis* in San Francisco Bay. He determined that the carbon isotope concentrations in the clam correlated to the amount of riverine, freshwater, input into the Bay while the nitrogen isotope concentrations could be correlated to the watershed nutrient loadings due to human activity.

The cost and efficiency of different techniques for processing rapid-assessment samples of macroinvertebrates were evaluated by comparing the ability of data generated by each technique to discriminate between unpolluted reference sites and sites with mild to severe pollution from municipal effluent and urban stormwater runoff (Growth et al., 1997). Of three metrics tested, SIGNAL had the most highly significant differences between reference and polluted sites and was the most robust to variations in processing method.

## **Surface-Water Impacts**

### ***General***

Schoonover et al. (2006) investigated the impacts of land cover on stream hydrology in the western Georgia Piedmont region. Rating curves between stream stage (i.e., water depth) and discharge were developed for each stream and the dependent variables were calculated from discharge data and categorized into four groups: flow frequency, flow magnitude, flow duration, and flow predictability and flashiness. Water quality in streams receiving urban runoff in Zhejiang China showed tremendous spatial variability and variability in maximum pollutant concentrations (Chen et al. 2006b). Matteo et al. (2006) studied the impacts of forest buffers on water quality and runoff in urbanizing areas. Forest runoff controls made the studied watershed more adaptive to handling adverse conditions, such as large storms, nonpoint source pollution, flooding and high winds.

Claessens et al. (2006) examined the effects of historical changes in land use and climate on the water budget of an urbanizing watershed in Massachusetts. White and Greer (2006) examined the effects of watershed urbanization on the stream hydrology and riparian vegetation of a creek in southern California. Watershed urbanization in coastal Southern California could significantly modify the character and integrity of stream and riparian ecosystems, which will have significant implications for their conservation. Qi and Luo (2006) presented the impacts of land-use change in an arid region of northwestern China. The results showed that land-use change had significant impacts, including runoff quantity and quality changes, groundwater table declines, degeneration of surface and groundwater quality, land desertification and salinization, and degradation of vegetation.

Robson et al. (2006) examined the stream quality in a small urbanized catchment. Variations in the general quality assessment parameters indicated a significant drop in quality downstream of the stormwater outfalls, with a marked drop in biological diversity noted at the onset of urbanization. The decline in biological quality, however, was greater than that suggested by physicochemical analysis alone.

Weyand and Schitthelm (2006) addressed the question of whether good ecological status can be achieved on a heavily-urbanized river. Their survey focused on the elaboration of an inventory, the identification of potentially attainable ecological objectives, and the discussion of measures with regard to their benefits and feasibility. The downstream economic benefits of conservation development were highlighted by Johnston et al. (2006). Modeling showed that the conservation design provided the same benefits but at a much lower cost, compared to conventional development.

Wilson (2005) performed a comprehensive watershed assessment in an urbanizing area near Lincoln, Nebraska. Factors

assessed included hydrology, geomorphology and water quality. The results were incorporated into models that were incorporated in the final watershed plan. Porto et al. (2005) evaluated the water quality impacts in a small watershed in the Sao Paulo (Brazil) metropolitan area. The results of the modeling showed the different impacts of point and nonpoint sources in the water quality of the river.

Verbunt et al. (2005) investigated the hydrologic impact of land-cover changes and hydropower stations in a Swiss Alpine Rhine Basin. Urbanization was shown through modeling to have a significant impact on local flood events, but its impact was negligible further downstream. Wang et al. (2005b) investigated the long-term impacts of land-use change on nonpoint source loads in the St. Louis (Missouri) metropolitan area. Modeling demonstrated minimal increases in total nitrogen even through three development scenarios. Similar results were seen for total soluble phosphorus and total phosphorus.

Baker et al. (2004) presented Phoenix, Arizona, as an example of the need for sustainability in rapidly growing urban ecosystems. Salt and nitrogen compounds have accumulated in the soils in urban areas, making the ecosystem vulnerable to disturbances such as severe droughts. Accelerated urbanization in the settlements of the Mزاب Valley (Algeria) has caused perturbations in the environmental hydrology, in conjunction with increased pollution and thermal discomfort (Bouchair 2004). The authors try to show the need to balance growth with the traditional methods of maintaining ecosystem balance.

Burian et al. (2004) review the impacts of urbanization on Houston (Texas) rainstorms. Major cities such as Houston appear to be modifying the convective activity in mesoscale circulation patterns, which results in modified rainstorm characteristics. Sources may include urban heat islands, drag effects of the built-up surface, and modified microphysical and dynamic processes from urban activities such as transportation.

Space-borne synthetic aperture radar (SAR) imagery was used to delineate coastal pollution hazards, such as stormwater and wastewater plumes and natural hydrocarbon seeps, in the Southern California Bight (DiGiacomo et al. 2004). The hazards are detectable because of the surfactants that they deposit on the surface, which produce areas of reduced backscatter on the images. Changes in hydrological data may indicate human-induced problems and need to be examined (Kundzewicz 2004). This is critical when designing urban water structures, which are designed based on static hydrology assumptions.

The impact of proposed Southern California developments on stormwater runoff was evaluated by Pitt and Jacobsen (2004) using PCSWMM. PCSWMM was used to predict EMCs and other runoff values. PCSWMM coefficients such as build-up rates were initially determined from literature sources, including SWMM guidance documents, HSPF, and LA and SD monitoring reports.

Capodaglio et al. (2003) studied the methods for estimating the diffuse pollution loads due to future urbanization in Mantua's Lake (Italy) and its impacts on future water quality.

The impact of three demographic and cultural trends - global urbanization, "quality of life" emphasis, and a move towards flexible management - on technology and the regulatory system was discussed by Ruta (2000), especially given the fact that many thousands of U.S. waterbodies still do not meet water quality standards. One example of the watershed-view of impacts was the Urban Pollution Management (UPM) procedure described by Artina and Maglionico (2000). This procedure was developed in England to evaluate the impact on receiving waters of pollutants discharged from sewer overflows during rainfall events. Garland and Pfeffer (2000) proposed using a watershed-based approach to evaluate the impacts of runoff from contaminated sites at the Oak Ridge DOE Reservation and for determining the optimum location and type of pollution control measures. They documented that pollutants released from the contaminated sites typically are transported to the Clinch River through subsurface shallow flow to surface waters where, if they bind well to sediments, they accumulate in aquatic sediments. Otherwise, they are transported off-site via the Clinch River.

Bertrand-Krajewski et al. (2000) reviewed their Experimental Observatory for Urban Hydrology project that demonstrated the need for improved knowledge about the interactions between urbanization, pollutant discharges, impacts on the natural environment, and socio-economics. The aim of the project will be to improve methodologies for investigating the sustainability of urban water systems. Collins et al. (2000) reviewed the USEPA's Clean Water Compliance Watch (CW2) Environmental Monitoring for Public Access and Community Tracking (EMPACT) project. EMPACT projects use state-of-the-art technology to track environmental conditions and to provide easy public access to

information in easily-understood language.

Fernando et al. (2000) presented the development of effectiveness indicators (“a measurable feature that provides managerially and scientifically useful evidence of stormwater and ecosystem quality or reliable evidence of trends in stormwater quality and program effectiveness”) for stormwater and watershed management programs and the development of a regional monitoring program for the Hampton Roads Planning District Commission (Virginia). As reported by Schaad and Kam (2000), the City of Kelowna completed a State of the Environment Report which examined air, land and water quality. Thirteen of the twenty-two indicators directly addressed watershed health. These indicators were designed to show current watershed health and future trends. Cloak (2000) described the implementation of twenty of the Center for Watershed Protection’s Environmental Indicators to Assess Stormwater Programs and Practice, and showed that the indicators were most useful when organized into a framework that could be used to inform stakeholders and the public. The investigation (Cloak et al. 2000) separated the indicators into two groups: The first group, the programmatic indicators targeted at measuring specific program activities, was useful for documenting and understanding pollution-prevention efforts. The second group of indicators (application of physical, water-quality, and biological measurements at a watershed scale) were useful for an overall assessment of stream function and an understanding of the natural and anthropogenic factors influencing those functions.

Albert and Limbeck (2000) reported on the effects of urbanization on storm water quality in five New Jersey watersheds. The report reviewed the water quality, instream habitat, benthic macroinvertebrates, and stream channel changes due to urban runoff. The work also examined various assessment methods to determine which of these methods could be used to develop non-point source or stormwater related goals and objectives.

McMahon and Cuffney (1999) described the U.S. Geological Survey’s National Water Quality Assessment (NAWQA) Program which was intended to study the relationship between varying levels of urban landuse development in drainage basins and in-stream water quality, as measured by physical, chemical, and biological indicators. These studies were being conducted near Boston (Massachusetts), Salt Lake City (Utah), and Birmingham (Alabama), where rapid urbanization was occurring.

David et al. (1999) performed a study to determine the response of stream water dissolved organic carbon (DOC) and organic acidity to increased inputs of ammonium sulfate to a whole catchment. Several mechanisms exist, including evaporative concentration, vapor-liquid phase partitioning, lowered washout volumes of atmospheric deposition water, and dry deposition, which may lead to elevated concentrations of trifluoroacetic acid (TFA) in atmosphere and surface waters above levels expected from usual rainfall washout (Wujik et al., 1999). Correll et al. (1999) reported on a study to determine the relationships between precipitation at the seasonal and annual scale and water discharge per surface area for seven contiguous first and second-order tributaries of the Rhode River, a small tidal tributary to the Chesapeake Bay, Maryland.

Consistently, N and P concentrations increased as the proportion of land area used for dairy waste application fields. The proportion of total P (TP) in runoff represented by soluble reactive P (SRP) also increased as the percent of dairy waste application fields above a sampling site increased; stormwater runoff of nutrients from dairy waste application fields was indicated as the predominant source of NPS nutrients impacting surface water quality in the upper North Bosque River (UNBR) watershed (McFarland et al., 1999). Mason et al. (1999a) reported that the chemistry of a first-order stream in Amherst, Maine with a catchment area of 103 ha has been strongly altered as a result of road salt application at a rate of approximately 4 t of NaCl per year in the lower 15% of the catchment.

Pesticide compounds, relative to the landuse composition of the basin, were detected in all 50 water samples collected from streams in New Jersey and Long Island, New York, during June 9-18, 1997. Physical and chemical properties as well as application rates of the pesticides studied affect their detection frequencies. Although all pesticide concentrations were within both EPA and State maximum contaminant levels (MCL) and health advisory levels (HAL), these criteria apply only to individual compounds, and more than one compound was detected in 49 of the 50 samples collected (Reiser and O’Brien, 1999). Watershed properties such as peatland area have considerable promise as predictors for estimating total mercury (THg) transport in streams draining forested watersheds in the Great Lakes States (Kolka et al., 1999). Sixteen largely agricultural watersheds in the upper portion of the North Bosque River of central Texas were reported by McFarland and Hauck (1999). The proportion of total P (TP) in runoff represented by soluble reactive P (SRP) also increased as the percent of dairy waste application fields above a sampling site increased.



Approximately 1,100 communities in the United States have combined sewer and stormwater systems whose capacity may be exceeded during moderate or heavy rainfall. Outflows may occur that can deposit water with varying concentrations of the components of sewage onto public areas, potentially resulting in a range of adverse health effects (Colford et al., 1999). Seasonal and event variations in stream channel area and the contributions of channel precipitation to stream flow were studied on a 106-ha forested headwater catchment in central Pennsylvania. Variations in stream velocity, flowing stream surface width and widths of near-stream saturated areas were periodically monitored at 61 channel transects over a two-year period (Crayosky et al., 1999). Johnson et al. (1999) presented information that suggest non-stormwater source, such as on-site sewage systems and illicit discharges, were major contributors to the contamination of the Rouge River in Wayne County, Michigan.

Weber (1998) reviewed the improvements of water quality of the Greater Cleveland, Ohio area over the past century to the present. In a study of the Ho Chi Minh City of Viet Nam (Phuong et al., 1998) found that the aquatic urban ecosystem is strongly influenced by long-term discharge of untreated domestic and industrial wastewaters, stormwater runoff, accidental spills and direct solid waste dumping.

A study of 22 streams in the Puget Sound Lowland ecoregion in Wash. demonstrated that the physical, chemical and biological characteristics of streams change with increasing urbanization in a continuous rather than threshold fashion (May, 1998). Urbanization history and flood frequencies of four low-order stream basins that underwent significant urbanization and two other control basins that did not were monitored in the Puget Lowlands between the 1940/50s and 1980/90s. Flood frequencies increased in the urbanized basins and salmon populations decreased while similar results were not documented in the control basins (Moscrip and Montgomery, 1997).

Booth and Jackson (1997) concluded that established methods of mitigating the downstream impacts of urban development may have limited effectiveness. Using continuous hydrologic modeling, detention ponds designed by conventional event methodologies were evaluated and deficiencies in actual pond performance were demonstrated when compared to their design goals. Novotny and Witte (1997) presented a methodology to calculate risk of wet-weather discharges to aquatic ecology (aquatic life). It can be used for ranking pollutants in wet-weather discharges as well for ranking the discharges themselves. The U.S. Environmental Protection Agency (U.S. EPA) (1997a) examined the published literature which revealed that hydrologic impacts on streams were caused by increased impervious areas in urban developments.

*Water Environ. & Technol.* (1996a) reported that the latest National Water Quality Inventory released by the EPA only showed a slight improvement in the attainment of beneficial uses in the nation's waters. Urban storm runoff was cited as the leading source of problems in estuaries, with nutrients and bacteria being the major problems. Problems in rivers and lakes were mostly caused by agricultural runoff, with urban storm runoff the third ranked source for lakes, and the fourth ranked source for rivers. Bacteria, siltation, and nutrients were the leading problems in the nation's rivers and lakes. Borchardt and Sperling (1996) stressed that many conditions may affect receiving waters from stormwater, specifically physical factors (such as shear stress) and chemical factors (such as oxygen depletion and/or nonionized ammonia).

### ***Temperature and Dissolved Oxygen***

The environmental impacts (surface temperature, rainfall runoff, and greenspace diversity) of urban land use and land cover change in the United Kingdom were modeled by Pauleit et al. (2005). The results showed negative environmental impacts for all land uses. Norton and Bradford (2005) used in-stream temperature modeling, in coordination with a hydrologic watershed model, to predict the effects of stormwater management practices on a river in southern Ontario (Canada). The evaluated management practices included increased riparian vegetation, increased flows from an upstream reservoir, removal of in-stream impoundments and decreased stream width. Compos (2005) reviewed the impact of rerouting a major highway underground on the existing drainage system and associated receiving water quality. The author stated that the re-routing should be beneficial because the drainage system could be improved and sewage water could be diluted, which would reduce oxygen demand.

Picksley and Deletic (1999) studied the thermal behavior of storm runoff from paved surfaces at two different urban catchments. The thermal trends were explained by equilibrium of thermal influences, based on the physical interaction of runoff and paved surfaces.

The impact to receiving water dissolved oxygen (DO) concentration of intermittent CSO and overflows from a treatment plant were investigated. Data from the River Maun, U.K. showed that an immediate, transient oxygen demand exists

downstream of an outfall followed by a separate, delayed oxygen demand (Jubb et al., 1998). The NYC Department of Environmental Protection (DEP) analyzed the feasibility of supplemental aeration in conjunction with a proposed CSO pollution control facility at the Paerdegat Basin, Brooklyn, N.Y. (Gaffoglio et al., 1998a). Aeration as a supplement to conventional CSO controls would address DO concerns, however, the continued discharge of solids during WWF would result in an increased sediment oxygen demand of the basin.

The Harrestrup river in Copenhagen, Den was subject to intensive online investigation of oxygen during both dry and wet weather (Harremoes *et al.*, 1997). An evaluation of oxygen fluctuations demonstrated noncompliance of oxygen standards both during dry and wet weather.

### ***Erosion, Channel Stability, and Sediment***

Nelson et al. (2006) reviewed the evolution of channel morphology and hydrologic response in an urbanizing basin in Maryland. The stability of this channel's platform was linked to geological controls of the channel and floodplain morphology.

Lawler et al. (2006b) examined the turbidity dynamics during spring storm runoff events in the United Kingdom. Six important and unusual features of the storm event turbidity response were apparent: (1) sluggish early turbidity response, followed by a 'rush'; (2) quasi-coincident flow and turbidity peaks; (3) recession-limb turbidity extensions; (4) increases in peak turbidity levels through storm sequences; (5) initial micro-pulses in turbidity; and (6) secondary turbidity peaks or 'turbidity shoulders'. Also in England, Old et al. (2006) examined the river flow and associated transport of sediments and pollutants through a highly urbanized catchment. The knowledge was applied to managing and monitoring downstream rivers in mixed-land-use catchments.

Roy et al. (2006) reviewed the importance of riparian forests in urban catchments on sediment transport and hydrology. The results showed that, at a minimum, catchment management strategies must simultaneously address hydrologic, sediment and riparian disturbances and their interactions.

Tetzlaff et al. (2005) used hydrological criteria to assess changes in the flow dynamic in urbanized catchments. Flow acceleration, peak discharge and discharge dosage were studied. Miller and Boulton et al. (2005) investigated the impact of urbanization and the associated hydrology and channel morphology on fundamental ecosystem processes such as leaf litter decomposition and transport, which is a crucial part of restoring urban watersheds and streams.

Prakash (2005) investigated the impact of watershed urbanization on stream stability and flooding. The paper compared surface runoff hydrographs, sediment yields and patterns of aggradation/degradation of the stream before and after a portion of the watershed had been urbanized with and without detention basins. Moses and Lower (2005) reviewed the natural stream channel design approach during modifications to natural watercourses. This approach developed using fluvial geomorphological principles. Yeager et al. (2005) discussed urbanization-induced stream erosion in southern California. The variability in stream response to urbanization was assessed.

The effect of urban development on interannual streamflow patterns in the Puget Lowland (Washington) was investigated by Konrad et al. (2005). Streams draining urban areas are typically wider and the size of the bed material increases, likely due to the brief duration of frequent high flows.

Shakoor and Smithmyer (2005) analyzed storm-induced landslides in colluvial soils overlying mudrock in southeastern Ohio. These landslides had affected an interstate and caused millions in property damage. The shallow landslides along the interstate occurred when the colluvial soils reached 90% to 100% saturation, depending on the slope angles.

Kepner et al. (2004) used GIS-hydrologic models to present baseline conditions (year 2000) in the San Pedro River and to model expected impacts on habitat, visual quality, sediment generation, and groundwater twenty years in the future. Previously-defined future scenarios were examined relative to their impact on surface runoff and sediment yield. Kokkonen et al. (2004) studied the relationship between effective rainfall and streamflow, which in turns drives the amount of energy in the channel. Wissman et al. (2004) evaluated the impacts of changing forest and impervious land cover on the hydrologic regimes of watersheds in the Cedar River near Seattle (Washington). Flood-frequency curves indicated that discharge rates for all watersheds were currently higher compared to historical conditions because of changing land covers. The largest increases in discharge rates were in urban watersheds, with rates for 2-year, 10-year,

and 25-year recurrence intervals being more than two times greater than the rate during historical conditions.

The hydrological characteristics of the Pearl River Delta (South China) have been greatly impacted by urbanization (Chen and Chen 2004) due to sand dredging in the river, reclamation of floodplains, and construction of dikes, bridges, dams, etc. Riverbed degradation, including a 2-m drop in stage at the same flow, has been noted. Stream erosion and instability has been identified as one of several stressors to streams in the Upper Cape Fear River Basin (North Carolina) (Doll et al. 2004). Models such as HEC-HMS and HEC-RAS could be used to evaluate channel velocity and specific stream power, and the results have been used to determine which subwatersheds to target.

Interrill runoff and erosion from composted organics applied to highway embankments was studied by Persyn et al. (2004). All compost treatments were effective at reducing interrill erosion rates and delaying the start of runoff under these study conditions.

Campisano et al. (2004) evaluated the scouring effects of flushing waves on sediment deposits in urban drainage networks through experimental and modeling techniques. The model was based on the semi-coupled solution of the complete De Saint Venant equations for the water flow and of the Exner equation for the sediment continuity.

Chebbo et al. (2003) reviewed the current state of knowledge about the solids at the sediment water interface in combined sewer networks. The literature showed that the solids were primarily organic with a high polluting potential. Eyles et al. (2003) investigated the impacts of urbanization on the geophysical and sedimentological characteristics in a Lake Ontario watershed. The urban-impacted watershed empties into the shallow, semi-enclosed coastal lagoon of Frenchman's Bay, which served as a trap for fine-grained contaminated sediment. Blazier et al. (2003) investigated particle agglomeration in runoff and treatment processes, including the effects of pH, ionic strength and Camp and Stein's velocity gradient. Agglomeration rates increased with lower pH and were optimized when mixing rates were set to avoid particle sedimentation and to avoid fluid shears.

Rose and Peters (2001) reported an investigation that examined streamflow characteristics that changed during the period from 1958 to 1996, in a highly urbanized watershed (Peachtree Creek) compared to less-urbanized watersheds and non-urbanized watersheds, in the vicinity of Atlanta, GA. Data were obtained from seven US Geological Survey stream gauges, 17 National Weather Service rain gauges, and five USGS monitoring wells. The fraction of the rainfall occurring as runoff in the urban watershed was not significantly greater than for the less-urbanized watersheds, but this ratio did decrease from the higher elevation and higher relief watersheds to the lower elevation and lower relief watersheds. For the 25 largest stormflows, the peak flows for the urban creek were 30% to 100% greater than the peak flows in the streams located in the less developed areas. The streamflow also decreased more rapidly after storms in the urban stream than for the other streams. The low flow in the urban creek was from 25 to 35% less than for the less developed streams, likely caused by decreased infiltration due to the more efficient routing of stormwater and the paving of groundwater recharge areas.

Weng (2001) describes how GIS was used in conjunction with distributed hydrological modeling. GIS was able to document the changing spatial patterns of urban growth in the Zhujiang Delta of southern China. Extensive urban growth over the past two decades has created severe problems in water resources management, indicated by an increase in annual runoff depth during the 1989-1997 period. The urbanization lowered potential maximum storage, and increased runoff.

An emerging concept in channel design uses sediment transport as the basis for quantifying channel stability. Byars and Kelly (2001) examined channel stability in the Austin, TX, area. They concluded that a channel that is not undergoing excessive erosion or sedimentation has a function and form similar to a natural stream and should be the goal of good channel design. This approach, however, requires a more comprehensive understanding of the local climate, geology, hydrology, and stream mechanics than historically utilized.

Hunt and Grow (2001) describe a field study conducted to determine the qualitative and quantitative impact to a stream from a poorly controlled construction site. They used fish electroshocking, Qualitative Habitat Evaluation Index, and zigzag pebble count studies. The 33 acre construction site consisted of severely eroded silt and clay loam subsoil and was located within the Turkey Creek drainage, Scioto County, OH. The number of fish species declined (26 to 19) and the number of fish found (525 to 230) decreased significantly when comparing upstream unimpacted reaches to areas below the heavily eroding site. The Index of Biotic Integrity and the Modified Index of Well-Being, common fisheries indexes for stream quality, were therefore reduced from 46 to 32 and 8.3 to 6.3, respectively. Upstream of the area of impact, Turkey Creek had the highest water quality designation available (Exceptional Warm Water Habitat); but fell to the

lowest water quality designation (Limited Resource Water) in the area of the construction activity. Water quality chemical analyses conducted on samples from upstream and downstream sites verified that these impacts were not from chemical affects alone.

Morrisey et al. (2000) described the sampling program used to confirm a predictive model of metal contaminant build-up (Cu, Pb, and Zn) in the sediments of sheltered urban estuaries in Auckland, New Zealand that have been subjected to urban runoff inflows. The results of their testing showed good general agreement between the model predictions and the observed concentrations of metals in the sediments. The paper by Butcher et al. (2000) described the problems encountered when developing mercury TMDLs for the Arivaca and Pena Blanca Lakes in Arizona. These two lakes lacked point-source discharges of mercury; however, the concentrations of mercury in fish bodies were sufficiently high to trigger TMDL development. The resultant TMDL addressed the problems inherent with controlling pollutants entering the lake when the lake sediment was found to be a primary source of the pollutant. Rate et al. (2000) investigated the concentration of heavy metals in sediments of the Swan River estuary in Perth, Australia. They found that the concentration of lead was elevated near stormwater drain outfalls when compared to areas away from the outfalls, likely due to vehicular material; no similar effect was seen for copper or cadmium. They also noted that since the vast majority of all heavy metals were bound to iron oxides or organic sediments, most of the metals are not bioavailable. The results of the study performed by Rochfort et al. (2000) on the effects of stormwater and CSO discharges on the benthic community showed that the levels of metals and PAHs in sediments below these discharges were high. However, biological effects were not seen - neither the toxicity endpoints nor the benthic community descriptors could be related to the sediment contaminant levels.

Ghani et al. (1999) found that the thickness of a sediment deposit on the bottom of a rigid rectangular channel greatly affects its erodibility of the deposits. They developed channel erosion equations that included terms for the deposit's thickness. Keshavarzy and Ball (1999) studied the entrainment of sediment particles in water and found that the number of entrained particles per unit time per unit area was found to be related to the instantaneous shear stress at the bed. These results were used to modify the Shields diagram. Ashley et al. (1999) investigated the integration of sewer solids' biodegradability into the existing UK waterway protection standards for solids erosion in sewers. This integrated standard would then be used to define the DO criteria in streams and to determine the allowable solids discharge. Rhoads and Cahill (1999) studied the elevated concentrations of chromium, copper, lead, nickel and zinc that were found in sediments near storm sewer outfalls. They noted that copper and zinc concentrations were greater in the bedload compared to the bed material and therefore were more likely to be mobilized during runoff events.

Anecdotal information regarding the impacts of changes in flow on receiving streams were collected, however, not all of it provided conclusive evidence as to the relationship between urbanization and flow-related stream impairment (Frederick and Corrigan, 1998).

Stormwater impacts to streams are not limited to the relatively short duration of runoff events. As an example, sediments can dominate the aquatic physiochemical and biological processing of nutrients; sediment contaminated by stormwater pollutants has a detrimental effect on the receiving-water-biological community. The EPA and other regulatory agencies are attempting to develop sediment quality criteria to determine where excessive concentrations of chemical constituents are present in sediments at sufficient concentrations and in chemical forms to be significantly adverse to the designated beneficial uses of the associated water body. Lee and Jones-Lee (1996a) presented the issues that need to be considered in evaluating the results of a sediment quality assessment procedure to determine whether the toxicity or excessive concentration found is a potentially significant cause of real water quality deterioration in the water body of concern. Maurer *et al.* (1996) analyzed sediment samples collected from five stations in the Newport Submarine Canyon, CA and six nominal 60-m shelf stations to test the following two hypotheses: (1) there is no increase in sediment contaminant concentration with water depth in the Canyon; and (2) there is no difference in contaminant concentration between the canyon and adjacent shelf. The data collected supported hypothesis one and rejected hypothesis two.

### ***Biological Impacts***

This section addresses issues of bioavailability of pollutants, and the impact of pollutants, and sources, where known, on the health of aquatic organisms.

Ellison and Brett (2006) studied the bioavailability of particulate phosphorus as a function of stream flow and land cover. The results showed that only 20% of the particulate phosphorus transported during storm events was immediately

bioavailable. Custer et al. (2006b) examined the contaminant exposure of barn swallows nesting in an estuary with urban influences in Louisiana and were compared to the same measures at a reference site. Pollutant concentrations in eggs and nestlings were at background levels and DNA damage was not observed. Custer et al. (2006a) determined the presence of stressors in streams receiving urban and agricultural runoff using a benthic in-situ toxicity identification evaluation bioassay (BiTIE). The BiTIE method appeared useful for discerning stressors using indigenous species in-situ.

Rossi et al. (2006) reviewed water quality criteria for total suspended solids in urban runoff discharges. The criteria proposed in this study cover the short-term impact of TSS on fish (acute quality criteria AQC), taking into account the duration of their exposure in the receiving water. Pergent et al. (2006) examined the variability of *Ruppia cirrhosa* in two coastal lagoons off France that received urban runoff and other flows. Linbo et al. (2006) investigated cell death in the peripheral mechanosensory system of larval fish due to dissolved copper. Copper has the ability to interfere with mechanosensory behaviors that are important for migration and survival of fish.

Dalto et al. (2006) investigated the impacts of metal concentrations and organic enrichment on muddy-bottom meiofauna in a lagoon. The density of the meiofauna was positively affected by the quantity of sediment organic matter, but negatively affected by the composition of the organic matter. Metals originating from mining and erosion had no impact, whereas urban metals negatively affected total meiofauna at the beginning of the rainy season. Gresens et al. (2006) investigated the temporal and spatial responses of benthic invertebrates to stormwater runoff of two streams. The abundance of fine particulate organic matter, including periphyton, on cobbles was greater in urban reaches with greater temporal variations than in rural reaches. Stormflow abrasion was found to have important negative effect on the invertebrate community.

Helson et al. (2006) examined the human impacts on a larval chironomid community in four tropical rivers. The most dramatic impacts were seen in the river reaches that were influenced heavily by urban runoff. Mallin et al. (2006) examined the factors contributing to hypoxia in rivers, lakes and streams. Remediation suggestions include reductions in BOD materials derived from urbanization and other land-disturbance activities. Lafont et al. (2006) examined the surface and hyporheic oligochaete assemblages in a French suburban stream receiving CSOs. The water quality was not severely impaired, but the assemblages below the CSO outfall contained mostly pollution-tolerant organisms. The effects of road runoff on the biomass and metabolic activity of periphyton in laboratory streams was investigated by Boisson and Perrodin (2006). The biomass, chlorophyll *a* content and metabolic activity increased after exposure to road runoff, due to the current velocity used in the tests, the runoff exposure duration and the organic and inorganic content of the runoff water. Haus et al. (2006) investigated the occurrence of platinum and other heavy metals from traffic in sediments and biota in aquatic habitats in Germany. Traffic-related heavy metals could be identified in sediment and biota samples as a combination of heavy metals (Pt, Sb, Cd, Pb for sediments and Pt and Sb for crustacean samples).

Metals uptake from stormwater by aquatic plants was investigated by Fritioff and Greger (2006). The results showed that Zn, Cu, Cd, and Pb were taken up by the leaves, stems, and roots, with the highest accumulation found in the roots. Schoonover and Lockaby (2006) investigated the impacts of land cover on stream nutrients and fecal coliforms in a river in West Georgia. The models could be used to forecast water quality changes under various land use scenarios in the developing Piedmont region of the US.

Winger et al. (2005) reviewed the use of both rapid bioassessment protocols and sediment quality triad to assess stream quality. The bioassessment protocol provided insight into contributions associated with physical habitat and the sediment quality triad contributed information on contaminants and sediment quality. The impact of urbanization on the epilithic diatom assemblages were investigated by Newall and Walsh (2005). The study suggested that reducing the amount of directly connected impervious area/piped drainage channels and improving infiltration in the urbanized area could mitigate the effects of urbanization and stream change on the diatom community. Courtenay et al. (2005) examined the use of intertidal rock assemblages as a measure of the impacts of urbanization. In Sydney Harbor, the intertidal assemblages were found to be degraded near zones of urban discharge and were capable of being a useful measure of biological impacts of urban runoff (including sewer overflows).

O'Keefe et al. (2005) investigated the contribution of urban nonpoint sources to the concentrations of fecal indicator organisms in beach surface waters. These results were compared to those from point sources such as municipal sewage effluents and CSOs.

The concentration of dissolved copper, lead and zinc were decreased and the suspended solids concentration was increased in the Provo River (Utah) following storm events in Provo (Gray 2004). Concentration returned to background levels within 12 hours of the end of the event. Urban stream reaches were dominated by pollution tolerant macroinvertebrates and were what would be expected based on the amount of impervious area.

Lewitus et al. (2004) examined the effect of urbanization on lowering bioavailable iron in an estuarine ecosystem in South Carolina. The results indicate that phytoplankton population growth from high salinity salt marsh estuaries can be Fe-limited. Sweeney and Sanudo-Wilhemly (2004) evaluated the potential biological effects of dissolved metal contamination in the East River-Long Island Sound system. Chlorophyll a, an indirect measure of biomass, was lower in the East River and could not be explained by nutrient or light limitation, water column stratification, or other natural controls. Dollar and Grigg (2004) reviewed the decline in Hawaiian coral reefs due to anthropogenic and natural stressors. They found that protection efforts need to be focused in embayments, which have limited circulation and a high recreation value.

Urban stormwater copper affected the mechanosensory structures in developing zebrafish embryos and larvae (Kao and Scholz 2004). These sensory mechanisms affect orientation, schooling, and predator avoidance in salmon and other fish. Sediments contaminated by PAHs in highway runoff were shown to affect grass shrimp (Lee et al. 2004). Lower embryo production and embryo hatching rates and greater DNA strand breaks were observed in the grass shrimp nearest the stormwater outfall.

Common carp exposed to water from the Las Vegas Wash (tertiary treated effluent, nonpotable shallow groundwater and urban runoff) were found by Snyder et al. (2004) to show minor effects of exposure to endocrine disrupting chemicals. However, the differences in various indicators between those exposed to the Wash water and to reference waters was not significant, demonstrating the need for multiple reference sites when evaluating water effects on fish development. Masero and Villate (2004) investigated the composition, vertical distribution and age of zooplankton benthic eggs in sediments from two estuaries of the Bay of Biscay. The density of eggs was reduced by an order of magnitude in the sediments of the estuary with a higher level of urbanization.

McCorquodale et al. (2004a and 2004b) reviewed the fate of pathogens and indicators in stormwater plumes entering a brackish waterbody. Results showed that the fine sediment was a significant transporting medium for the indicator organisms. A forecasting model was developed to predict pathogen indicator concentrations at recreational sites affected by stormwater outfalls. A case study in Lake Pontchartrain was presented. The Bacteria Source, Transport and Fate Study was performed for beaches in the Milwaukee Harbor (Thuman et al. 2004) to assess whether the sources of bacteria were related to the operations of the Milwaukee Metropolitan Sewer District. The results showed that bacterial problems due to CSOs and WWTPs were limited in duration and occurred during storm events when recreational use of the beaches was curtailed. Fecal coliform bacteria modeling in Omaha, Nebraska, and Wichita, Kansas, were compared by Christiansen et al. (2004). In addition to the similar analyses, Wichita sampling also included sediment sampling, antibiotic resistance analysis, and wet- and dry-weather hydrographic sampling.

Booth et al. (2004) reviewed the impacts of land use, hydrology, biology and human behavior in reviving urban streams in the Puget Sound lowlands (Washington). The authors argue that impervious area alone is a flawed surrogate of river health and propose that hydrologic metrics be used instead since they reflect chronic altered streamflows.

Christen (2003) investigated potential links between stormwater management practices and West Nile virus. Municipalities were concerned since the Phase II stormwater regulations require that small and mid-size communities install treatment practices such as retention ponds, drainage ditches, artificial wetlands, grassy swales and rain gardens – all of which have the potential to develop areas of stagnant water if they are poorly designed and maintained. Schiff and Bay (2003) investigated the impact of stormwater discharges on the nearshore benthic environment of Santa Monica Bay. Both the urban and non-urban sites were characterized as having an abundance, species richness, biodiversity and benthic response index similar to shallow water areas distant from creekmouths throughout the Southern California Bight. Sherrard et al. (2003) investigated the comparative toxicity of chlorothalonil (a commonly used fungicide appearing in urban runoff) on *Ceriodaphnia dubia* and *Pimephales promelas*. *P. promelas* was more sensitive than *C. dubia* to chlorothalonil exposures. All mortality of *P. promelas* and *C. dubia* resulting from these chlorothalonil exposures occurred within the first 96h and no sublethal effects (i.e., growth or reproduction) were detected following 7-day exposures.

For 20 years, King County, WA, has progressively implemented more demanding structural and nonstructural strategies in an attempt to protect aquatic resources and declining salmon populations from the cumulative effects of urbanization (Booth, *et al.*, 2002). They found that costly structural retrofits of urbanized watersheds can mitigate certain problems, such as flooding or erosion, but they cannot restore the predevelopment flow regime or habitat conditions. They concluded that the preservation of aquatic resources in developing areas will require integrated mitigation which must include impervious-surface limits, forest-retention policies, stormwater detention, riparian-buffer maintenance, and protection of wetlands and unstable slopes. However, the same management goals cannot be achieved in both developed and undeveloped watersheds.

Burleson (2002) reports that coastal counties in southern South Carolina have experienced rapid growth. During this time, a number of shellfish areas have been closed permanently, or on a conditional basis, due to exceedences of the fecal coliform water quality standard for shellfish waters (14 FC/100ml). Proposed developments that will discharge to receiving waters on the 303(d) list are now required to demonstrate that discharges from their site will meet numerical limits. Existing retention/detention options were not able to meet these limits. Spreadsheet evaluations and monitoring at two developments are investigating the application of different stormwater controls to meet the fecal coliform standard. Preliminary results indicate that it will be very difficult to meet this bacteria standard.

Horwitz *et al.* (2001) examined the different fish communities in paired reaches of streams having forested vs. unforest riparian zones. The streams traversed land uses ranging from rural to highly urban. Their preliminary results found that the type of buffer had little effect on the fish communities in the rural reaches. However, the fish community patterns were much more variable in the urban reaches, being affected by the effects of urbanization on channel morphology, habitat, hydrology, and water quality. Sonneman *et al.* (2001) studied the effects of urbanization on the benthic diatom communities in streams near Melbourne, Australia. The subcatchments had imperviousness levels ranging from 0 to 51%. They found that the differences observed were best explained by variations in nutrient concentrations (phosphorus, ammonia, and total nitrogen). The level of urbanization, along with the presence of small sewage treatment plants at a few sites, influenced the nutrient concentrations found. They observed that diatoms were better indicators of nutrient enrichment, while macroinvertebrates were better indicators of catchment disturbance. Walsh *et al.* (2001) reported the effects of macroinvertebrates at the same Melbourne area locations as reported by Sonnenman *et al.*, (2001). Responses were more obvious in the eastern areas (having a wide range of development) and were associated with conductivity, while the western areas (having little development) had little observed variations. The metropolitan areas were all severely degraded, having high abundances of a few tolerant taxa. Extensive development of urban drainage systems, even in areas having low urban densities, increased the observed degradation.

Fifty *et al.* (2001) investigated the impact of wastewater and stormwater discharges on the coastal receiving waters on a coral atoll in the middle of the Pacific Ocean (Kwajalein Atoll), a pristine marine environment. They used *Tridacna maxima*, a giant clam species, as an indicator organism. Juvenile clams were deployed for a 3-month period in the vicinity of pollutant sources and reference sites, and then analyzed for metals, PAHs, pesticides, and PCBs. The clams were a successful bioindicator, with tissue samples from sites near pollutant sources (contaminated sediment and stormwater) containing higher concentrations of chemicals than at the reference sites.

Grant *et al.* (2001) reported frequent elevated levels of enterococci bacteria in the surf zone at Huntington Beach in southern California. They studied the sources of these indicators and found high levels in urban runoff, bird feces, marsh sediments, and on marine vegetation. They concluded that urban runoff had relatively little impact on these elevated surf zone bacteria levels because of the long travel time needed for the urban runoff to travel from the source areas to the ocean. They found that marsh sources were more likely responsible for the high surf zone bacteria levels. Jiang *et al.* (2001) used a nested-PCR analytical method to detect viruses in coastal waters at 12 beach locations in Southern California. The sampling locations were all impacted by urban runoff sources. The sampling locations were all located at the mouths of major rivers and creeks. Human adenoviruses were detected in 4 of the 12 samples (880 to 7,500 per L), coliphages were found in all 12 samples (5.3 to 3330 PFU/L), and F-specific coliphages were found in 5 of the 12 samples (5.5 to 300 PFU/L). The bacterial indicator levels (total coliforms, fecal coliforms, and enterococci) all exceeded the California recreational water quality limits, but the bacteria levels found did not correlate well with the observed human adenovirus levels. They concluded that the standards that rely on bacteria observations to indicate viral quality of recreational waters be re-evaluated, and that more routine monitoring of human viruses be conducted on a regular basis.

Mahin (2001) reviewed recently completed epidemiological studies conducted after the publication of the 1986 EPA bacteria guidance. The Massachusetts Dept. of Environmental Protection were concerned about the risk level that is

associated with stormwater runoff to recreational waters, and if enterococci or *E. coli* can adequately predict the range of possible illnesses that may affect swimmers in contaminated marine waters. Crowther et al. (2001) examined the relationships between microbial water quality and environmental conditions in coastal recreational waters along the Fylde coast, UK. Eight designated bathing beaches continued to exhibit unreliable compliance with the Imperative standards for total coliforms and fecal coliforms, despite significant reductions in geometric mean concentrations following major improvements in the sewerage infrastructure. Fecal streptococci concentrations have remained high. Before the improvements, higher bacterial concentrations were strongly associated with rainfall; and sewage sources were important for TC and FC, but less important for FS. Since the improvements, catchment sources seem to be of greater importance. Pendleton (2001) reported that despite posted warnings and educational campaigns warning about the health risks associated with storm water pollution, swimmers continue to swim in Southern CA coastal areas polluted by stormwater. Passive means of preventing exposure to marine pollution (e.g., posted signs) were found to be more effective if combined with the active management of other beach amenities. Pendleton et al. (2001) further found that despite documented successes in the battle to clean up the coastal waters of Southern California, Los Angeles County residents continue to view the ocean more as a place of pollution than a healthy place for bathing and swimming. Survey results suggest that perceptions of coastal water quality may be influenced less by “current coastal education campaigns” and more by the media and other factors.

One impact of stream habitat degradation that could not be accounted for through chemical and biological monitoring would be the effect of elevated flows on habitat availability. A study by Finkenbine et al. (2000) indicated that restoration of stream health in an urban area was best accomplished by the establishment of a healthy buffer zone and the introduction of large woody debris (LWD) into the stream. They found that, after a stream has reached its equilibrium with the flow, detention pond retrofits had few hydrological benefits.

Bailey et al. (1999) investigated the potential toxicity of stormwater runoff from sawmills in British Columbia to juvenile rainbow trout, and found that the toxicity was related to the divalent cation concentration, especially for zinc. They also determined that the zinc toxicity was directly related to the low hardness in the stream, with the range of LC50 of 72 – 272 µg/L associated with hardnesses of 9 – 100 mg/L. Ambrose and Meffert (1999) investigated the fish assemblages in Malibu Lagoon, a small estuary in California, and found that the species diversity and richness were small compared to large estuaries, but were comparable to other small estuaries with less anthropogenic impacts. Hatch and Burton (1999), using field and laboratory bioassays, demonstrated the impact of the urban stormwater runoff on *Hyalella azteca*, *Daphnia magna*, and *Pimephales promelas* survival after 48 hours of exposure. The significant toxicity seen at the outfall site was attributed to the contaminant accumulation in the sediments and the mobilization of the top layers of sediment during storm events. A comparison of highway runoff toxicity with typical urban runoff toxicity was performed by Marsalek et al. (1999). Their study found that approximately 20% of the samples collected at the edge of a multi-lane divided highway (>100,000 vehicles/day) were severely toxic, while only 1% of the typical urban runoff was severely toxic. Skinner et al. (1999) showed that stormwater runoff produced significant toxicity in the early life stages of medaka (*Oryzias latipes*) and inland silverside (*Menidia beryllina*). Developmental problems and toxicity were strongly correlated with the total metal content of the runoff and corresponded with exceedances of water quality criteria of Cd, Cu, W, and Zn.

Ecotoxicological experiments were used by Delbec and Mouchel (1999) to develop a wet-weather quality potential ( $\Phi$ ) that can be used to evaluate oxygen depletions during WWF. The quality potential was used to demonstrate the impact of seasonal hydrological conditions on the occurrence of damaging situations in the River Seine. Pess and Bilby (1999) identified Coho salmon (*Oncorhynchus kisutch*) distribution and abundance in Puget Sound rivers and explained the distribution by using both stream-reach and watershed-scale habitat characteristics, including the influence of urban areas on the habitat. Tree swallows were used by Secord et al. (1999) to determine the impact of contamination of a watershed and waterway with PCB. The elevated PCB concentrations in the swallows and in the sediments indicate that PCBs in the sediments can be passed up the aquatic food web of the Hudson River ecosystem to the terrestrial and avian wildlife that depend on the River for food. Mallin et al. (1999) documented the effects of Hurricanes Bertha and Fran on the biological community in the Cape Fear area of North Carolina. The natural hurricane effect of swamp water flooding into river basins was reduced DO levels that resulted in fish kills. However, this damage, such as the length of the low DO levels, was considerably increased by anthropogenic practices, including sewage diversions into the rivers and flooding and discharge from swine waste lagoons sited adjacent to the river. The relationship between benthic chlorophyta (*Ulothrix zonata*) and urban stream water quality was demonstrated by Shigemitsu and Hiratsuka (1999).

While exact cause-and-effect relationships have not yet been determined between toxic blooms and algae, dinoflagellates,



and similar organisms, evidence suggested that nutrients from agricultural runoff or sewage may stimulate the growth of harmful organisms such as *pfiesteria* spp (Pelley 1998) . High P loading to Como Lake, a shallow lake in Minn., from the surrounding urbanized watershed caused eutrophic conditions. Despite efforts to manipulate fish and macrophyte populations, and DO levels in the lake, maintenance of healthy populations of fish, macrophytes, and plankton in the lake will require control of the large P inputs (Noonan, 1998). Heinzmann (1998) described efforts in Berlin, Ger. to reduce P loading to surface water bodies. The response of algae to suspended clay and P loading in an urban lake in N.C. showed that clay tended to reduce algae production, while P tended to increase algae production in this study. However, high P loadings produced nuisance algal blooms and mitigated the adverse effects of high clay loading on algal production (Burkholder et al., 1998).

DNA strand breakage, growth rate, condition index and percentage tissue water were measured in freshwater Asiatic clams (*Corbicula fluminea*) exposed in-situ to a stream that received urban and industrial stormwater runoff versus a non-impacted reference stream. After four weeks, DNA strand lengths of the exposed clams were significantly shorter than from reference clams which suggested a reduction in DNA integrity in the exposed clams, possibly indicating exposure to genotoxic chemicals, while no significant differences were observed in the growth rates (Black and Belin, 1998). Loumbourdis and Wray (1998) detected high concentrations of Cu, chromium, molybdenum, Zn, manganese, and aluminum, in the tissues of frogs living in a small river in Macedonia, north. Greece, corresponding to highly polluted areas. The main sources of the river pollution seem to be fertilizers containing heavy metals as trace elements, pesticides with heavy metals in their formula, urban runoff, and various light industries along the river. The bioaccumulation and toxicity of Zn in *Spirogyra Fluviatilis* Hilse (chlorophyta), from two populations in the River Seyhan, Adana, Turkey, showed little difference in Zn bioaccumulation between *Spirogyra* from a site showing mild organic pollution or that from a site subjected to considerable inputs from urban and motorway runoff. Cellular damage was evident in *Spirogyra* subjected to 0.5 mg/L Zn, and increased with increasing Zn concentration (Saygideger 1998).

Wernick et al. (1998) compared land-use indicators to streamwater nitrate-N levels in the Salmon River watershed near Vancouver, British Columbia, Can. and found that urbanized areas, as indicated by septic tank density, contribute to elevated nitrate-N levels in an urban-rural fringe environment. In the main tributary of the Salmon River, nitrate-N levels correlated with urban land use, but not with agricultural land use as indicated by animal unit density, indicating that urban land use is the primary source of nitrate-N in that basin.

Winter and Duthie (1998) documented the adverse effects of urbanization on periphyton and macroinvertebrate community structure in Laurel Creek, a rapidly urbanizing subwatershed of the Grand River in southern Ont., Can. Pesacreta (1997) monitored the benthic life of the urban Morgan Creek of Carrboro and Chapel Hill, N.C. The macroinvertebrate *Pteronarcys dorsata*, which is intolerant to pollution was observed as a sub-lethal toxicity indicator. Schultz (1998) presented a brief overview of how urban streams got into their current predominantly degraded conditions and the activities and results of several recent programs aimed at rehabilitation of urban streams.

A correlation between runoff events and poor water quality in Lake Michigan established that runoff events have had significant impact on the drinking-water quality in Milwaukee, Wis. where 400,000 people were infected with *cryptosporidiosis* in 1993 (Christensen et al., 1997). *Giardia* and *Cryptosporidium* were monitored monthly for two years to determine their occurrence in the Allegheny and Youghiogheny Rivers of Pennsylvania, their source, and the efficiency of their removal by the Pittsburgh Drinking Water Treatment Plant. Sources investigated included a dairy farm stream, wastewater treatment plant (WWTP) effluent, and several samples from CSO (States et al., 1997).

Macrobenthic communities were surveyed in 1987-88 as part of a comprehensive study of fish kills and water quality in the upper Trinity River of Texas (Davis, 1997). While some impact was evident in certain reaches from pesticides, dissolved metals, and WWTP effluents, the overall impacts were relatively slight on a long-term basis and a high aquatic-life use was attained at most sites. The Bloomington and Normal Water Reclamation District of McLean County, Ill. began an ongoing biological survey of Sugar Creek in 1983 (Callahan 1997). Improvement in the fish community was linked to the discontinuation of effluent chlorination through an annual exemption in 1991, while the addition of nitrification, construction of CSO controls, and tertiary filter failure did not demonstrate immediate and directly attributable affects. In many southern California salt marshes, increased freshwater inflows have promoted the establishment of exotic plant species. Kuhn and Zedler (1997) proposed that salt applications may be a practical method for controlling exotic plant invasions in areas receiving urban stormwater runoff or other unwanted freshwater inflows.

Hellou et al. (1997) exposed rainbow trout to waste crankcase oil, a recognized source of PAH contamination in urban

stormwater runoff. The accumulation of compounds in muscle tissue, the elimination of bile metabolites, the activity of 7-ethoxyresorufin O-deethylase (EROD) in liver, and morphometric variables were compared at different concentrations and times of sampling. Jennings *et al.* (1997) extracted ten pollutant phenols from an oil-refinery discharge, urban stormwater, and WWTP effluent with the highest concentration found in the WWTP effluent. Bioaccumulation experiments were conducted using the mussel, *Mytilus edulis* and the fish, *Trachurus novaezelandiae* with similar concentrations, and both species depurated all accumulated phenols to concentrations below detection within 24 h when placed in clean seawater. Magaud *et al.* (1997) developed a quantitative model of the instantaneous death probability of juvenile rainbow trout as a function of time, concentrations of unionized ammonia (NH<sub>3</sub>), and dissolved oxygen (DO). This model found the survival probability of rainbow trout exposed simultaneously to NH<sub>3</sub> and low DO was lower than the predicted survival probability derived from the simple addition of the individual effects. Moore and Farris (1997) conducted 48-h acute-toxicity tests with *Ceriodaphnia dubia* (cladoceran) and *Pimphales promelas* (fathead minnow) on stormwater runoff, laboratory synthetic water, and irrigation (ground) water with the herbicide Stam®M-4 (active ingredient Propanil [3',4'-dichloropropionanilide]). No effects on survival were observed in this study following 48-h toxicity testing with the stormwater. Siewicki (1997) estimated the risks posed by fluoranthene (a four-ring PAH) in urban stormwater runoff by modeling and exposure assessment of a portion of Murrells Inlet in South Carolina. Results suggested bioconcentration of fluoranthene in oysters is related to adjacent land uses and can be predicted by understanding the major factors affecting its transport and fate. An approach is described to test alternate landscape modifications for minimizing impacts on both resident fauna and seafood consumers. Villeneuve *et al.* (1997) used an in vitro bioassay with PLHC-1 (*Poeciliopsis lucida*) fish hepatoma cells to assess potential toxic potency of aryl hydrocarbon receptor (AhR-active) compounds, collected by semipermeable membrane devices (SPMD) exposed to Lincoln Creek water Milwaukee County, Wis. as part of a comprehensive study on the effects of stormwater runoff. A log-log correlation of total PAH and toxic potency of dialysates (expressed as bioassay-derived 2,3,7,8-tetrachlorodibenzo-p-dioxin equivalents [TCDD-EQ]) yielded an  $r^2 = 0.802$  and empirical evidence suggested that AhR-active PAH can account for about 20% — 50% of the potency observed.

The detection and assessment of pollution in the aquatic environment and their effects upon the biological community are rapidly becoming a central focus of state agency water-resource programs. Bioassessments are particularly useful because they reflect the condition of the resident biota from cumulative effects as a result of both nonpoint and point source impacts (Barbour, 1996). Barbour and Stribling (1996) presented a summary of the physical instream and riparian habitat features of a visual-based habitat assessment and their relationship to and influence on biological communities. The quality and stability of stream and riparian-physical habitat, rated in relation to unimpaired streams of similar site-specific and regional characteristics, provide an estimate of the biological potential of a stream system. Preliminary results of research on the application of an aquatic-invertebrate-bioassessment protocol suitable for wetland conditions indicate that ecological integrity of wetlands is affected by the amount of impervious surface in the watershed and that aquatic-macroinvertebrate communities serve as indicators of wetland condition (Hicks and Larson, 1996). Jones *et al.* (1996) reported that macroinvertebrate bioassessment indicated substantial impairment of streams in a heavily-suburbanized Virginia watershed relative to a companion forested watershed, while a lightly developed adjacent watershed showed an intermediate level of impairment. Severe impairment of the benthic-macroinvertebrate community was found further downstream below the discharge of large quantities of unmitigated stormwater. McCarron *et al.* (1996) discussed the need and rationale for alternative sampling and assessment procedures that provide a more ecologically-based manner of determining the cumulative environmental effects of nonpoint sources of pollution. The Florida Department of Environmental Protection's multi-year effort to refine and enhance current biological-community-assessment methods was described.

Evaluation of Central Texas streams using the bioassessment techniques developed for perennial streams indicates that these methods fail to accurately assess the degree of impact on the local community structure due to biological seasonality and intermittent flow (Hansen, 1996). Current assessment techniques need to be modified or new techniques developed for intermittent streams that will enable investigators to distinguish between aquatic-biota impacts due to natural, environmental variations and impairments related to anthropogenic activities in the local watershed. A study was conducted to provide the Texas Natural Resource Conservation Commission with information concerning the nonpoint source discharges from the City of Uvalde to assist in developing appropriate rules to implement provisions in the Texas Water Code requiring cities with populations over 5,000 to develop and submit Water Pollution Control and Abatement Plans (Coonan *et al.*, 1996). The results indicated that the samples taken from areas subject to urban storm runoff from the City exhibited statistically lower concentrations for numerous parameters; an impact on aquatic communities in the urban storm-runoff receiving-water was not observed.

Claytor (1996a) summarized the approach developed by the Center for Watershed Protection as part of their EPA sponsored research on stormwater indicators (Claytor and Brown, 1996). The 26 stormwater indicators used for assessing receiving-water conditions were divided into six broad categories: water quality, physical/hydrological, biological, social, programmatic, and site, and were presented as tools to measure stress (impacting receiving waters), to assess the resource itself, and to indicate stormwater control program implementation effectiveness.

Pereira *et al.* (1996) assessed the effects of human activities and land use on the water quality of the San Joaquin River and its major tributaries. This study focused on pesticides and organic contaminants and examined water, particulate forms, sediment, and bivalve shellfish.

The biological communities in Delaware's Piedmont streams have been severely impacted by stormwater, after the extent of imperviousness in the watersheds exceeds 8-15%, according to a review article (Claytor 1996c). If just conventional water quality measures are used, almost all (87%) of the state's nontidal streams supported their designated biological uses. However, when biological assessments are included, only 13% of the streams satisfactorily meet their uses.

Weed invasion in the bushland surrounding the Lane Cove catchment in Australia was related to contamination of the floodplain by heavy metals and nutrients, plus increased flooding from the urban development surrounding the bushland (Riley and Banks, 1996). Aesthetics has historically been difficult to quantify in urban receiving-water studies, but it has been an important parameter for many uses, especially recreation. Heidtke and Tauriainen (1996) developed an aesthetic rating system for the Rouge River (Detroit, MI), using a combination of water clarity, water color, odor, and visible debris. Preliminary work suggests that the index is an effective tool for tracking time and space trends in aesthetic characteristics of the receiving water and for public education.

### **Microbiological impacts**

Evason and Ambrose (2006) investigated the sources and growth dynamics of fecal indicator bacteria in a coastal wetland in southern California. The results showed that sediment associated fecal indicator bacteria were distinct from those found in the water samples. Increases in sediment-associated bacteria may result from internal growth and/or from increased survival due to changes in water parameters from rain events.

Kleinheinz *et al.* (2006) evaluated avian waste and bird counts as predictors of *E. coli* contamination. These results indicated that neither avian waste enumeration nor bird counts could successfully be used to predict microbial contamination of recreational waters at the beaches tested. Lee *et al.* (2006c) investigated the persistence of fecal indicator bacteria in Santa Monica Bay beach sediments. These bacteria were able to grow in both overlying water and sediment from all beaches. Krometis *et al.* (2006) investigated the intra-storm variability in microbial partitioning and loading rates. Higher concentrations of both settleable particles and microbes entering the water column soon after the onset of a storm led to higher loading rates of settleable microbes in the storm's earliest stages. Noble *et al.* (2006) assessed the role of particle attachment in the fate and transport of microbial indicators and pathogens in an eutrophic estuary in North Carolina. Concentration increases in enterococci and *E. Coli* coincided with increases in particle content during storm events. Resuspension of bottom particles by wind was also a source of these bacteria.

Hepatitis A and enteroviruses were analyzed quantitatively near the United States-Mexico border at recreational beaches during dry and wet weather flow. Dry weather flow samples showed virus levels below the limit of detection, while during wet weather, the viruses were detectable and correlatable with indicator bacteria (Gersberg *et al.* 2006). Hou *et al.* (2006a) investigated the concentrations of pathogenic indicator microorganisms and heavy metals in Lake Pontchartrain following Hurricane Katrina. Short-duration elevated levels of indicator bacteria were found near the points of floodwater discharges in both water column and sediment samples.

The coastal water-quality impacts of stormwater runoff from an urban watershed in Southern California were investigated by Ahn *et al.* (2005). Their results showed that surf zone water quality was poor with regular exceedences of California's ocean bathing water criteria for fecal indicator bacteria. These exceedences were reduced if the runoff was discharged well offshore. Jeong *et al.* (2005) investigated the contribution of several marinas to fecal coliform impairment in Newport Bay (California) and found that dry-weather flows and urban runoff contribute to the fecal coliform impairments. Rees *et al.* (2005) evaluated the transport of *Cryptosporidium* and *Giardia* in watersheds during storm events. The resultant database consisted of wet-weather transport data for 21 storm events and three dry-weather spatial basin sampling events. Bacterial source tracking was used by Iyer *et al.* (2005) in the Lynnhaven River (Virginia) to investigate the source of the fecal coliforms in the watershed. One-quarter of the fecal coliforms could be attributed to

human sources, such as sewage overflows. The authors proposed monitoring optical brighteners that are added to laundry soap as a surrogate for sewage contamination.

Coliform concentrations were used to evaluate the impact of climate change, tidal mixing and urbanization on the water quality of Newport Bay (southern California) (Pednekar et al. 2005). The results showed that efforts to improve water quality will have the greatest impact in dry summer months. The detection and frequency of occurrence of *Cryptosporidium* and *Giardia* was analyzed by Arnone (2005). A secondary objective was to evaluate the method variability and recoveries of these protozoa when they are extracted from runoff.

Resuspension and persistence of *E. coli* were investigated in a natural stream in Ontario, Canada by Jamieson et al. (2005). The study demonstrated that survival was possible for up to 6 weeks in the sediment and that the rising limb of the hydrograph was the section of the storm where resuspension was most prevalent. Davis et al. (2005) investigated the survivability of *E. coli* in karst springs and streams and discovered that *E. coli* are able to survive in the stream sediments for at least four months. The partitioning of microorganisms to settleable solids in urban streams during both wet-weather and dry-weather flow regimes was investigated by Characklis et al. (2005). Bacterial indicator association was relatively constant, but low, while the *Clostridium perfringens* had the highest associations of the microorganisms investigated.

Sanders et al. (2005) modeled the dry-weather tidal cycling of fecal indicators in an intertidal wetland in Huntington Beach, California. Urban runoff and resuspension of contaminated wetland sediments were the primary sources of surface water contamination of fecal indicators. The results also showed that wetland-dependent animals were also sources of these fecal indicator bacteria, indicating the limitations of using these indicators as an indicator of human pollution. The changes in coral reef communities and associated reef fish species were documented by Nagelkerken et al. (2005) and the impact of anthropogenic sources was evaluated. The greatest decline in reef complexity was noted in shallow areas, documenting the impact of anthropogenic and storm sources. The cost of illnesses from recreational waters was assessed for two Southern California beaches that have known impacts from urban runoff (Dwight et al. 2005). Illnesses assessed included gastrointestinal, respiratory and eye.

Jin et al. (2003) preliminarily studied of coastal water quality monitoring and modeling in the Lake Ponchartrain (LA) basin. Results indicated that runoff drainage canals constituted a significant microbial loading to lake waters. Significant reductions of indicator microbes are observed in the water column following two to three days after storm pumping events into the lake. Hyland et al. (2003) investigated the spatial and temporal distribution of fecal indicator bacteria within the Oldman River basin (southern Alberta, Canada). Spikes in fecal coliforms and *E. coli* concentrations were observed in surface waters following heavy rainfall events.

Borst and Selvakumar (2003) investigated particle-associated microorganisms in stormwater runoff and the impact of these microorganisms on the analysis of microbial water quality. They found that measured concentrations of these organisms, except for *E. coli*, increased after blending samples to detach/de-clump these particle-associated microorganisms.

Turner, *et al.* (2002) reported that urban wet weather pollution has been identified as a major cause of high bacteria levels found in the Ohio River near Cincinnati. Calibrated and validated hydrodynamic (RMA-2V) and water quality (WASP5) models were linked to provide a two-dimensional representation of the study area. Improvements in water quality were evaluated using screening level combined sewer overflow (CSO) control alternatives. This work indicated that bacteria loadings originating from CSOs have an adverse impact on water quality, and that controls were expected to have mixed results. They found that the amount of rainfall obviously influences the significance of the CSO loadings and the effectiveness of the CSO controls. However, the in-stream concentrations were also found to exceed 400 #/100 mL during dry weather in some areas of the river.

An investigation of shoreline microbiological contamination conducted by Robertson et al. (2000) in Orange County, California, showed that the likely cause of the elevated fecal coliforms was dry weather urban runoff from the San Gabriel River and storm drains up the coast, rather than the Orange County's WWTP effluent ocean outfall. As a result of seventeen *E. coli* O157:H7 cases, investigation of the potential contamination on the Mar del Plata beaches due to combined sewer overflows was performed by Perez Guzzi et al. (2000). Their investigation detected no *E. coli* O157:H7, although other strains of *E. coli* were detected in 75% of the samples. None of the 98 strains detected in the outfalls were the strains that were known to cause human illness. However, the presence of *E. coli* in the drainage water indicated fecal contamination and the resulting potential for illness should a toxic strain be present in the sewage. Rose et al. (2000),

through climate and epidemiological records, demonstrated a potential correlation between extreme precipitation events and waterborne disease outbreaks. The authors found that statistically significant relationships could be developed between large precipitation events and waterborne disease outbreaks for both surface and ground water, although the relationship was much stronger for surface water outbreaks. The impact of urban runoff and the potential resuspension of settled parasites in Paris rivers at the drinking water intakes was investigated by Rouquet et al. (2000). Their results showed that parasite sedimentation was high, but that resuspension due to urban runoff was also likely. Rangarajan et al. (2000) developed a model for the City of Edmonton for predicting the impact of rainfall on combined sewer overflows and hence on river water quality. This model would be used to predict elevated fecal coliforms in the river, and hence, for determining when microbiological standards for recreational waters would be exceeded.

Crabill et al. (1999) presented their analysis of the water and sediment in Oak Creek in Arizona, which showed that the sediment fecal coliform counts were on average 2200 times greater than that in the water column. Water quality standards for fecal coliforms were regularly violated during the summer due to the high recreational activity and animal activity in the watershed, as well as the storm surges due to the summer storm season. Lemke and Leff (1999) analyzed the bacterial populations at five sites, including two in disturbed urban streams. The results indicated that anthropogenic disturbance of watershed and stream can alter some bacterial populations (*Acinetobacter calcoaceticus*) but not others (*Burkholderia cepacia*, *Pseudomonas putida*). Haile et al. (1999) presented the results of an epidemiological cohort study of swimmers in Santa Monica Bay, California where untreated urban runoff from Los Angeles was discharged. Higher risks of upper respiratory and gastrointestinal infections were found for swimmers near storm-drain outfalls, in waters with a low ratio of total to fecal coliforms, and in waters where enteric viruses were detected. Herrmann et al. (1999b) demonstrated through modeling that, for a German city with a combined sewer system, blackwater separation by vacuum toilets and urine separation can reduce nutrient discharges during overflow events by 90%, especially in the summer when the river water may contain up to 50% sewage. These reductions in nutrient discharges might improve the river water quality sufficiently to meet swimming water quality criteria during most, if not all, of the year.

*Water Environ. & Technol.* (1996c) reported on an epidemiology study conducted at Santa Monica Bay, CA that found that swimmers who swam near stormwater outfalls were 50% more likely to develop a variety of symptoms than those who swam 400m from the same outfalls. This was a follow-up study after previous investigations found that human-fecal waste was present in the stormwater-collection systems. *Environ. Sci. & Technol.* (1996b) also reported on this Santa Monica Bay study. More than 1% of the swimmers who swam in front of the outfalls were affected by fevers, chills, ear discharges, vomiting, and coughing, based on surveys of more than 15,000 swimmers. The health effects were more common for swimmers who were exposed on days when viruses were found in the outfall-water samples.

Eggleston et al. (1996) reported that closures of the Boston area's Tenean Beach were due to either exceedance of Massachusetts' fecal-coliform limit (200MPN/100mL) or both the fecal coliform and the EPA's criterion for *Enterococcus* in bathing beaches in marine waters (104 MPN/100mL). It was cited that past epidemiological research demonstrating fecal-coliform concentration to be a poor indicator of public-health risk in marine waters and the exceedance of the EPA's *Enterococcus* standard as the basis for questioning the degree of public-health risk posed by swimming in these waters. Su et al. (1996) further document problems with the fecal-coliform test. It was concluded that the *E. coli* criteria can do a superior job of reflecting the public perception of a desirable water body for swimming.

### **Chemical Impacts**

Dougherty et al. (2006b) quantified long-term NPS flux in an urbanizing watershed in the Washington, D.C., area. Higher fluxes in one basin indicated the seasonal impact of replacing vegetation with impervious surfaces. Sainz and Ruiz (2006) examined the influence of very polluted inputs on adjacent littoral sediments in southwestern Spain using three statistical analysis techniques. Three zones were noted, ranging from moderately-to-strongly polluted, to nonpolluted. Liu et al. (2006a) documented the impacts of different vegetation types and soil properties on runoff chemical characteristics. Chemical characteristics in surface runoff and groundwater were similar to that in rainfall. Nicolau et al. (2006) discussed the transfer of nutrients and metals from the land to the sea in a small Mediterranean river. Heavy-rain events contained high concentrations of some metals and organic carbon, with the pollutants mainly associated with the particulate fraction.

Brilly et al. (2006) monitored the impact of urbanization on the Glinscica stream in Slovenia for two years. The results showed substantial seasonal and along-the-channel variations of concentration of dissolved oxygen, nitrate and ammonium content due to biochemical processes in the channeled stream. Gonzalez-Caccia and Boyer (2006) proposed a nutrient loading budget for Biscayne Bay, Florida. Their research showed that nutrient concentrations in the Bay were

affected by canal (urban drainage), atmospheric and groundwater loadings. Crouch et al. (2006) investigated the impacts of fire retardant on surface water quality. Minimal impacts were found, including for cyanide compounds.

Ellis (2006) investigated the presence of pharmaceutical and personal care products in urban receiving waters. Increasing loads of these compounds were correlated with increasing urbanization. These products were captured in the shallow soil profile during infiltration. Rumbold and Fink (2006) evaluated the spatial variability and concentration range of methylmercury in a constructed wetlands in the Everglades. The monitoring resulted led to the management of flow rate and water depth as a means to alter sulfur biogeochemistry and, thereby, reduce in-situ mercury methylation. Cheng et al. (2006) described the distribution of PCBs and suspended solids in the Yangtze estuarine and coastal areas in China. The study area, which was near an area of PCB manufacture and use, was more contaminated compared to other areas.

Masson et al. (2006) investigated the geochemical signals and source contributions to heavy metal fluxes to a French estuary. The authors stated that monitoring these fluxes and signals may greatly improve understanding of contaminant transport.

Fries et al. (2006) described the attachment of fecal indicator bacteria to particles in an estuary receiving input from anthropogenic activity in order to determine attachment and settling rates for incorporation in models.

Pardue et al. (2005) evaluated the results of the sampling program in New Orleans floodwater following Hurricane Katrina. Their analysis showed that what distinguished the floodwater was not the very elevated concentrations of toxic pollutants, but the large volume of and human exposure to the floodwater.

Vos and Roos (2005) reviewed the causes and consequences of algal blooms in Loch Logon, an urban impoundment. Orosz (2005) examined in-stream nitrification rates in an urban watershed. Conditions affecting nitrification rates were ammonium concentration, temperature, pH, DO, hydrology and substrate quality. The risk of nutrient emissions to surface waters in Ireland was assessed by Donohue et al. (2005). Positive associations were found between the extent of high productivity grasslands and urban areas with elevated nutrient loads and the most biologically-available fraction of nutrients.

Chemical tracers as indicators of human fecal pollution at stormwater outfalls were investigated by Sankaramakrishnan and Guo (2005). The fecal coliform to fecal streptococci ratio was not useful in distinguishing the source of the pollution, whereas the chemical tracers (caffeine, anionic surfactant, fluoride and a brightener compound) were higher during wet-weather flow. A strong correlation also was found between fecal coliforms and the chemical parameters. Irvine et al. (2005a) analyzed the data from continuous monitoring Datasondes to determine the effect of CSO discharges into the Buffalo River. The turbidity data showed a net sediment sink in the river, and the dissolved oxygen showed that not all CSO events caused oxygen sags downstream.

Monitoring of Stockholm Archipelago sediments by Jonsson et al. (2005) demonstrated that organic matter and associated substances that are partly generated by the city of Stockholm were remineralized and released to the water or transported away from this archipelago. The distribution and persistence of pyrethroids in urban and agricultural runoff sediments was investigated by Gan et al. (2005). Pesticide enrichment was seen along the runoff path and was correlated with enrichment of the organic and clay fractions in the sediment. The fate and transport of roadside-applied herbicides was modeled by Massoudieh et al. (2005). The model accounted for advection, dispersion, equilibrium linear sorption in the soil and first-order decay kinetics. Infiltration was modeled using the Richards' equation.

An analysis of the sediments in the River Manzanares (Madrid, Spain) showed that the river is heavily influenced by urban runoff, spills and illegal dumping (De Miguel et al. 2005). In the final stretch of the river, the presence of carbonate appeared to control the amount of zinc and copper immobilized in the sediment. Sediment contamination and distribution in two marinas was investigated by Hinkey et al. (2005). The distance from the storm drain outlet and the characteristics of the sediments themselves were greater indicators of the sediment contamination than the prevalence of specific marina activities.

Estuarine sediments were shown to be a sink for indicator organisms associated with stormwater solids (Jeng et al. 2005). Entrapment/entrainment in the estuarine sediments improved the survivability of these indicator organisms.

Contamination of mangroves sediments and leaves due to urban runoff was examined by Defew et al. (2005). Iron, zinc and lead were found in levels high enough to pose a threat to the regeneration and growth of the mangrove. Ke et al. (2005) examined the spatial and vertical distribution of PAHs in mangrove sediments and found that elevated concentrations were localized. Sources for these elevated concentrations were municipal and industrial wastewater, stormwater runoff, oil leakage from boats and accidental oil spills.

The effect of tubificid worms on the fate of organic matter and pollutants in stormwater sediments was investigated by Mermillod-Blondin et al. (2005). The results showed that the worms increased the release of ammonium, phosphate and dissolved organic matter. Oxygen uptake was also increased. No release of heavy metals or hydrocarbons was noted.

The impact of human activities on the nutrient chemistry of the Pinios River (Greece) was studied by Bellos et al. (2004). Concentrations of nutrients and organic carbon in the water increased as the river flowed past urban areas. DeCarlo et al. (2004) investigated the chemical composition of water in urban drainage canals in Oahu, Hawaii. Pb, Zn, Cu, Ba and Co had increased concentrations in the urbanized portions of the watersheds. Particulate concentrations varied temporally during storms due to road runoff inputs, which containing varying concentrations of these elements.

The relationship between urban density/drainage structure in Melbourne, Australia, and pollutants loads in small urban streams was examined by Hatt et al. (2004). DOC, conductivity, reactive phosphorus and total phosphorus were independently correlated with the degree of drainage connectivity, while pH and TSS could not be related to any of the basin variables (degree of drainage connectivity, imperviousness, etc.). The environmental pollution assessment of the Ebrie Lagoon (Ivory Coast) showed that the sources of nitrogen and BOD into the lagoon were primarily anthropogenic (Scheren et al. 2004). Reduction of non-point source pollution (urban and agricultural) was determined to have the most effective results.

The metal content of Porites coral collected at the Hija River mouth (Okinawa) was analyzed for anthropogenic metal inputs (Ramos et al. 2004). Lead enrichment in the corals was noted, as was the potential for continued Mn, Cd, Zn and Ag enrichment. Lead concentrations were likely elevated because of its increased ability to partition to the sediments and be readily available for uptake. Kurkjian et al. (2004) used lead isotope modeling to predict the long-range, downstream effects of urban runoff and acid mine drainage on the Debed River (Armenia). Lead concentrations increased after the river passed through the urban area and decreased after interactions with  $Al(OH)_3$ , causing lead precipitation in the river.

Leishman et al. (2004) demonstrate the enrichment of soil phosphorus below urban stormwater outlets in Australia. Natural enrichment was shown to be highly unlikely; therefore the enrichment has been attributed to the phosphorus content of the runoff water, which binds with the soil particles. Filoso et al. (2004) modeled the nitrogen transport in the Ipswich River basin (Massachusetts) using HSPF and showed that land use changes from undeveloped to urban resulted in increased stream nitrogen concentrations. High density residential lands generated the highest N concentrations according to the model.

Fecal coliform loadings from an urbanizing watershed were simulated in HSPF for Polecat Creek watershed (Virginia) (Im et al. 2004). While loads were slightly underpredicted, HSPF was able to reasonably represent the hydrology and microbiological water quality in the watershed and could be used as a planning tool for predicting the impacts of urbanization.

Cunningham and Wilson (2003) reviewed the accumulation of marine debris on beaches in the Greater Sydney Region (Australia). The vast majority (89.8%) of debris was plastic, particularly hard plastic (52.3%) predominantly originating from stormwater or beachgoers.

Boxall et al. (2003) investigated the changes in water quality parameters due to in-sewer processes. The results highlighted the hydraulic differences between storm and dry weather conditions, such as increased travel times and mixing under storm conditions. Chemical reactions and decay within the sewer system were found to be consistent with oxygen limitation.

Johannesson et al. (2003) investigated the influence on sediment geochemistry of an urban stream that is heavily impacted by contaminated urban runoff in Goeteborg Harbor, Sweden. The metals were highly associated with total organic carbon (TOC) in both the stream and harbor sediment, but were negatively correlated to fine-grained particles ( $<16 \mu m$ ). Bloom et al. (2003) assessed particulate and dissolved dioxin concentrations in stormwater runoff reaching Houston (TX)-area

waterways. High-volume sampling was used because of the typically-low concentrations in runoff.

Washburn et al. (2003) studied the spatial scales and the evolution of stormwater plumes in Santa Monica Bay. Salinity maps showed that the plumes typically extended 4.7 km offshore and 10 km or more alongshore. Carrasco et al. (2003) assessed the levels of urban and industrial contamination in the Bay of Cadiz, Spain. Physical-chemical data revealed that sediments and waters analyzed were moderately contaminated. No significant differences were found between rising and ebbing tide conditions. Yang and Carlson (2003) reviewed the evolution of antibiotic occurrence in a Colorado river through pristine, urban and agricultural landscapes. By the time the river had exited the urban area, 6 of the 11 antibiotic compounds that were monitored were found in the samples. At Site 5, which had both urban and agricultural influences all five of the tetracyclines monitored were detected indicating both urban and agricultural influences.

Diamond et al. (2001) found that the effects of toxicants depended on a combination of both chemical and flow characteristics. Conventional laboratory testing of toxicants with constant exposure concentrations are not very applicable to wet weather flow conditions. They surveyed more than 30 toxicological investigations that have used time-dose or pulsed/intermittent exposure, 15 contaminants, and 10 different species. They concluded that it is possible to predict the chronic effects of fluctuating exposures of fast-acting contaminants (such as ammonia or sodium chloride) using available acute toxicological models. Wong et al. (2001) developed a monitoring method using the green alga *Selenastrum capricornutum* to predict levels of heavy metals in water. When exposed to stormwater samples, the specific activity of the peroxidase in the cell extract was directly related to the copper and lead concentrations. The peroxidase responses were also correlated with the 96 hr biomass toxicity assay of *S. capricornutum*. They concluded that the use of this peroxidase can be used as a marker for testing heavy metal toxicity in the water.

Work by Standley et al. (2000) demonstrated that the source of the impacts on a receiving water could be determined using molecular tracers. Polycyclic aromatic hydrocarbons were seen to be excellent tracers for evaluating pollution from urban runoff, while caffeine plus consumer product fragrance materials were excellent markers for WWTP effluent. The investigation by Foster et al. (2000) showed that higher amounts of PCBs, PAHs and organochlorine pesticides in the Anacostia River were associated primarily with the particulates and occurred during high flow events. Analysis of the PAHs showed that they were characteristic of weathered or combusted petroleum products. Aromatic hydrocarbons in urban runoff were found to be likely sources of PAH fluxes to the tidal waters of Chesapeake Bay. O'Meara et al. (2000) described the work done to remove 556,000 Mg of sediment and 12,700 kg of fish contaminated with PCBs from Newburgh Lake in Wayne County, Michigan. The result was that the lake was found to be fit for human recreational activity. Shinya et al. (2000) investigated the concentrations of metals and PAHs in the runoff from four urban-highway rainfall drains. The results showed a first flush of both metals and PAHs. Most of the metals were tied up with the particulate matter, as were the higher molecular weight PAHs. Mutagenicity was appreciably associated with the PAHs in the particulate fraction, although the dissolved fraction also showed positive mutagenic response.

The impacts of combined sewer overflow solids were predicted using a model that could describe the solids movement and the erosion of previously-deposited solids in the sewers (Saul et al. 2000). This model was then used to predict the quantity and arrival time of the first flush of sewer solids into a receiving water after a rainfall.

Oberts et al. (2000) reviewed the impacts of snowmelt on urban water quality. They reviewed research on urban snowpacks accumulating large quantities of solids and other pollutants from sources such as airborne fallout, vehicular deposition, and applied grit and salt. They also reported on instances where the first flush of snowmelt has been found to be highly toxic and where water quality deterioration due to snowmelt runoff have been documented.

Stieber et al. (1999) statistically related the pollutant load in urban runoff to interevent dry period and rainfall intensity with the ultimate goal of developing a simple relationship between the rain variables and the pollutant loads. The relationship could be used by planners and engineers to evaluate the effectiveness of pollutant reduction mechanisms. Bamford et al. (1999) investigated the fluxes of PAH at the air-water interface of the Patapsco River and found that the fluxes were highest adjacent to stormwater discharges due to the elevated concentrations of PAH in the stormwater runoff. A major source of the PAH, benzo(ghi)perylene, pyrene and fluoranthene in the rivers in the Paris metropolitan area was found by Ollivon et al. (1999) to be car-park dust due to motor vehicle combustion. During heavy rainfall events, PAH primarily were leached from urban surfaces and transported to the rivers. Zheng et al. (1999) related the high concentrations of petroleum hydrocarbons and PAH in Hong Kong marine sediments to the heavily urbanized or industrialized areas surrounding the most heavily polluted sites. They showed that the oil and its products were the major sources of hydrocarbons in sediments. Stormwater runoff from an urban highway in Xi'an, China was shown by Zhao et



al. (1999) to contain BOD, COD and suspended solids concentrations at least as strong as typical domestic effluents. However, the biodegradability of the organic compounds in the runoff (BOD:COD = 0.167) was low. Regression equations were developed for BOD and COD and for suspended solids and COD in urban runoff from the highway. Gupta et al. (1999) investigated the sources of pollutants to Talkatora Lake in Jaipur, India. They found, using a mass balance of the lake, that the major cause of pollution to the lake was the first flush of stormwater runoff from the adjacent residential and commercial areas.

Bendoricchio et al. (1999) demonstrated that nutrient concentrations in runoff varied during rain events and that the deterioration of water quality in the Lagoon of Venice, Italy, was related to the diffuse pollution sources in the watershed. As the point sources of pollution were controlled, the relative importance of NPS increased, and effectiveness of the Lagoon restoration would depend on controlling the diffuse sources of the nutrients. A water quality index (WQI) was developed by Peters and Kendell (1999) for streams in the Atlanta, Georgia region, and the sampling data showed that the WQI for nutrients was best for the low-density residential areas and worst for the industrial area. Yung et al. (1999) investigated the physico-chemical and biological changes in Victoria Harbor, Hong Kong and found that water temperature, total and ortho-phosphorus, and fecal bacteria were increasing, while pH, total nitrogen, TKN, BOD and chlorophyll a were decreasing. However, sampling sites not in the main Harbor did not reflect these trends, although all sites reflected the fact that Victoria Harbor and its vicinity were polluted by sewage effluent, stormwater runoff, marine traffic, construction, and industrial activities.

Crosbie and Chow-Fraser (1999) investigated the impact of land use on the water and sediment quality in 22 marshes in Ontario, Canada. The concentration of inorganic solids, sediment phosphorus, metolachlor, and ionic strength were positively correlated with the percentage of agricultural land in the watershed, while the concentrations of PAH were positively correlated with the percentage of urban land. Heal (1999) demonstrated the accumulation of copper, nickel and lead in the sediments of a wetland and two detention ponds receiving urban storm runoff in Scotland. Sediment metals concentrations, however, were highly variable within each structure, possibly indicating short-circuiting through the ponds and wetland. Platinum, palladium and rhodium were found in road sediments by Rauch et al. (1999) with their concentrations increasing since 1984. The increase in bioaccumulation of rhodium in *Aseltus aquaticus* in urban rivers was linked to the increased sediment concentrations of these automobile-derived metals. Shafer et al. (1999) investigated the partitioning of trace metal levels (Al, Cd, Cu, Pb, and Zn) in Wisconsin rivers and found that the concentrations in the rivers were comparable to recent data collected in the Great Lakes and other river systems where 'modern' clean methods were used for sampling and analysis. They also found that the variation in the partitioning coefficients of each metal between sampling locations could be explained by the amount of anthropogenic disturbance in the watershed and by the concentration of dissolved organic carbon (DOC) in the water.

Arid western rivers have many characteristics that distinguish them from rivers in more temperate areas. The Denver area's South Platte River, in which flow is dominated by municipal effluent, has the following characteristics: nutrient abundance; wide, shallow and unshaded channel; high primary productivity produces variations on pH that can have a strong influence on nonionized-ammonia concentrations (Harris *et al.*, 1996).

Inaba *et al.* (1997) studied the effects of trace metals, e.g., cobalt (Co) and Fe in sanitary wastewater. Elevated concentrations have been shown to increase the frequency of algal blooms in water bodies. Haygarth and Jarvis (1997) studied the transfer of P and N by stormwater runoff from cattle grasslands and concluded that grassland soils are a significant source of diffuse P inputs to surface and estuarine waters and may cause eutrophication.

The physical and chemical properties of sediment in a stormwater pond were studied. Analysis of the sediment determined that Cr, Cd, Cu, Fe, Pb, manganese (Mn), Ni, and Zn were present (Marsalek *et al.*, 1997). In a study to investigate the fate of infiltrating stormwater runoff, natural-organic matter facilitated metal transport into near surface soils (Igloria *et al.*, 1997). The metal transport was a function of volume and depth of stormwater and increased concentrations of natural-organic matter allowed for greater metal attenuation.

Hay and Battaglin (1996) described how an integrated system consisting of a large historical receiving-water-quality database, a geographic-information system (GIS), a scientific-visualization system, and multimedia software are used to produce an interactive data-analysis tool. The integrated system allows users to analyze the data in the U.S. Geologic Survey's (USGS) National Stream Quality Accounting Network (NASQAN), describes the water quality of the Nation's streams and rivers on a systematic basis and to identify temporal trends in the concentration of measured constituents. Stream water-quality data from NASQAN and USGS's Hydrologic Benchmark network are now available on CD-ROM

(Alexander *et al.*, 1996). These networks provided some of the best available data for quantifying changes in the water quality of major United States streams during the past 20-30 years, estimating the rates of chemical flux from major continental watersheds of the United States, and investigating relations between water quality and streamflow as well as water quality to watershed characteristics and pollution sources.

Sampling and monitoring of New York City's Jamaica Bay have confirmed the eutrophic state of some areas of the Bay (Fitzgerald *et al.*, 1996). It is known that the probable root causes of this problem are both the extremely high nutrient loading to the Bay from anthropogenic sources as well as the lack of adequate flushing also resulting from human intervention.

Glazewski and Morrison (1996) presented results showing the effects of photoreduction of Cu in urban streams. It was concluded that pollutant speciation and potential toxicity of Cu, Cr, and Fe is greatly affected by photoreduction reactions.

### **Toxicity**

Lewis *et al.* (2006) used microbial genotoxicity as an environmental indicator of impacts from stormwater runoff. Genotoxicity was observed in one-quarter of the golf course pore water and three-quarters of bayou sediments. Sediment and water toxicity in a small urban river in Denmark was investigated by Christensen *et al.* (2006). The results showed that urban and road runoff slightly (but with statistical significance) affected the reproduction of an algae.

Water quality changes during a storm event were continuously monitored over a 24 h period at a single location along an urban stormwater drain in Butte, Montana (Gammons *et al.* 2005). The results showed that infrequent storm events had the potential to generate large runoff volumes whose water quality exceeded Montana standards for acute exposure of aquatic life to copper, as well as depressed levels of dissolved oxygen. Accumulation of polybrominated diphenyl ethers (flame retardants) in the eggs of marine and freshwater birds was studied in British Columbia by Elliott *et al.* (2005). The concentrations in eggs of both herons and cormorants were calculated to be 5.7 years. The toxicity of two herbicides, glyphosphate and diuron, was measured in highway runoff using standard toxicity tests (Huang *et al.* 2005). The results showed no additional toxicity due to these herbicides at the concentrations found in the runoff.

Bay *et al.* (2003) investigated the water quality impacts of urban stormwater discharges to Santa Monica Bay. Surface water samples collected within the Ballona Creek (urban watershed) stormwater discharge plume were always toxic whenever the concentration of stormwater in the plume exceeded 10%. Toxicity identification studies indicated that zinc was the primary cause of toxicity in both Ballona Creek stormwater and the discharge plume. Gersberg *et al.* (2003) studied the temporal pattern of runoff toxicity in the Tijuana River Watershed. Toxicity of waters in the Tijuana River was generally low under baseflow conditions, but increased markedly during high flow runoff events. The temporal pattern of toxicity, both during a given storm event and seasonally, indicated that wash-off by rainfall may have depleted the supply of toxicity available for wash-off in subsequent events. Boulanger and Nikolaidis (2003) investigated the mobility and aquatic toxicity of copper from copper-based products used in an urban watershed. Despite exceeding the dissolved concentration based criteria, cupric ion concentrations at the system outlet remained below 0.05 µg/L for all storms analyzed, and no acute toxicity (using *Daphnia pulex* as the test organism) was measured in samples collected from the stream.

Milam *et al.* (2000) investigated the effects of several pesticides (chlorpyrifos, malathion, Permethrin(R), Abate(R), Scourge(R), B.t.i. and Biomist(R)) on both standard toxicity-testing organisms (*Ceriodaphnia dubia*, *Daphnia magna*, *Daphnia pulex*, and *Pimephales promelas*) and resident mosquito fish and mosquito larvae. They demonstrated that the current pesticide application rates were sufficient to affect non-target organisms when the pesticides were washed off in stormwater runoff.

Toxicity of river sediment near major cities on the Mississippi River was evaluated, both up- and down-river of the cities, and was not found to be toxic to the organisms studied (Winger and Lasier, 1998). Most stormwater samples from Ballona Creek which is one of the largest sources of stormwater inputs to Santa Monica Bay, Calif. were toxic (Jirik *et al.*, 1998). Receiving water samples were also toxic, with the magnitude of effects generally corresponding to the concentration of runoff present. The study implicated divalent trace metals, particularly Zn as the probable toxic constituents.

One of the key objectives of the Chesapeake Bay restoration effort is to reduce the impacts of toxicants. Alden and Hall

(1996) described the Toxics Reduction Strategy based on water-column- and sediment-chemical analyses, benthic-community health, and fish-body burdens. More than 40% of the sites have displayed some degree of water-column toxicity and about 70% of the sites have displayed sediment toxicity. Garries *et al.* (1996) further described how the list of Toxics of Concern was developed for Chesapeake Bay.

The need for endpoints for assessments using multiple stressors was discussed by Marcy and Gerritsen (1996). Five watershed-level ecological-risk assessments were used to develop appropriate endpoints based on specific-project objectives. Dyer and White (1996) also examined the problem of multiple stressors affecting toxicity assessments. It was thought that field surveys rarely can be used to verify simple single-parameter-laboratory experiments. A watershed approach integrating numerous databases in conjunction with *in-situ* biological observations to help examine the effects of many possible causative factors was developed. *Environ. Sci. & Technol.* (1996a) reported that toxic-effect endpoints are additive for compounds having the same “mode of toxic action”, enabling predictions of complex-chemical mixtures in water. According to EPA researchers at the Environmental Research Laboratory in Duluth, MN, there are about five or six major action groups that contain almost all of the compounds of interest in the aquatic environment. Much work still needs to be done but these new developing tools may enable the instream toxic effects of stormwater to be better predicted.

Ireland *et al.* (1996) found that exposure to UV radiation (natural sunlight) increased the toxicity of PAH-contaminated-urban sediments to *C. dubia*. The toxicity was removed when the UV wavelengths did not penetrate the water column. Toxicity was also reduced significantly in the presence of UV when the organic fraction of the stormwater was removed. Photo-induced toxicity occurred frequently during low-flow conditions and wet-weather runoff and was reduced during turbid conditions.

Johnson *et al.* (1996) and Herricks *et al.* (1996a) described a structured-tier-testing protocol to assess both short-term and long-term wet-weather-discharge toxicity that was developed and tested. The protocol recognizes that the test systems must be appropriate to the time-scale of exposure during the discharge. Therefore, three time-scale protocols were developed, for intraevent, event, and long-term exposures. The use of standard-whole-effluent-toxicity (WET) tests were found to over-estimate the potential toxicity of stormwater discharges.

Schueler (1996c) summarized *in-situ* assessment methods of stormwater-impacted sediments. The use of *in-situ*-test chambers, using *C. dubia* eliminates many of the sample disruption problems associated with conducting sediment-toxicity tests in the laboratory. Arhelger *et al.* (1996) presented the results of a study of toxicity in the Houston Ship Channel area that included analyses of water and sediment toxicity. A comparison of the toxicity of sediments from all stations to *Ampelisca abdita* versus all available physical and chemical data led to the conclusion that the toxicity was most likely related to sediment-oxygen demand.

The results of studies conducted by Crunkilton *et al.* (1996) were inconclusive in determining if toxicants alone played a role in observed degradation of a stream community. This question was posed because most stormwater-remediation efforts implemented to protect streams have focused on mitigating physical degradation of habitat. In an assessment of the response of aquatic organisms to short-term exposures to urban storm runoff, Herricks *et al.* (1996b) found that toxicity testing in single events may not be predictive of long-term effects in receiving waters but multiple event analysis provides information on sources and variability of toxicity that is useful in watershed management. Similarly, Herricks *et al.* (1996c) found that commonly used toxicity-testing techniques of long-exposure times to constant concentrations will not adequately predict short-term toxicity.

The effects of stormwater on Lincoln Creek, near Milwaukee, WI, were summarized by Claytor (1996b). The Creek drains a heavily-urbanized watershed of 19 mi<sup>2</sup> and is 9-mi long. On-site-toxicity testing was conducted with side-stream flow-through aquaria using fathead minnows plus instream-biological assessments along with water- and sediment-chemical measurements. The continuous flow-through-mortality tests indicated no toxicity until after about 14 days of exposure, with more than 80% mortality after about 25 days, indicating that short-term toxicity tests likely underestimate stormwater toxicity. The biological- and physical-habitat assessments supported a definitive relationship between degraded-stream ecology and urban storm runoff.

Rainbow (1996) presented a detailed overview of heavy metals in aquatic invertebrates. It was concluded that the presence of a metal in an organism cannot directly prove whether that metal is poisoning the organism. However, if compared to concentrations in a suite of well-researched biomonitors, it is possible to determine if the accumulated

concentrations are atypically high, with a possibility that toxic effects may be present. Allen (1996) also presented an overview of metal-contaminated-aquatic sediments. This book presents many topics that would enable the user to better interpret measured heavy-metal concentrations in urban-stream sediments.

Pitt *et al.*, (1996b) reported on various laboratory-toxicity tests using 20-stormwater and -CSO samples. It was found that the most promising results are associated with using several complementary tests, instead of any one-test method. However, simple screening-toxicity tests are useful during preliminary assessments or for treatability tests.

A number of papers presented at the 7th International Conference on Urban Storm Drainage, held in Hannover, Germany (Sieker and Verworn 1996), described receiving-water studies that investigated organic- and heavy-metal toxicants. Handová *et al.* (1996) examined the bioavailability of metals from CSOs near Prague, Czech Republic. The results were compared with biomonitoring. The metals were ranked according to their mobility as: Cd (95%), Zn (87%), Ni (64%), Cr (59%), Pb (48%), and Cu (45%). The mobile fraction was defined as the metal content that was exchangeable, bound to carbonates, bound to iron and manganese oxides, and bound to organic matter. Boudries *et al.* (1996) and Estèbe *et al.* (1996) investigated heavy metals and organics bound to particulates in the River Seine near Paris, France. The Paris CSOs caused a significant increase in the aliphatic and aromatic hydrocarbons bound to river sediments. The high flows during the winter were associated with lower heavy metal associations with the sediment, compared to the lower summer-flow conditions. These differences were found to be due to dilution of the CSOs in the river and to the changing contributions of rural versus urban SS during the different seasons.

### ***Habitat Management and Restoration***

Van Duin and Garcia (2006) investigated the impacts of urbanization on a Canadian Creek. The increased runoff rates were shown to be affecting the fisheries habitat through changed hydrologic regime and stream morphology.

Matsuyama (2005) identified the challenges facing any wetlands restoration in southern California. Many of these challenges were related back to the extensive development in the affected basins. Martinez Fernandez *et al.* (2005) reviewed how a hydrologic model has been used to simulate the impact of heavy rainfall events on nutrient concentration in a coastal lagoon in the western Mediterranean (Mar Menor). The current research investigated how this increased nutrient load has impacted the aquatic bird communities. Grebe appearance and abundance seemed to follow the nutrient cycle. One of the piscivore birds was not affected by the increased eutrophication.

Schindwein (2005) placed stream restoration and probability for success into a broader Quaternary classification. This classification was shown to greatly affect historical floodplain and stream channel evolution. Jin *et al.* (2005) compared reference and impaired streams for the quality of their aquatic habitats. Parameters investigated were bottom substrate, cover, flow conditions, channel geometry, sediment deposition, bank stability, vegetation and streamside cover. Niezgoda and Johnson (2005) identified relationships between channel form and processes that are critical to urban stream restoration. The authors proposed that further research occur in the area of process-based methodologies. Trumbauer and Straughan (2005) examined the development-induced changes in stream channel morphology. The study goal was to develop a tool that allows water resources managers to better control indirect impacts to water resources given specific watershed characteristics and stream morphology. Smith and Prestegard (2005) investigated hydraulic performance of a morphology-based stream channel design for urban stream restoration. The findings illustrated the need for more consideration of the relationship between channel stability and hydraulic conditions at multiple locations along a stream and over a range of flow conditions.

Maloney *et al.* (2005) examined the influence of military land disturbances on stream physical characteristics and organic matter. Stream instability was related to the percent of disturbed land. Organic matter was correlated with the percent of disturbed land and road cover. White and Greer (2005) documented the effects of watershed urbanization on the stream hydrology and riparian vegetation of a California creek. Urbanization has dramatically changed the streamflow characteristics and channel geomorphology. This has resulted in changes in the historic riparian vegetation community. Matthews (2005) reviewed the restoration of several stream meanders in Little Sugar Creek (Mecklenberg County, North Carolina), including the demolition of concrete-lined banks and a dam-sluice gate structure. Bank stabilization was performed by planting trees and shrubs. Constructed riffles were also included in the restoration design to provide habitat for the aquatic biota.

Kreutzberger *et al.* (2004) reviewed the efforts of the “watershed approach” implemented by Charlotte, North Carolina, in mitigating the effects of urban stormwater runoff. This effort has shown that a combination of BMP and stream/wetland

restoration projects within the focus areas can reduce annual sediment loading in the range of 30 to 50 percent within the focus areas.

Uluocha and Okeke (2004) reviewed the implications of wetlands degradation and the lessons learned in Nigeria. White et al. (2004) compared the water quality in an urbanized versus a relatively-pristine salt marsh estuary in the southeastern United States (South Carolina). Summer chlorophyll *a* concentrations were typically higher in the urbanized estuary, as were salinity and inorganic nutrients. The biotic health of lotic communities typically is negatively correlated with the amount of urban land in a watershed (Miltner et al. 2004). The health of streams, as measured by the Index of Biotic Integrity, declined significantly when the amount of urban land use measured as impervious cover exceeded 13.8%, and fell below expectations consistent with Clean Water Act goals when impervious cover exceeded 27.1%.

Murdock et al. (2004) investigated the relationship between flow, nutrients and periphyton in a heavily impacted urban stream. Floods capable of scouring all visible periphyton from the stream were produced from rainfall events as small as 1.3 cm (47 periphyton biomass reset events in 22 months) and the high frequency of these flood events limited the development of a steady-state assemblage of periphyton.

Krause et al. (2004) examined the influences of urban development on the thermal habitat of Back Creek watershed (Virginia). It was estimated, using HSPF and the Stream Network Temperature Model, that development and the resultant loss of shade cover could cause increases of 1oC, which would cause the stream to violate state temperature regulations and could impact the fish communities. Li and James (2004a and 2004b) developed a general model to compute runoff temperature with fine resolutions of both time and space. The model was then calibrated/verified using data from an urban shopping mall and from a treatment wetland. The resultant model, called HEATRAN, computed runoff temperature directly using a distributed heat balance that reflected the temperature contributions from overland surface flow, enclosed pipe flow, open channel flow and pond effects.

Link (2003) presented the idea of “managing bankfull, sinuosity and shopping carts in urban stream restoration projects.” The idea presented is one that a successful restoration project should not just focus on restoring the natural functions of streams but also on public education to control illegal dumping and further deterioration of streams’ riparian areas.

Valkenburg and Johannes (2003) presented a case study of urban stream restoration: Davis Creek. The primary technique used in stream restoration and focused on in the paper was timely sediment removal. Baker (2003) reviewed the restoration of Gypsum Creek, an urban stream in Wichita, KS. The success of the project depended solely on the improvement of stream habitat and aquatic life. The paper presented the methodology used to conduct the following assessments: the Water Quality and Aquatic Habitat Assessment, the Wetland and Riparian Area Assessment, and the Fluvial Geomorphic Assessment. Landers (2003e) reviewed the use of a water-quality trading program to restore natural river flows in the Charles River and its tributaries in northeastern MA.

Aquatic life impairments make up a large proportion of the 303(d) listed water bodies nationwide. Martin, *et al.* (2002) report that in Virginia, approximately 35 percent of the impaired streams are listed on the 303(d) list because of aquatic life impairments. Virginia and EPA, working with Tetra Tech, Inc., have developed a Total Maximum Daily Load (TMDL) methodology to evaluate streams having impaired benthic communities. The TMDL process establishes a link between the impairment and benthic community stressors. The reference watershed selection process is based upon a comparative analysis of key watershed attributes. The Virginia Ridge and Valley Multimetric Bioassessment Index (VRVMBI) was developed specifically for this project using metric discrimination analyses. This process reviewed water and sediment quality data, toxicity test results, and physical processes to determine the primary causes of impairment. Impaired and reference watersheds were modeled to determine the conditions necessary to support a healthy benthic community.

A number of stream restoration efforts have been carried out in small watersheds in Maryland for the past ten years. The goal of virtually all of the restoration projects was to reduce high sediment supply from bank and bed erosion and to increase sediment transport, thus restoring a condition of equilibrium between sediment supply and sediment transport.

The purpose of the EPA-funded Arid West Water Quality Research Project is to conduct scientific research to develop appropriate water quality criteria and improve the scientific basis for regulating wastewater and stormwater discharges in the arid and semi-arid West. Meyerhoff et al. (2001) described a study where historical and site reconnaissance level data were gathered on ten effluent dependent waters. They found that while the aquatic community may be limited, significant

benefits occurred in the terrestrial communities that developed in response to the created aquatic environment. Based on the concerns raised during this research, the EPA's Region IX published a "net ecological benefit" guidance document that provided an opportunity to recognize the non-aquatic benefits gained from effluent discharged to otherwise dry riverbeds.

Bragg and Kershner (1999) investigated another aspect of biological impacts – the impact on the habitats of aquatic life – and they found that coarse woody debris in riparian zones can be used successfully to maintain the integrity of these ecosystems. Larson (1999) evaluated the effectiveness in urban areas of these habitat restoration activities using large woody debris and found that in urban areas, the success of restoration may be hindered by the high sediment loads and increased flow associated with urbanization. Markowitz et al. (1999) documented the CSO Long Term Control Plan implemented by the City of Akron, Ohio which focused on habitat preservation and aquatic life use of the receiving waters. The plan included these non-traditional alternatives: riparian setbacks in undeveloped areas, stream restoration, linear parks or greenways and artificial riffles for stream aeration, and were found to cost less than five percent of the typical cost of controlling CSO flows. A methodology to investigate the chronic and cumulative degradation of the river Orne due to CSO and urban runoff was presented by Zobrist et al. (1999), with the results being used to evaluate management activities. O'Meara et al. (1999) reported on the restoration of Newburgh Lake on the Middle Rouge River in Wayne County, Michigan. The \$11.8-million restoration consisted of removing PCB-contaminated sediment and fish, construction of new fish habitat, and restocking of beneficial fish and aquatic plants. Xu et al. (1999) reported on the improvement plan being used for a river passing through the downtown area of a city in Western Japan and the problems that were inherent with developing a compromise strategy between flood control and mitigation and the desire to have an attractive waterway through the city. The final improvement plan recommended construction of a new flood drain tunnel and a new underground flood control reservoir.

Cianfrani et al. (1999) used a GIS system to document the results of a comprehensive inventory of the natural resources of the Fairmount Park (Philadelphia, Pennsylvania) stream system, including vegetation communities, fish, aquatic and terrestrial insects, birds, mollusks, amphibians, reptiles, and streams. The stream assessment also included the characterization of stream reaches by in-stream habitat, geomorphology and riparian zone. This GIS inventory then was used in planning the restoration of sites in the Fairmount Park system. Derry et al. (1999) reported on the habitat management strategies implemented by the City of Olympia, Washington, to control the degradation of aquatic habitats by urban stormwater runoff. These management strategies provided a basis for resolving the conflict between growth and the protection of aquatic resources. Ishiakwa et al. (1999) reported on the efforts to restore the hydrological cycle in the Izumi River Basin in Yokohama, Japan while Saeki et al. (1999) have documented the efforts of the Tokyo Metropolitan Government and its Basin Committee to restore the natural water cycle in the Kanda River. Kennen (1999) investigated the relationship between selected basin and water-quality characteristics in New Jersey streams and the impact on the macroinvertebrate community and its habitat. He found that urban areas had the greatest probability of having impacted stream areas, with the amount of urban land and the total flow of treated sewage effluent being the strongest explanatory variables for the impact. He also found that levels of impairment were significantly different between the Atlantic Coastal Rivers drainage area and the Lower Delaware River drainage area.

Jarrett et al. (1999) analyzed the data collected from 1991 through 1998 as part of the stream-monitoring program implemented in Louisville and Jefferson County, Kentucky. They found that recreational contact standards for fecal coliforms were exceeded during WWF and that much of the pollutant loadings of suspended solids and BOD were also contributed by WWFs. However, they found that the nutrient loadings were more varied with some impact seen from wastewater treatment plants. The concentrations of phosphate, total phosphorus, and total volatile solids in the streams were reduced as more of the watershed was sewered. Reduction of eutrophication through the treatment of stormwater runoff with storage facilities and wetlands for Lake Biwa was proposed by Hidaka et al. (1999). It was estimated that this storage and treatment could reduce the COD load to the lake by nearly 70%. However, wetlands could be overloaded and the water quality of its effluent degraded, as demonstrated by Noguchi et al. (1999) in their study of the regulation pond/wetland in Isahaya Bay, Japan. In order to prevent eutrophication of the regulatory pond it was found to be necessary to control nonpoint sources of nutrients in runoff.

Changes in physical stream channel characteristics can have a significant effect on the biological health of the stream. Schueler (1996a) stated that channel geometry stability can be a good indicator of the effectiveness of stormwater control practices. In addition, once a watershed area has more than about 10-15% effective impervious cover, noticeable changes in channel morphology occur, along with quantifiable impacts on water quality, and biological conditions. Stephenson (1996) studied changes in stream-flow volumes in South Africa during urbanization. Increased stormwater runoff,

decreases in the groundwater table, and dramatically decreased times of concentration were found. The peak flowrates increased by about two-fold, about half caused by increased pavement (in an area having only about 5% effective-impervious cover), with the remainder caused by decreased times of concentration.

### ***Environmental Effects of CSO and SSO***

Black and Endreny (2006) evaluated the impact of combined sewer separation on stormwater outfall duration, magnitude and volume in Syracuse, New York. The separation increased the runoff duration, magnitude and volume of the separate stormwater discharges at the prior CSO outfall, as this runoff was no longer being partially directed to the wastewater treatment facility. Rechenburg et al. (2006) investigated the impacts of treatment plants and CSO basins on the microbial quality of surface waters. During storm events, downstream (below CSO discharge locations) concentrations were two logs higher than dry weather conditions. The annual load from the CSO was greater than the annual load from the treatment plant. Fugate and Chant (2006) calculated the aggregate settling velocity of CSO water. A strong inverse relationship between the size of the aggregates and the aggregate density were used to calculate fractal dimensions of the aggregates.

The study by Westphal et al. (2005) was designed to identify the sensitivity of the river to point and nonpoint source pollution. The study conclusions will be based on comprehensive in-stream monitoring of approximately 135 km of river and simulation models that will predict the effects of CSO and urban runoff abatement.

Woodward et al. (2004) reviewed the Overflow Abatement Program (OAP) implemented by the City of Nashville (Tennessee). The Program includes a comprehensive water quality monitoring program that is used to provide data to determine the need for stormwater abatement facilities.

Hughes et al. (2004) investigated the effects of CSOs and SSOs on the Rouge River Basin (Michigan). The purpose of the project was to implement an intensive monitoring program to assess existing conditions, identify primary pollution sources, and track long-term trends. Components include continuous monitoring of dissolved oxygen (DO), temperature, flow, and rainfall; intermittent dry and wet weather water quality sampling; and periodic assessments of the trophic status of major impoundments, stream geomorphology, sediment quality, and macro-invertebrate populations. Oxygen deficits downstream of a CSO outfall in the Seine River (France) were modeled by Even et al. (2004). The relevant variables in explaining the oxygen deficit were the quantity of bacteria from the overflow and the concentration of biodegradable dissolved organic carbon. In addition, the CSO was toxic to phytoplanktonic photosynthesis.

Garcia and Allen (2003) reviewed the lessons learned from the C21 sanitary sewer failure at the Trinity River (Dallas, TX), which was caused by a massive failure in the south bank of the river. Johnson and Cave (2003) discussed the project to restore and protect the quality of the Rouge River, where the project included controlling CSOs and other nonpoint sources of pollution and implementing watershed management practices.

Greer and Stow (2003) investigated the conversion of vegetation types in Los Penasquitos Lagoon, CA as a function of watershed urbanization using aerial photography. Increases in the areal extent of urban development within the watershed was positively correlated to the areal extent of brackish marsh and riparian vegetation, and negatively to the areal extent of salt panne and mudflats. There was no significant relationship between urban development and salt marsh vegetation.

Yingling and Haywood (2002) discussed the strategies needed to reduce flooding in the Doan Brook watershed in northeast Ohio. The problem has been caused by CSOs, channelization through the park, and restrictive bridge crossings. Jones et al. (2002a) reviewed the difficulty of assessing CSO water quality impacts Kokomo, Indiana, when the CSOs discharge into two Operating Units of the Continental Steel Superfund Site with the pollutants of concern being heavy metals and organic chemicals.

O'Meara et al. (2002) reported on the Oxbow Restoration Project on the Rouge River. The purpose of the project is to enhance the ecological viability of the western-most Oxbow by creating valuable fish and wildlife habitat, restoring functioning riverine wetlands, improving water quality and modifying the existing CSO outfall.

Borchardt and Reichert (2001) describe their study of the River Lahn, a moderately polluted 5th order stream in Germany for which the connectivity of surface/subsurface flows and mass fluxes within river sediments have been intensively investigated. The hyporheic flow between a downwelling and upwelling zone of a riffle-pool reach of the river was studied using tracers and continuous records of water chemical characteristics. High diurnal fluctuations of oxygen

traveled to considerable depths in the sediment and oxygen levels in the interstitial water decreased considerably while traveling through the riffle reach. The resulting model is being used to examine the effects of CSO discharges. They found that CSOs may cause anoxic sediment oxygen conditions for extended periods of time. Michels (2001) described a CSO Basin study conducted on the Menominee River, MI, to see if the facility met the Michigan water quality standards and if it provided adequate treatment. Four sets of samples were collected upstream and downstream of the facility for comparison during discharge events. They found that the water quality standards were not violated during overflow discharges to the Menominee River.

CSO and SSO can have damaging impacts on receiving waters. Sanudo-Wilhelmy and Gill (1999) compared current pollutant concentrations in the Hudson River Estuary, New York with concentrations measured in the 1970's. The concentrations of Cu, Cd, Ni, and Zn have declined, while concentrations of dissolved nutrients ( $\text{PO}_4$ ) have remained relatively constant during the same period of time, suggesting that wastewater treatment plant improvements in the New York/New Jersey Metropolitan area have not been as effective at reducing nutrient levels within the estuary. Rather than inputs from point sources, the release of Pb and Hg from watershed soils, and Ni and Cu from estuarine sediments, may represent the primary contemporary sources of these metals to the estuary. Approximately 1,100 communities in the United States have combined sewer and stormwater systems whose capacity may be exceeded during moderate or heavy rainfall. Colford et al. (1999) proposed and applied three analytic methods to evaluate the impact of such outflows on public health. David and Matos (1999) discussed the difficulties of modeling and regulating the effects of CSO and stormwater discharges on the water quality in Portugal's rivers. Ephemeral river flows, rainfall patterns that differ from north to south, the effects of pollutant transport dynamics in sewers and pavements, and bed river resuspension during storms all influence river water quality. To understand the effect of CSO on the river Seine (France), a characterization of effluent in terms of organic matter and bacterial biomass was carried out during several sampling campaigns performed in a combined sewer located in Parisian suburbs under wet- and dry-weather conditions. The only two small differences in relative composition that could be observed between dry and wet weather were slightly lower content of organic carbon in suspended solids and a lower biodegradability of this material during rain events (Servais et al. 1999). Vollertsen et al. (1999a) characterized the biodegradability of combined-sewer organic matter based on settling velocity. Fast settling organic matter, which represents the largest fraction of the organic material, was found to be rather slowly biodegradable compared to the slow settling organic fraction. The biodegradability of sewer sediments was argued to be taken into account for detailed characterization when dealing with CSO impacts. Vollertsen et al. (1999b) investigated the effects of temperature and DO on kinetics of microbial transformation processes of suspended sewer sediment particles. No differences between sewer-sediment particles, wastewater particles and wastewater were found for the oxygen-saturation coefficients examined.

By means of measurements and numerical simulations, it was shown that the first flush of dissolved compounds effect caused a significant impact of dissolved compounds on the receiving water, when a CSO occurs, and also on the wastewater treatment plant when the sewer network was flat and catchment area was big (Krebs et al., 1999). Mason et al. (1999) showed that the Chesapeake Bay was an efficient trap for mercury. However, in the estuary, methylation of the mercury occurred, the Bay became a source of methylmercury, and on a watershed scale, only about 5% of the total atmospheric deposition of mercury was exported to the ocean. Venkatesan et al. (1999) investigated the potential for using sediment cores to determine the history of chlorinated pesticide and PCB application in a watershed. They found that the sediment cores accurately reflected the length of use of these chemicals in the watershed, and that the surface sediment layer, after mixing and resuspension was accounted for, reflected the reduction in use that had occurred during the last few years.

Bellefleur et al. (1999) summarized the data available on the water quality of combined sewer flow in Roeschwoog. The data that these flows impacted the physical and chemical water quality of the Sauer; however, an impact of CSO on the biological integrity was not easily seen. Classification of the rainfall into eleven types of events allowed the investigators to estimate the total loads from polluted overflows during a typical year. Herrmann et al. (1999a) found that the discharge of urea, which hydrolyzes to ammonia with a corresponding increase in pH, could cause fish toxicity after a CSO event. The concentration of ammonia plus urea in the combined sewer discharge was found to be a more relevant measure of the likelihood of a fish kill after an overflow event than the concentration of ammonia alone. Saul et al. (1999) investigated the production of undesirable solids in combined sewer flows as it related to social, economic and ethnic factors. The goals of the research were first to determine the differences in the characteristics of the solids in the sewers that were ultimately discharged to the receiving water and then to use the solids' characteristics to predict the efficiency of CSO treatment devices, especially CSO chambers. St. Michelbach and Brombach (1999) showed that the nutrient content, especially of dissolved phosphorus, from CSO and existing wastewater treatment plants (WWTP) was endangering the



health of Lake Constance. They proposed a simple methodology to estimate the nutrient loads from CSO to the Lake, the results of which can be used to determine the cost-effectiveness of CSO improvement versus WWTP improvement.

Fish and macroinvertebrate sampling defined and prioritized the needs of CSO systems and assessed where other watershed pollutants caused more harm than CSO (Markowitz, 1998).

CE-QUAL-W2 was used to determine the impacts of CSO during a four-year study to mathematically model the water quality of Cheatham Lake on the Cumberland River below Nashville, Tenn. (Adams *et al.*, 1997).

Mulliss *et al.* (1996) found that several wet-weather flow (WWF) discharge parameters regularly pose a serious threat with regard to freshwater aquatic- life. Widera and Podraza (1996) investigated instream biological conditions and water quality during 52 CSO events in three years in a small stream near Essen, Germany. Notable observations were that ammonium concentrations increased by up to 70 times during CSO discharges, protozoa counts were significantly higher downstream of the CSO, while macroinvertebrate counts showed little difference. However, the composition of the aquatic-life communities differed substantially between upstream and downstream locations, showing that common ecological indices (such as the index of diversity) are not suitable tools for detecting these changes because they do not correctly reflect the differences in community structure.

The main impact of a CSO is generally a decreased level of oxygen in the receiving waters, according to Seidl *et al.* (1996). An extensive monitoring program in a Paris, France suburb to measure the bacteria and organic carbon content of a combined sewer under both wet- and dry-weather conditions in order to more accurately predict the resulting dissolved-oxygen (DO) conditions was conducted. Lammersen (1996) examined DO and ammonia (NH<sub>3</sub>) conditions in receiving waters affected by stormwater in northern Germany. No events during a three-year-monitoring period were found to have caused critical conditions for these two parameters. Brosnan and O'Shea (1996) reported on the decrease in coliform bacteria concentrations in the receiving waters of New York's Hudson-Raritan Estuary. Among the contributors to this water-quality improvement is the increased capture of wet-weather CSOs.

### ***Risk Assessment***

Baun *et al.* (2006) proposed and evaluated a methodology (Ranking and Identification of Chemical Hazards or RICH) for ranking and identifying xenobiotic organics in stormwater runoff. This approach was applied to stormwater runoff to determine which compounds required monitoring. Roser *et al.* (2006) performed a microbial risk exposure assessment of an urban recreation lake in Australia. The studies resulted in the identification of a transition point where human-fecal pathogen risks increased. Urban drainage system hazard indicators were evaluated by Hauger *et al.* (2006). This evaluation included indicators of vulnerability and risk, as well. They proposed alternative definitions of risk as a function of the hazard.

Shen *et al.* (2005) reported on the effects of urbanization on water resources development in China. The hydrological system was documented to have changed significantly due to urbanization, including the loss of groundwater recharge as measured by the spatial distribution of tritium along the river. Khan (2005) used Landsat Thematic Mapper images and neural networks to link urban development and the increased risk of flooding in Houston, Texas. When land-use change data is compared with runoff ratio data, relationships between increased runoff and urban development become apparent. A hazard assessment of stormwater priority pollutants was conducted by Eriksson *et al.* (2005). The study demonstrated that forty xenobiotic organic compounds had hazard ratios above one, indicating that they were typically found in concentrations of concern. The authors demonstrated how a risk assessment methodology would be adaptable to other locales to assess the risks posed by their urban runoff. An innovative, risk-based approach to implementation planning for a bacterial TMDL was developed by the agencies discharging to Santa Monica Bay (California) (Susilo and Tam 2005). The plan uses an integrated water resources management approach. The model simulates the effectiveness of the preliminary sizing approaches for storage and treatment.

Sakai *et al.* (2004) discussed the management of rainfall-related environmental risks in urban areas, such as flooding and water-quality degradation. Risk management process and control options for rainfall-related risks were discussed and a scheme proposed to raise the risk perception level of urban residents.

Existing information was used by Nafu and Geiger (2004) to evaluate the effects of urban drainage on river water quality. The method included an approach to estimate urban imperviousness and sewer overflow volumes at the river basin scale. Results were compared to prior studies to determine compatibility. Chen *et al.* (2004a and 2004b) investigated the impacts

of low DO from CSOs on the health of fish in the Love River in South Taiwan. Based on those results, a system-based approach to minimize the ecological risk of CSOs was used with the focus of the approach is on maintaining the richness of the fish community and uses DO as an indicator of river health. Modeling was performed to document what effect of a detention pond on improving water quality in the river.

With water resources becoming tight in arid areas, Hammond (2004) estimated that approximately 10 GL/acre of stormwater was available for reuse in Adelaide, Australia, should it be decided to capture and reuse stormwater runoff.

Kimaro et al. (2003) evaluated land-use change effects on flood peaks in the Yasu River basin. The changes were detected using remote sensing and were incorporated into rainfall-runoff models which showed that the 2% increase in urbanization and the addition of golf courses predicted a 6% higher flood peak and 16-minute shorter travel times compared to 1976 data.

Sulski and French (2003) presented a use attainability analysis (UAA) of the Chicago Area Waterway System, which is impacted by sewer overflows. The purpose of the UAA is to determine if other use classifications are more appropriate for CAWS or any portions thereof.

Sutton (2003) proposed a scale-adjusted measure of urban sprawl, which can be used to predict environmental degradation, using nighttime satellite imagery. Cities that have more "Urban Sprawl" by this measure tended to be inland and Midwestern cities such as Minneapolis-St. Paul, Atlanta, Dallas-Ft. Worth, St. Louis, and Kansas City. The aggregate measures derived here are somewhat different than similar previously used measures in that they are 'scale-adjusted'.

Bosley et al. (2001) described a study on the Upper Roanoke River Watershed (URRW) in southwest Virginia, using HSPF to evaluate the hydrologic impacts of land use change. Continuous simulations were conducted to investigate the hydrologic effects of various spatial arrangements of development in residential areas, with and without networks of primary and secondary roads. Beckers and Frind (2001) used a steady-state stormwater model of the Oro Moraine aquifer in Ontario to examine long-term temporal variations in the flow regime associated with changes in aquifer recharge. They found that nearby urban development would have a significant impact on the baseflow to the swamp, in addition to baseflow impacts to nearby local streams. The model also is being used as a guide to future data collection in the area.

The Office of Water at EPA (1999) published *CSO: Guidance for Monitoring and Modeling* as a reference for persons and institutions involved in evaluating the effects of CSO on all users of an impacted receiving water. Bickford et al. (1999) reported on the methodology developed and implemented by Sydney Water to assess the risk to humans and aquatic organisms in creeks, rivers, estuaries and ocean waters from WWF. The model used in this study was designed to predict concentrations of various chemicals in WWFs and compare the values to toxicity reference values. Brent and Herricks (1999) proposed a methodology for predicting and quantifying the toxic response of aquatic systems to brief exposures to pollutants such as the contaminants contained in stormwater runoff. The method contains an event-focused toxicity method, a test metric (ETU, event toxicity unit) to represent the toxicity of intermittent events, and an event-based index that would describe the acute toxicity of this brief exposure. The toxicity metric proposed (PE-LET50 [post-exposure lethal exposure time]) was the exposure duration required to kill 50% of the population during a pre-specified, post-exposure monitoring period. Colford et al. (1999) proposed three methods of analytically evaluating the impact of storm sewer and combined sewer outflows on public health, especially in areas that may receive through deposition the harmful agents in sewage and combined sewage. In the Puget Sound region of the U.S. Pacific Northwest, Greenberg et al. (1999) developed and evaluated the Urban Stream Baseline Evaluation Method to characterize baseline habitat conditions for salmonids. The methodology, based on assessment of geomorphic suitability, fish distribution and habitat alteration, was recommended for use to prioritize recovery actions. Stewart et al. (1999) collected diatoms (*Bacillariophyta*) and water quality samples from three streams that drain the Great Marsh in the Indiana Dunes National Lakeshore. They found that diatom species diversity could be used as indicators of water quality, which could then be linked to land use in a watershed. Diatom species diversity was most variable in areas with poorer water quality and was directly correlated to the total alkalinity, total hardness and specific conductance of the water in the stream.

Easton et al. (1999a and 1999b) presented the first phase of a project for determining the risk associated with human contact with waters contaminated with sewage-borne pathogens. Determination of the survival rates for these pathogens has been found to be crucial for determining the length of time after a contamination episode that the water was unsafe for human contact such as wading, swimming, etc. Die-off rate studies for total coliforms, *E. coli* (including *E. coli* 0157:H7), *Enterococci*, and *Giardia lamblia* were performed in situ in a stream known to have SSO. The survival rates,

when combined with local hydrologic data, would be used to predict fate and transport of these microorganisms. Wakeham (1999) reported on the results of the investigation to determine why an \$800 million investment program designed to improve swimming water quality in the northwest coast of England was not effective. They found that the problem of compliance with water quality criteria for human exposure to pathogens was more complex than originally believed and that current data analysis techniques and models by themselves could not completely describe the complex environment.

### **Groundwater Impact**

The effectiveness of microbial and chemical indicators to detect sewer leakage impacts on groundwater quality was evaluated by Cronin et al. (2006). The authors stated that the use of multiple parameters to predict groundwater quality impacts was better than the use of single parameters.

Bauer et al. (2004), using the integral groundwater investigation method, was able to identify source plumes of PCE and TCE contamination in an industrialized urban area in Austria. The data from the time-series approach was used to determine contaminant flow rates, mean concentrations and plume shapes.

Fischer et al. (2003) investigated the quality of the shallow groundwater beneath retention and detention basins used to treat stormwater runoff in southern New Jersey. Basin groundwater had significantly lower levels of dissolved oxygen, which impacts the concentration of major ions. Patterns of volatile organic compound and pesticide occurrence in basin groundwater reflected the land use in the drainage areas served by the basins. Ammann et al. (2003) investigated the potential for groundwater contamination due to infiltration of roof runoff from an industrial complex. The experiment identified cation exchange reactions that were influencing the composition of the infiltrating water. These processes occurred under preferential flow conditions in macropores of the material. Non-reactive tracers exhibited fast breakthrough and little sorption.

According to research by Dale et al. (2000), urban runoff, in addition to leaking underground fuel storage tanks and pipelines, has been shown to transport methyl tert-butyl ether (MTBE), a fuel oxygenate, to groundwater supplies. A survey performed by the authors also demonstrated that personal watercraft that use fuel containing MTBE is another potential source of MTBE to surface waters and groundwater. Di Carlo and Fuentes (2000) investigated the potential in Florida for monosodium methanearsonate (MSMA) to be transported to the groundwater after its application on golf courses. The results of their modeling showed that the unconfined Biscayne Aquifer was susceptible to MSMA and arsenate contamination. Uddin (2000) reported on the deterioration of groundwater in Malaysia due to agriculture, and industrial and human activities. The results showed that phenolic compounds, coliforms, iron, manganese and mercury had the highest frequencies of exceeding water quality standards. The water quality studies performed by Thomas (2000) indicated that the shallow groundwater near Detroit, Michigan, had higher median concentrations of nitrate, chloride and dissolved solids in areas with residential development. These groundwaters appeared to be impacted greatest by septic tank effluent in urban stormwater infiltration, especially runoff from paved surfaces. Zobrist et al. (2000) investigated the potential of using roof runoff for groundwater infiltration/recharge. The authors found that a first flush of pollutants was seen from the inclined tile and inclined polyester roofs and that corrosion of drains released copper in sufficient quantities to potentially damage the groundwater and surface receiving waters.

Standish-Lee (2000) reviewed the work performed by the Palmdale (California) Water District as part of their Wellhead Protection Plan. This project determined that the groundwater supply was most vulnerable to leaking septic tanks, illegal activities/dumping, trunk sewer lines, US Air Force Plant 42, dry wells, gas stations, junk/scrap yards and leaking underground storage tanks. Other locations of groundwater contamination sources included stormwater runoff detention basins, highways, railroads, golf courses, housing developments, hardware stores and repair shops. Stuurman (2000) outlined the Netherlands "National Groundwater Flow Systems Analysis (NGFSA)" project, which was designed to map the regional groundwater flow system and the associated groundwater/surface water interactions. The purpose of this project was to provide this information for urban planners in order to prevent the water systems from being stressed by drought, flooding, and/or pollution.

NPS contamination of surface and groundwater resources with nitrate-N ( $\text{NO}_3\text{-N}$ ) has been linked to agriculture across the midwestern United States (Cambardella et al., 1999). Moorman et al. (1999) reported that herbicide, mainly atrazine and metribuzin, transport in subsurface drainage and shallow groundwater can result in unacceptable levels of contamination in surface waters. An investigation of the Walnut Creek watershed, California was performed to characterize the geology, groundwater flow, and water quality in geological units impacted by agriculture (Eidem et al.,

1999). The infiltration of dissolved herbicides and metabolites from a tributary stream can occur where the stream crosses a floodplain overlying an alluvial aquifer causing the contamination of shallow alluvial aquifers at rates that exceed in-field leaching by up to three orders of magnitude (Burkart et al., 1999).

Hatfield et al. (1999) examined a multi-disciplinary study on the effect of farming practices on subsurface drainage, surface runoff, stream discharge, groundwater, volatilization, and soil processes that influence water quality. Groundwater was vulnerable to contamination in karst areas where highway stormwater runoff may flow directly into karst aquifers with little or no natural attenuation and transport highway-derived contaminants rapidly from sinkholes to locations in the aquifer. Field testing sites were located in Knoxville, Tennessee and Frederick, Maryland. A pilot-scale stormwater runoff treatment system, in Knoxville (Tennessee) and Frederick (Maryland), has been designed using peat, sand, and rock to remove contaminants by sedimentation, filtration, and adsorption prior to groundwater recharge.

Control of stormwater in sinkhole areas of Springfield, Missouri has involved the utilization of several standard approaches: concrete-lined channels draining into sinkholes; installation of drainage pipes into the sinkhole "eyes" (swallow holes); filling of sinkholes; elaborate drains or pumps to remove stormwater from one sinkhole and discharging into another drainage basin or sinkhole; and enlargement of swallow holes by excavation to increase drainage capacity. Three sites were analyzed to examine the effectiveness of contrasting design approaches to stormwater management. These sites differ in vegetation, on-site/off-site considerations, and types of development proposed (Barner, 1999). Since little was known about the influence of microorganisms which develop in urban stormwater infiltration basins on the transfer of heavy metals. Herbard and Delolme (1999) examined the transfer of zinc solutions (2-20 ppm) at different pH (4-7) by columns of sterile sand or sand colonized with *Pseudomonas putida*. By the analysis of the observed time series of streamflow from catchments, the main components of the underlying groundwater balance, namely, discharge, evapotranspiration loss, storage and recharge, can be identified and quantified. This holistic estimation method was demonstrated for the Harris River catchment in southwest Western Australia (Wittenberg and Sivapalan, 1999).

Fan and Bras (1998) presented an analytical solution to a hillslope-based formulation of subsurface storm flow and saturation overland flow (Suzuki et al., 1998) examined pesticide concentrations in groundwater and in water leaching from a golf course in Japan and found that the golf course represented an area of high pollution potential compared to agricultural land. Their study emphasized the need to examine subsurface drainage in addition to runoff water when examining pesticide transport from golf courses. The relationship between stormwater and shallow groundwater in urban areas was evaluated (Lopes and Bender, 1998). Urban land surfaces were found to be the primary NPS of most VOC, with urban air being a secondary source. Using oxygen and deuterium isotopes, Iqbal (1998) traced the sources of storm runoff in a watershed in Iowa. The isotopes determined the relative contributions to river flow from rainwater and from ground water which had been flushed from the soil by infiltrating stormwater. The feasibility analysis of a simulation system to assess the impact on groundwater of various hypothetical situations (in the field of water management, land use, etc.) focused on the infiltration of stormwater in a periurban environment and involved space and time scales that apply to mid- and long-term management of groundwater resources (Bernard and Miramond, 1998).

Barrett and Charbeneau (1997) studied the impact of an urban watershed contributing recharge to the Barton Springs and Edwards Karst Aquifer in Austin, Tex. Results indicated that changes in N concentration in the aquifer would not be noticeable. Garrett and Petersen (1997) developed a series of lakes at Green Valley Park for both groundwater recharges and stormwater management in Payson, Ariz.

One of the major concerns of stormwater infiltration is the question of adversely impacting groundwater quality. Pitt *et al.* (1996a) reviewed many studies that investigated groundwater contamination from stormwater infiltration. A methodology was developed to evaluate the potential of stormwater contamination and it was concluded that there is only minimal potential of contaminating groundwaters from residential-area stormwaters (chlorides in northern areas remains a concern).

### ***Planned groundwater recharge***

Groundwater recharge using urban runoff has been proposed by many regulatory authorities. Keim et al. (2006) performed a virtual experiment on the effects of canopy evaporation and smoothing/abatement of peak intensities on subsurface stormflow. The experiments showed that canopy evaporation was responsible for most of the effects seen, including delayed subsurface stormflow generation. Trcek et al. (2006) described the vulnerability of karst springs to contamination. As a result of high recharge rates, epikarst water may be up to 50% of the spring discharge during precipitation events in this area of Slovenia.

Ammann et al. (2002) investigated where the infiltration of urban/industrial roof runoff into permeable subsurface material may adversely impact the groundwater quality and endanger drinking water resources. The pollution potential was found to be high and non-reactive tracers exhibited fast breakthrough and little sorption.

A water balance model was developed for a semiarid landscape of Spain (Bellot et al., 2001). The components were the soil water content, the actual evapotranspiration (Eta), and both the aquifer recharge (deep drainage) and runoff, which reflected water recharge, human use and soil erosion impacts. Combining the model predictions with the land cover vegetation units on the aquifer recharge area, the effects of some management policies on the deep drainage and runoff in five simulation scenarios were compared. Extreme precipitation during a wet year led to a higher erosion risk. Well clogging will impede the use of aquifer storage and recovery (ASR) wells (Dillon et al., 2001). In this study, the Membrane Filtration Index (MFI), a standard test of the rate at which water clogs a membrane filter, has been used with turbid and organic-rich waters. Waters from 12 sites (mains, urban stormwater and reclaimed water) which are or have the potential to be water sources for aquifer storage and recovery (ASR) in southern Australia, were analyzed for MFI, turbidity, total suspended solids, total organic carbon, particle size and SEM. Little more than half the variance in MFI could be explained with the measured water quality parameters, likely due to the complex nature of the inorganic and organic particles present in the waters. The ongoing field study has been designed to determine if MFI can be related to well clogging at one of the focus sites.

Dillon et al. (1999) reported on the use of storage aquifers under urban areas to enhance groundwater recharge and to decrease the volume of surface runoff and combined sewer effluent reaching the receiving waters. Similarly, Lin et al. (1999) discussed the use of reclaimed wastewater plus stormwater to recharge the groundwater in the Caprock Aquifer in Oahu, Hawaii. Munevar and Marino (1999) developed a model for evaluating the artificial recharge potential on alluvial fans in the Salinas Valley in California. They found that average recharge/infiltration rates ranged between 0.84 and 1.54 cm/hr and that recharge efficiency ranged from 51 to 79%. Their model results demonstrated that planned recharge and streamflow augmentation could significantly reduce the groundwater overdraft and seawater intrusion in the area. Shentsis et al. (1999) reported on the transmission losses and groundwater recharge, including transmission losses from the vadose zone, from rainfall-runoff events in a wadi in Israel. They found that, during large events, evaporation was substantially smaller than the losses. However, in general, the annual recharge was very small, while losses were on the same order of magnitude as the stream flow. Wittenburg and Sivapalan (1999) used streamflow recession analysis and baseflow separation to quantify the components of the groundwater, i.e., discharge, evaporation losses, storage and recharge. Groundwater evaporation through water uptake by trees biased the recession curve. Data analysis of the data, stratified by time of the year, allowed the evaporation loss to be quantified as a function of time of the year and the used groundwater storage.

Generally, igneous and metamorphic rocks have been considered to be barriers to groundwater flow, while carbonates were assumed to allow flow through their fractures. Thyne et al. (1999) found, however, recharge occurring in the Indian Wells Valley through flow in a fractured bedrock that was originally thought to be impermeable. Their results demonstrated that using surface topography along with a knowledge of the location of the bedrock to estimate groundwater flow quantity and direction may not be suitable.

### ***Chemical groundwater impacts***

One concern for groundwater recharge using stormwater runoff is chemical contamination of the groundwater. Wolf et al. (2006) assessed the sewer-groundwater interaction in a German city. A series of new marker species were evaluated for determining if wastewater had contaminated groundwater. Fischer et al. (2006) addressed the geotechnical and geohydrological concerns of urban development in karst terrain. Concerns included groundwater contamination probability, risks to constructed facilities, costs of construction, and stormwater management difficulties.

The transport dynamics of solutes and dissolved oxygen in shallow groundwater below a stormwater infiltration basin was investigated by Datry et al. (2006). The authors documented that the trapped organics may serve as a source of dissolved pollutants to the shallow groundwater.

The mobility of heavy metals in urban runoff and in the interstitial waters of an infiltration pond were related to colloidal specification by Bechet et al. (2006). Lead and cadmium seem to be associated with the colloidal and particulate fractions, while zinc, copper, nickel and chromium are distributed in all fractions. Guo et al. (2006) examined the impacts of in-situ

infiltration on the partitioning and speciation of urban runoff pollutants. Results indicated that higher rainfall intensity resulted in higher dissolved fraction ( $f_d$ ) values for influent Zn, Cu and Cd, but did not have a significant influence on partitioning of Pb. They found that the partial exfiltration reactor was capable of removing these dissolved pollutants. Leung and Jiao (2006) investigated heavy metal and other element distributions in groundwater below natural slopes and urban areas in Hong Kong. The results and methodology could be used to determine risk of groundwater contamination and leakage from sewer pipes. Murray et al. (2006) examined the dissolved heavy metal concentration in shallow groundwater in a southeastern Michigan urban watershed. Current and former land uses had a substantial impact on the observed water quality.

Marcos et al. (2002) performed a study and modeled zinc and lead migration in sandy soils due to stormwater infiltration of runoff from road surfaces. The potential existed for the heavy metals from the road to migrate through the soils down to the groundwater.

Barraud et al. (1999) reported on the quality of the groundwater below two infiltration sites in urban areas of France. Kayabali et al. (1999) investigated the chemical contamination of the groundwater in alluvial aquifers adjacent to Ankara Creek since it was believed that Ankara Creek pollution was contaminating the local groundwater. However, it was determined, using analysis of basic ions, organics and metals, that Ankara Creek was not responsible for groundwater contamination, partly because a blanket of fine sediment in the bottom of the creek was expected to adsorb pollutants and to reduce infiltration rates. Lerner et al. (1999) combined a water balance with multiple solute balances to model the flow of water and chemicals into the groundwater under Nottingham, UK. They found that sewers contributed only about 13% of the total nitrogen loading, while leaking drinking water mains was about 36% of the total. The remaining 50% of the nitrogen loading came from parks, gardens, landfills and industrial spillages. Reddy (1999) reviewed the available data from public water suppliers in Wyoming which use groundwater. Nitrate and pesticides were two of the most frequently detected contaminants in groundwater and two of the most frequently detected pesticides were aldicarb and atrazine. Groundwater contamination was found to be a problem especially in areas that were heavily agricultural. Stephenson et al. (1999) investigated the impact of highway stormwater runoff flowing through a karst area and found that little to no attenuation of the runoff pollutants occurred. For most of the contaminants analyzed, the peak loadings arrived at the groundwater table and at the spring it recharges approximately one hour after they were found in the sinkhole that received the highway drainage. Nowicki et al. (1999) found that denitrification of groundwater was not significant in a well-oxygenated vadose zone and aquifer. Denitrification was found to occur to a greater extent in the estuary which receives the groundwater.

Lin et al. (1999) used the boron isotope ratio to trace reclaimed wastewater in a directly recharged aquifer on the Island of Oahu in Hawaii. They also investigated other tracers, such as chloride and silica, and found that, because of the influence of seawater, they were not suitable tracers for the reclaimed water. The results of this study were used in conjunction with mixing curves to determine the fraction of reclaimed water in a well and could be used to calibrate or modify fate and transport models for this aquifer with regard to other pollutants in the recharged water. Mengis et al. (1999) used nitrate-to-chloride ion ratios, concentrations of 15-Nitrogen and 18-Oxygen and an in-situ nitrate/15-N tracer experiment to investigate whether nitrate was being attenuated in the vadose zone and/or the aquifer below a riparian zone. Their results confirmed that denitrification rates could be measured in situ using this procedure. They also confirmed that this methodology could distinguish between water being recharged from the riparian zone versus that being recharged from irrigation of the nearby agricultural fields.

The Technical University of Denmark (Mikkelsen *et al.*, 1996c and 1996d) has been involved in a series of tests to examine the effects of stormwater infiltration on soil and groundwater quality. It was found that heavy metals and PAHs present little groundwater-contamination threat if surface infiltration systems are used. However, concern was expressed about pesticides which are much more mobile. Squillace *et al.* (1996) along with Zogorski *et al.* (1996) presented information concerning stormwater and its potential as a source of groundwater MTBE contamination. Mull (1996) stated that vehicular-traffic areas are the third most significant source of groundwater contamination in Germany (after abandoned industrial sites and leaky sewers). The most significant contaminants are chlorinated hydrocarbons, sulfate, organic compounds, and nitrates. Heavy metals are generally not significant groundwater contaminants because of their affinity for soils. Trauth and Xanthopoulos (1996) examined the long-term trends in groundwater quality at Karlsruhe, Germany. It was found that the urban-land use is having a long-term influence on the groundwater quality. The concentration of many pollutants have increased by about 30-40% over 20 years. Hütter and Remmler (1996) described a groundwater-monitoring plan including monitoring wells that were established during the construction of an infiltration trench for stormwater disposal in Dortmund, Germany. The worst-case problem expected is with zinc, if the infiltration

water has a pH value of approximately 4.

### ***Microbiological groundwater impacts***

Barrett et al. (1999) suggested the use of chemical and biological markers for identification of urban groundwater recharge sources. Their paper documented only the sewage 'fingerprint,' a combination of stable nitrogen isotopes and microorganisms. Trihalomethanes had been proposed as a marker for leaks in the drinking water mains, but they were not found in sufficient quantity in the drinking water itself to be an effective measure of groundwater contamination. Markers were not presented for precipitation.

Soil application was proposed as a means of disposal of propylene glycol-based aircraft deicing fluids (ADF). ADF biodegradation was investigated by Bausmith and Neufeld (1999) and the results showed that biodegradation of solutions of less than 20% by weight ADF could be degraded in the soil profile prior to reaching the groundwater. Hebrard and Delolme (1999) investigated the ability of the soil to adsorb the zinc from the infiltration water. Their work showed that the adsorption of zinc retarded the arrival of zinc to the groundwater. Adsorption was found to be reversible except at pH 6 and 7 and was found to be non-instantaneous. These results demonstrated that contact time and conditions control the amount of biofilm removal and retention of zinc from percolation water. Degradation of the groundwater by human and animal excrement was documented by Buckles et al. (1999) for an area in Ecuador where the groundwater table was rising. The degradation of the groundwater in combination with the rising water table produced swamp-like conditions where the water and land were not suitable even for subsistence farming.

## **Decision-Support Systems**

### ***Numerical Models***

The impact of climate change on the hydrology and hydraulics of an urbanized area in southwestern Ontario were examined by Cunderlik and Simonovic (2005). For this region, the climate change scenarios modeled appeared to mitigate the currently-occurring hydrologic extremes. Remote sensing algorithms were used by Ibrahim et al. (2005) to monitor eutrophication in a stormwater reservoir in Japan. Algorithms from spectral absorption ratios were well correlated to chlorophyll concentrations. The impact of sinkholes on flood mapping was investigated by Campbell (2005). SWMM 5.0 was used to calculate the runoff and hydraulics for a complex system of sinkholes in the Bowling Green, Kentucky, area.

Barros et al. (2005a) demonstrated the application of the SCS Curve Number method to predict the peak flood runoff for Sao Paulo as it undergoes rapid urbanization. Pimental Da Silva et al. (2005) described the characteristic Impervious Rate that would be used in a web-based Multicriteria Decision Support System (MC-DSS). The MC-DSS also included public participation as a component in the decision-making process when establishing an integrated water and land-use management system. A parameter, called Kinetic Energy, was promoted by Davison et al. (2005) as a method for predicting the total rainfall erosivity from daily or monthly rainfall data in England and Wales. The purpose of this parameter is to evaluate the risk of sediment detachment, and accompanying phosphorus detachment and transport. Biegel et al. (2005) used ArcEGMO-URBAN to model point and nonpoint sources in river basins draining urbanized watersheds. The model inputs included land use and anticipated pollutant loads, as well as point source discharge data, sewer system information and population. The numerical modeling used in the Southeastern Pennsylvania Waterways Restoration Program was presented by Byun et al. (2005). The foundation of the modeling was the Storm Water Management Model, including the RUNOFF and EXTRAN subroutine. The Western Washington Hydrology Model (WWHM), which uses HSPF in the background to analyze rainfall data, was presented by Beyerlein et al. (2005). The model has been used to demonstrate whether or not structural stormwater treatment practices are capable of meeting the Department of Ecology's goal of having post-development flow durations not exceed pre-development durations for the range of erosive flows.

Anonymous (2005b) announced the release of the updated Storm Water Management Model (SWMM 5.0), which has a graphical user interface. Molnar and Burlando (2005) analyzed the properties of a simple discrete multiplicative random cascade model for rainfall disaggregation in urban hydrology. The canonical models performed substantially better in capturing the variability in rainfall. Using spatial analysis techniques, spatially distributed watershed characteristics and measurements of rainfall and runoff, Beighley et al. (2005) demonstrated an approach for modeling basin hydrology that integrated hydrogeological interpretation and hydrologic response unit concepts. Kanso et al. (2005b) applied a Monte Carlo Markov Chain method to the calibration and uncertainty analysis of a stormwater quality model. The purpose was to estimate the accumulation, erosion and transport of pollutants on surfaces and in sewers.

The impact of micro-topography on the failure of storm drainage inlets to capture their maximum flow was modeled by Aronica and Lanza (2005) using Saint Venant equations. The modeling confirmed that micro-topography effects can cause localized flooding. Vazquez et al. (2005) addressed the issues involved in one-dimensional and three-dimensional hydraulic modeling of CSOs. Both modeling approaches were validated by data collected on a small-scale model in France. Coonrod et al. (2005) reviewed the physical modeling done by the Albuquerque Metropolitan Arroyo Flood Control Authority to predict how diverting a portion of the storm flow into a constructed wetland would affect the hydraulics of the drainage system. The modeling included both a diversion baffle and a weir, as well as the debris removal system.

Jeon and Kim (2005) used artificial neural network rainfall-runoff models to predict streamflows in Korea. The results showed that the ensemble neural network outperformed the single neural network. Wu et al. (2005) demonstrated the application of an artificial neural network for watershed-runoff and streamflow forecasts. One important result of this research was the development of a methodology for input data organization, model performance evaluation and artificial neural network processing techniques. The paper by Di Pierro et al. (2005) proposed a new Multi-Objective Genetic Algorithm (MOGA), the Preference Ordering Genetic Algorithm, which would alleviate the drawbacks of conventional methods. The efficacy of the algorithm is demonstrated on the calibration of a physically-based, distributed sewer network model and the results are compared with a traditional MOGA. Grey system theory was used to develop a runoff prediction model in India (Trivedi and Singh 2005). The model had lower values of various error indices and higher values of correlation, indicating that the model was able to predict storm runoff with reasonable accuracy.

A new approach to evaluate the importance of spatial and temporal distribution of rainfall-runoff model inputs was introduced by Andreassian et al. (2004). The most appropriate level of spatial distribution was assessed using chimera watersheds, which associated two actual watersheds of similar size to constitute a third, highly heterogeneous virtual basin. The knowledge of spatialized flows in the chimera watershed enable it to be used to test spatial disaggregation approaches (e.g., lumped vs. distributed). Results suggested the need to focus on spatially distributed rainfall data prior to the disaggregation of watershed parameters.

Several studies investigated hydrologic processes simulated in rainfall-runoff models and assessed the impact of alternative representations on model output. Andreassian et al. (2004) studied the impact of improved areal estimates of potential evapotranspiration (PE) on rainfall-runoff model results. Simple assumptions on watershed PE input were found to yield the same results as more accurate input obtained from regionalization, but results were found to be sensitive to PE input. An approach to represent infiltration at the parcel scale was presented by Morel-Seytoux (2004). Starting with formulas for infiltration capacity and ponding time at a point scale, and statistical distributions of conductivity, equations representing infiltration at the parcel scale were derived. Gregory and Cunningham (2004) described a method to estimate soil storage capacity for specific soil types using data that are readily available in geographic information system (GIS) format. The objective was to improve the current curve number based approaches relying on general soil and land use characteristics. A spatial averaging technique integrating land use and soil properties to develop physically-based Green and Ampt infiltration parameters was reviewed by Smemoe et al. (2004). The method was used to derive parameters for the HEC-1 watershed model.

Artificial neural network (ANN) based models of the rainfall-runoff relationship do not require representation of individual hydrologic processes. Cigizoglu and Alp (2004) tested three ANN models and found them to compare well with a conventional multi linear regression technique. Agarwal and Singh (2004) presented a multi-layer back propagation ANN to simulate rainfall-runoff for two watersheds in India at weekly, 10-day, and monthly time scales. The performance of the ANN models were found to be superior when compared with results of a developed linear transfer function model. Castellano-Mendez et al. (2004) compared predictions of monthly and daily runoff using a Box-Jenkins model and an ANN approach. The ANN's ability to model the complex rainfall-runoff relationship was noted and the performance of the ANN compared to the Box-Jenkins model was found to be an improvement. Rajurkar et al. (2004) presented an ANN approach to simulate daily flows during flood events. Anctil et al. (2004) evaluated the short-term forecasting improvement of an ANN model by including low-frequency inputs (e.g., potential evapotranspiration, soil moisture). Results indicated only the soil moisture index time series were useful for improving the one-day-ahead stream flow forecasting of the ANN model.

Nazemi et al. (2004) developed a method to compare soft-computing based approaches to model rainfall-runoff. Based on the two-stage competition among all modeling choices, the results indicated fuzzy clustering-based neural networks



are the most efficient and accurate paradigm among intelligent systems used to model rainfall-runoff. Sen and Altunkaynak (2004) presented a fuzzy systems approach in rainfall-runoff modeling in an effort to account explicitly for internal uncertainties.

Anctil and Tape (2004) developed a hybrid approach using ANN and wavelet decomposition. The hybrid ANN-wavelet approach provided slightly improved prediction accuracy compared to a classical ANN approach. Anctil et al. (2004) noted the lack of a systematic way to efficiently train ANN rainfall-runoff models. To address this gap the authors assessed the impact of length of observed records on the performance of multiple-layer perceptrons (MLPs) and found the MLP prediction to improve with length of record compared to a conceptual model. Pan and Wang (2004) introduced a state space neural network (SSNN) and a new learning algorithm to perform short term rainfall-runoff forecasting. Convergence of the learning algorithm was verified and the performance of the SSNN proved its appropriateness for hydrological forecasts.

Addressing the criticism of ANN models as being black boxes, Jain and Srinivasulu (2004) and Jain et al. (2004) presented development of integrated deterministic and ANN techniques for hydrologic modeling. The so-called gray box models were evaluated and found to perform better than the purely black box type ANN models. Ali and Dechemi (2004) compared predictions of daily rainfall-runoff from two conceptual models and two black box models – the ARMAX model and a neuro-fuzzy model combining neural structure and fuzzy logic. The exercise resulted in the combining of the conceptual approach and the neuro-fuzzy system to produce a better model.

ANN models have also been presented for real-time applications. Chang et al. (2004) presented an algorithm for two-step ahead forecasting of streamflow using a real-time recurrent learning (RTRL) neural network. The RTRL was shown to have an efficient ability to learn and had comparable accuracy to a least-square estimated autoregressive modeling average with exogenous inputs. Chiang et al. (2004) performed a systematic comparison between static ANN models (one backpropagation and one conjugate gradient) and the RTRL algorithm. The RTRL was found to be able to produce better and more stable flow forecasting than the static networks.

Besides ANN models, statistical and probabilistic approaches to estimate rainfall-runoff continue to evolve. Marshall et al. (2004) presented a comparative study of Markov chain Monte Carlo methods to predict rainfall-runoff. Techniques were found to be accurate and provided a relatively simple basis to estimate parameter (and model) uncertainty to allow the assessment of risk.

Bhattacharjya (2004) presented a nonlinear optimization model to transmute a unit hydrograph into a probability distribution function. Results were compared to a linear programming approach and found to be fairly similar. Singh (2004) demonstrated the use of a two-parameter gamma distribution as the instantaneous unit hydrograph to compute direct runoff from a complex storm. The computation of the gamma function is performed indirectly. The new procedure, which is simple enough to be applied in a spreadsheet, was compared to tabular or computer-based methods to obtain the gamma function and found to produce nearly the same values.

Chen et al. (2004) presented an application of the Watershed Environmental Hydrology (WEHY) model. Comparisons of WEHY predictions with observations suggested good model performance. Liu et al. (2004) presented a two-dimensional kinematic wave model of overland flow and compared simulation results to experimental results collected on a hillslope receiving artificial rainfall. The model-simulated results satisfactorily compared with experimental observations. Panday and Huyakorn (2004) addressed an area of significant uncertainty in hydrologic modeling by developing a distributed model to evaluate surface/subsurface flow. Surface flow is simulated using the diffusive wave equations for overland flow and subsurface flow is simulated using three-dimensional saturated-unsaturated flow equations. Coupling takes place at the watershed interface and in stream and channels. Demonstration of the coupled model indicates the need for a rigorous, fully coupled solution to the set of equations, for comprehensive analysis of surface-subsurface interaction.

Accurate representation of urban areas in hydrometeorological models is critical for accurately predicting surface fluxes in urban environments. Requisite is the need to simulate urban hydrologic processes with a high degree of spatial resolution. Several studies have addressed this issue. Rousset et al. (2004) presented a hydrometeorological modeling study of the Seine basin using the SAFRAN-ISBA-MODCOU system. The objective of the work was to improve the understanding of the hydrological function of the Seine basin, specifically the influence of the large aquifers and the impact of the urbanized areas. The improved ability to simulate the evolution of the aquifers and the partition between surface runoff and drainage leads to an improved simulation of Seine floods. Zhou et al. (2004) coupled a regional

climate model (RegCM2) with a hydrological model to simulate rainstorms and surface runoff. The linkage improved the modeling of moisture convergence, increased the moisture content in the atmosphere below 700 hPa, and enhanced precipitation in the basin.

Approaches to simulate snowmelt in urban areas are not developed as frequently as rainfall-runoff simulation approaches. Consequently, current urban snowmelt capabilities are not as advanced. Valeo and Ho (2004) provided a valuable contribution in this area by exploring current urban snowmelt models and proposing a new model that uses parameters developed specifically from urban snow studies. The Urban Snow Model (USM) was tested against flow data from a small residential community and compared with predictions made using a degree-day method for snowmelt and the SWMM model. The USM and a modified version fared well and based on the results were recommended over other approaches tested.

Updates to the U.S. EPA Storm Water Management Model (SWMM) continued as part of the SWMM redevelopment project. Rossman et al. (2004) reviewed the rewriting of SWMM's engine using an object-oriented approach and providing a rudimentary graphical user interface. Chan et al. (2004) presented a graphical user interface (GUI) to translate SWMM4 input files to SWMM5 input files. The translator was tested using over 200 input files and quality assurance tests indicated performance was acceptable. The source code for the translator will be made available on the Internet.

Burgess et al. (2004) discussed the considerations water resources engineers face when choosing between open source code versus proprietary software for an application. They stressed the important benefits of open source software from a broader perspective of the profession. There was an effort from seven European countries to develop an open modeling interface to link new and existing hydraulic models of sewers and rainfall-runoff models (Anonymous 2004). The objective was to provide a European-wide standard that will enable models to interface with one another and satisfy the integration requirements of a wide group of users.

Bhunya et al. (2003) presented a simplified two-parameter Gamma distribution for the derivation of a synthetic unit hydrograph. The revised version required approximate, but accurate empirical relationships for the parameters that affect the shape of the dimensionless hydrograph. Chapman (2003) hypothesized that the curvature in semilog plots of hydrograph recession could be explained by a linear groundwater system with a continuous flow from the vadose zone. Confirmation work in Australia showed that significant recharge occurred during the recession limb of the hydrograph. Ocaik and Bayazit (2003) modeled linear reservoirs in series to develop a unit hydrograph of finite duration. A computer program was used to simulate the conversion of rainfall excess into runoff and to optimize the model parameters. Jeng and Coon (2003) showed that the initial value of an instantaneous unit hydrograph based on linear reservoirs should be a positive value because overland flow derived for a plane of uniform width was based on the kinematic wave solution. A three-parameter IUH, with a storage coefficient and two weights for the linear reservoirs, was suggested by the authors as a standard.

Ali Awan (2003) reported on the use of weather-radar distributed hydrologic modeling in the Indus Basin. These radar estimates of intensity were then put in flood forecast models which then determined the subsequent mitigation measures on a real-time basis. Schombert et al. (2003) reviewed the development and expansion of a calibrated radar rainfall monitoring system for the 3 Rivers Demonstration Program in Allegheny County, PA. The system was implemented to improve control of CSOs. Anctil et al. (2003) compared ANN output updating of lumped conceptual rainfall/runoff forecasting models to the use of parameter updating techniques for the models and to ANN models of the rainfall-runoff relationship. The application was one- and three-day forecasting and the ANN-updated models were superior to even the ANN rainfall-runoff model. Wilby et al. (2003) examined the internal behavior of an artificial neural network rainfall-runoff model. It is demonstrated that specific architectural features can be interpreted with respect to the quasi-physical dynamics of a parsimonious water balance model.

Dorado et al. (2003) used ANN and genetic programming (GP) to predict and model the relationship between rainfall and runoff in a typical neural network. The eventual outcome of the project was a real-time alarm system for floods or subsidences. Solomatine and Dulal (2003) presented model trees (MTs) as an alternative to neural networks in rainfall-runoff modeling. The result shows that both ANNs and MTs produce excellent results for 1-h ahead prediction, acceptable results for 3-h ahead prediction and conditionally acceptable result for 6-h ahead prediction. MT produced results that are more understandable and that allow the building of a family of models of varying complexity and accuracy. Zhang and Govindaraju (2003) investigated geomorphology-based ANNs (GANNs) to estimate direct runoff over watersheds. The architecture of the GANNs as well as a part of the network connection strengths are determined by

watershed geomorphology, leading to a parsimonious ANN modeling tool. This study reveals GANNs to be promising tools for estimating direct runoff.

Jordan et al. (2003) evaluated using dual polarization radar in rainfall-runoff modeling using a case study in Sydney, Australia. Dual polarization was compared to using calibration rain gauge networks for single polarization radar rainfall. Jain and Indurthy (2003) compared event-based rainfall-runoff modeling techniques (deterministic, statistical and ANN) for the Salado Creek in San Antonio and found that the ANN models consistently outperformed conventional models and provided a better representation of an event-based rainfall-runoff process, including better prediction of peak discharge and time to peak discharge. Brahm and Varas (2003) reduced the learning time of ANNs by selecting an adequate algorithm and by reducing the number of parameters. Principal Component Analysis (PCA) produced faster learning periods without diminishing fitness quality. The authors recommended the Levenberg-Marquardt algorithm for training feed-forward artificial neural networks and the use of PCA in models with a large number of correlated explanatory variables.

Mikhopadhyay et al. (2003) applied kinematic wave theory to predict flash flood hazards on coupled alluvial fan-piedmont plain landforms in New Mexico. The models suggested that the flood hazard zones on coupled alluvial fan-piedmont plain landforms should be delineated transverse to the flow directions, as opposed to the flood hazard zones with boundaries in the longitudinal direction of the axis of an alluvial fan. Jasper and Kaufman (2003) investigated coupled runoff simulations as validation tools for regional atmospheric models. It is shown that the hydrological model was sufficiently sensitive to provide substantial information for the validation of atmospheric models. Najafi (2003) presented a distributed physiographic conceptual watershed model (based on the principles of flow continuity and momentum) to transform rainfall excess into runoff. The kinematic wave theory was applied for the overland runoff computations from these subwatersheds, and then the overland flows were superimposed onto the main channel. Dynamic wave theory was used to route the flows through the main channel.

Perrin et al. (2003) discussed improvements to a parsimonious model, GR4J model – a daily lumped rainfall-runoff model – for stream flow simulation. The tests indicated that a four-parameter structure corresponded to the maximum level of complexity that could be afforded in the model. Adding more free parameters did not bring significant improvements.

Pizarro Tapia et al. (2003) evaluated Budyko's, Turc-Pike's, and Pizarro's rainfall-runoff formulas in Achibueno Basin, Chile, using graphic and analytical methods (Bland-Altman's agreement analysis, R<sup>2</sup>, standard error of estimate and analysis of variance [ANOVA]). Using annual data, all three formulas produced similar results, but for dry years, the ANOVA showed statistically significant differences for Pizarro's formula indicating it should not be used in dry-weather years. Syed et al. (2003) assessed the ability of simple geometric measures of thunderstorm rainfall to explain the runoff response of a watershed. The most important variable in runoff production was found to be the volume of the storm core. It was also observed that the position of the storm core relative to the watershed outlet became more important as the catchment size increased, with storms positioned in the central portion of the watershed producing more runoff than those positioned near the outlet or near the head of the watershed.

Vieux and Moreda (2003) reviewed the achievable accuracy of a physics-based distributed hydrological model and concluded that the best accuracy achieved (watershed: the Illinois River (2300 km<sup>2</sup>)) was 1.6%, which met the goal of errors < 10% by volume. Wagener et al. (2003) used dynamic identifiability analysis to reduce uncertainty in conceptual rainfall-runoff modeling. The approach analyzed the performance of the model in a dynamic fashion resulting in an improved use of available information. Wendling and James (2003) compared neural networks to Ormsbee's method for rain disaggregation in Toronto, Ontario. It was shown the radial basis function network model performed poorly for rainfall disaggregation while the multi-layer perceptron achieved results comparable to Ormsbee's continuous deterministic model and exceeded in the prediction of maximum incremental rainfall depth.

Yoon and Kavvas (2003) applied a probabilistic solution to a stochastic overland flow equation and presented a solution for the resulting Fokker-Planck equation. The second approximation to the diffusion coefficient provided a good fit in terms of the shape of the probability density function (PDF) and the ensemble average of the overland flow depth when compared to Monte Carlo simulation-based PDFs. Pelaez (2003) presented statistical issues related to maximum flow estimations in hydrologic models. The authors determined that Rational method did not have to be dependent on the hypothesis of being the same the storm duration and the time of concentration of the basin.

Chirico et al. (2003) investigated soil moisture time-series, flow at the outfalls of two subcatchments, rainfall and other

meteorological data to develop in a downward approach a terrain-distributed model that could explain the flow in the subcatchments. Michel et al. (2003) proposed the use of an exponential store in conceptual, soil-moisture accounting rainfall-runoff models. The study showed that the common way of dealing with this store – without integration in time – is mathematically and physically flawed. This misuse could result in poorer reliability and efficiency of rainfall-runoff models that included such a store, especially when used for the simulation of flood events. Czachorski and Van Pelt (2003) reviewed a time-series methodology to extract the diurnal component of wet-weather flows in a sewer system. When attempting to analyze and model inflow and infiltration effects within a sanitary system, nuances in long-term infiltration dynamics and rapid peaking during large rain events can be lost or obscured if the diurnal is extracted improperly.

Kanso et al. (2003) reviewed a Bayesian approach for the calibration of models and applied it to an urban stormwater pollution model. Unlike traditional optimization approaches, the Metropolis algorithm identifies not only a "best parameter set", but a probability distribution of parameters according to measured data. The studied model includes classical formulations for the pollutant accumulation during dry weather period and their washoff during a rainfall event. Results indicate mathematical shortcomings in the pollutant accumulation formulation used.

### **Rainfall analyses**

Pielke et al. (2006) provided an overview of the impacts of regional land use and cover on rainfall. Guo (2006c) promoted updating rainfall IDF relationships to improve urban drainage designs. The authors proposed that these updates are necessary in light of anticipated climate change impacts.

Spatial variability of rainfall was an issue addressed by many authors this year. Das et al. (2006) studied the influence of spatial variability in a distributed rainfall-runoff model. The simulated hydrographs were compared using the Nash-Sutcliffe coefficient and other measures of goodness-of-fit. Giulianelli et al. (2006) examined the influence of spatial and temporal variability in rainfall on the generation of urban runoff. They documented, during studies in Rome, the need for very high space-time rainfall resolution to accurately predict flash floods and sewer system behavior. Ciach and Krajewski (2006) analyzed and modeled the spatial correlation of small rainfall events in Oklahoma. Kuzuha et al. (2006) investigated the role of spatial variability of rainfall intensity on the annual maximum discharge. The work was performed using Eagleson's classical regional flood frequency model.

Jensen et al. (2006) presented the need for high resolution rainfall information in urban runoff modeling. Grid spacing of rain information recommendations was given. Kang et al. (2006b) used digital elevation modeling (DEMs) to describe the influences of rainfall and slope on watershed isochrones.

Error analysis also was a major topic during 2006. Hong et al. (2006b) focused on quantifying the propagation of errors in hydrologic modeling resulting from uncertainty in quantifying satellite precipitation estimates. The proposed framework provided a more realistic quantification of this error and offered improvements to uncertainty estimates of the error's effects on hydrologic simulations. Xavier et al. (2006) applied Bayesian kriging and Generalized Likelihood Uncertainty Estimation (GLUE) to estimating uncertainty of rainfall representations in hydrologic models. The results reinforced that a poor representation of precipitation fields in hydrological models is a considerable source of uncertainty.

Xiong et al. (2006) used a linear perturbation model (LPM) with a kernel estimator to smooth the seasonal mass of rainfall and runoff for future use in identifying the seasonality structure of rainfall-runoff and in quantitatively expressing this relationship. The performance of the LPM was influenced much more by the seasonal characteristics of the rainfall and runoff processes in a catchment, as expressed by the proposed seasonality index SI, than by the methods used to smooth the seasonal means.

***Rainfall Variability and Effects on Modeling.*** Aronica et al. (2005) analyzed the influence of rainfall temporal resolution on the uncertainty of the response of rainfall-runoff modeling in urban environments in Palermo, Italy. The results of the simulations were used to derive the cumulative probabilities of peak discharges conditioned on the observation according to the GLUE (Generalized Likelihood Uncertainty Estimation) methodology. A method for estimating the distribution of sub-hourly extreme rainfalls at sites where data for time interval of interest do not exist, but rainfall data for longer duration are available, was proposed by Aronica and Freni (2005). The proposed method is based on the "scale-invariance" (or "scaling") theory. It was shown that the statistical properties of the rainfall series have a simple scaling

property over the range of duration 10 min-24 h.

Improving the accuracy of rainfall data and reducing the uncertainty associated with design information extracted from rainfall data is crucial for wet weather flow modeling activities. Crisci et al. (2002) performed a comprehensive analysis of extreme rainfalls in Tuscany, Italy to assess the hydrological consequences of climate variability and the impact on the design of hydraulic structures. Seremet et al. (2002) recommended temporal and spatial resolution requirements for rainfall monitoring to obtain data suitable for infiltration/inflow assessments. Einfeld and Maul-Kotter (2002) compiled survey results from potential users of radar data for hydrological services and found that besides better technical information of the concept, more education and training of radar derived information use in hydrology was needed. Jacquet et al. (2002) reviewed the requirements of radar data services in urban environments for accurate use as inputs into hydrologic simulation models. Spies et al. (2002) described efforts to develop standards for collection and data processing of rainfall measurements with time increments suitable for urban hydrology.

### **Rainfall – runoff modeling parameter estimation**

Kavetski et al. (2006b) presented an improved optimization and analysis method for the calibration of hydrological models. This framework will enable parameter estimation using techniques including: (i) Newton-type optimization and (ii) principal-component-type (Hessian-based) uncertainty analysis. Kay et al. (2006) compared three approaches to spatial generalization of the parameters required in rainfall-runoff models. With one exception, there were no clear relationships between performance of any model/method and catchment type. Sen and Altunkaynak (2006) proposed a comparative fuzzy logic approach to runoff coefficient and runoff estimation. The authors concluded that the fuzzy logic approach yielded the least relative error among the various alternative runoff calculation methods. Jonsdottir et al. (2006) proposed a parameter estimation method for stochastic rainfall-runoff models. Parameter estimations for simulations in Iceland were performed using a maximum likelihood method. Oudin et al. (2006) examined the impact of biased and randomly corrupted inputs on the efficiency and parameters in watershed models. The models were almost insensitive to random errors in the potential evapotranspiration series, but they were very sensitive to errors in rainfall series. Systematic errors had a greater impact than random errors.

Zoran (2006) analyzed urban surface biophysical parameters from remote sensing imagery in Bucharest. This imagery was able to provide information regarding net radiation and heat flux associated with urbanization.

Chen and Pi (2006) described relationships between the parameters in the linear reservoir and kinematic wave models for runoff. Conversion relationships were developed. Dupont et al. (2006) presented the hydrological component of the Submesoscale Soil Model, urbanized version (SM2-U). Urban hydrological parameters largely influenced the available water on artificial surfaces for evaporation and, to a lesser extent, the evapotranspiration from natural surfaces. Merz et al. (2006) reported on the spatial-temporal variability of event runoff coefficients. The primary factors affecting these coefficients were climate and runoff regime, and hence antecedent soil moisture in addition to event characteristics. Parak and Pegram (2006) calibrated the Rational coefficient C to past flood peak and volume pairs for many catchments in South Africa. Kaheil et al. (2006) proposed a new Bayesian recursive technique for estimating parameters required in a hydrologic model (Sacramento Soil Moisture Accounting model). The new approach resulted in faster convergence toward the optimal parameter set using minimal training/calibration data. Wagener and Wheater (2006) examined concerns for parameter estimation and regionalization for continuous rainfall-runoff models that incorporate uncertainty. The main conclusions were that the uncertainty in the locally estimated model parameters is a function of their importance in representing the response of a given catchment.

The Natural Resources Conservation Service (NRCS) Curve Number (CN) model was examined by several researchers. Mishra et al. (2006a) provided an improved initial abstraction-storage relationship that incorporated antecedent moisture conditions in curve number hydrological modeling. Mishra and Singh (2006) investigated the variation of the curve number values given by the National Engineering Handbook with antecedent moisture condition and soil type. Using volumetric concepts involving soil, water, and air, the NEH-4 tables were substantially reduced.

Vasconcelos et al. (2006a) reviewed current issues in modeling extreme inflows to stormwater systems. The results showed that the values selected for the variables used to solve the mass and momentum equations has an impact in the solution of discontinuous flows. They also showed that numerical models without shock-capturing capabilities have limited ability to model flow discontinuities. Vasconcelos et al. (2006b) described improved simulations of flow regime transitions in sewers using a two-component pressure approach. This new approach exploited the identity between the

unsteady incompressible flow equations for elastic pipe walls and the unsteady open-channel flow equations.

A genetic algorithm (GA) method was developed by Wan and James (2002) to optimize the SWMM RUNOFF parameters. The method was coupled with the sensitivity wizard in PCSWMM to produce a sensitivity-based method for automating the calibration process. Testing of the method indicated that the calibrated model was within 97% of the target dataset after approximately 58 cycles of the GA. The GA method was successfully incorporated into PCSWMM and applied by James et al. (2002) to a sample SWMM calibration process. The automated calibration tool significantly reduced the effort required for calibration and design optimization. Inference models were developed by Choi and Ball (2002) to estimate SWMM parameters for the Centennial Park Catchment in Sydney, Australia. The inference models ranged from spatially invariant parameter values to different values for each subcatchment. The results of the study provided insight into the complexity and structure of models used in the calibration process.

### **Rainfall-runoff models and new programming tools**

Artificial Neural Networks (ANNs) were discussed by several researchers. Grabrecht (2006) compared three alternative ANN designs for monthly rainfall-runoff simulations. The ANNs typically slightly underpredicted high runoff and overpredicted low runoff values. Khan and Coulibaly (2006) applied a Bayesian neural network to model rainfall-runoff. The authors stated that this modeling approach outperformed conventional ANN modeling since the Bayesian model already addressed overfitting and underfitting of the model.

ANN modeling was compared to a physically-distributed rainfall-runoff model in the Blue Nile catchment by Antar et al. (2006). The model comparisons showed that there was a bias in the ANN model, likely due to too short of a rainfall record for calibration. Srinivasulu and Jain (2006) performed a comparative analysis of training methods for ANN rainfall-runoff models. The real-coded genetic algorithm (RGA) trained ANN model significantly outperformed the ANN model trained using back-propagation algorithms (BPA), and was also able to overcome certain limitations of the BPA ANN rainfall-runoff model reported by others.

Chen and Adams (2006c) integrated ANN with conceptual models for rainfall and runoff. The verification showed that the incorporation of ANN improved the conceptual model predictions. ANNs were also incorporated into tank models by Chen and Adams (2006d) to improve catchment modeling. ANNs with tanks were able to reflect the nonlinear nature of runoff transformations. Zhan et al. (2006) modeled the rainfall-runoff process using ANN networks coupled with a simple linear model. Rather than using previously known runoff as an input, predicted runoff was used as the model input and can be used in catchments with sparse data.

Improving HYDROWORKS (currently Infoworks) using a black-box/systems model was evaluated by Bruen and Yang (2006). The nonlinear ANN model was slightly better compared to a linear time series model. Jain and Kumar (2006) evaluated an ANN technique for determining infiltration model parameters. They suggested using a wide variety of statistical measures to evaluate the performance of various ANN models.

Other genetic algorithm and optimization tools were proposed to improve rainfall-runoff modeling. Di Pierro et al. (2006) discussed using genetic algorithms to calibrate urban runoff models in the context of a multi-objective multiple-event (MOME) paradigm. The MOME paradigm outperformed the others tested in the presented case study. Khu et al. (2006) used a preference ordering genetic algorithm to incorporate spatial and temporal information in the calibration of an urban drainage model. The results closely resembled both the calibration and validation data events. Herrera et al. (2006) presented a multi-objective calibration for SWMM to improve the simulation of the hydrologic regime. The method used was the non-dominated sorting genetic algorithm (NSGA-II).

Gill et al. (2006) introduced a relatively-new global optimization tool, called particle swarm optimization (PSO), to estimate hydrological parameters. Three case studies were compared to a conventional model, with encouraging results. Rainfall-runoff forecast optimization through mean areal rainfall optimization was presented by Antil et al. (2006). Genetic algorithms were used to improve the rainfall forecast performance, which were then applied to improved streamflow forecasts. Vrugt et al. (2006) applied a stochastic parameter optimization technique, the Shuffled Complex Evolution Metropolis algorithm, to the Sacramento Soil Moisture Account (SAC-SMA) model. The results demonstrated that most of the 13 SAC-SMA parameters were well identified by calibration to daily streamflow data.

Kavetski et al. (2006c) discussed inherent difficulties in calibrating conceptual hydrological models, including old perceptions about applying classical analysis methods, such as Newton-type optimization and derivative-based uncertainty analysis, to optimization. Boughton (2006) discussed calibration of a daily rainfall-runoff model using poor-quality data. Methods of data enhancement, including scaling based on known runoff and eliminating the month of maximum recorded runoff, were used to retrieve usable data from two-thirds of a poor data set.

Ewen et al. (2006) discussed the errors and uncertainties of modeling catchment change effects on the rainfall-runoff process. The authors reviewed the standard approach to pre- and post-development/change runoff. Bardossy et al. (2006) proposed a methodology for accounting for the uncertainties in the unit hydrograph method. The uncertainty in the runoff calculation was represented in terms of fuzzy vagueness by the width of these range of values. Kuczera et al. (2006) characterized model error using storm-dependent parameters and a Bayesian total error analysis. The results showed that the uncertainty in the rainfall data dominated the model uncertainty. Kavetski et al. (2006a) presented the theory behind the Bayesian analysis of input uncertainty as applied to hydrological modeling. The modeler, using this methodology, must incorporate, test and refine the existing understanding associated with all sources of data uncertainty.

Cloke et al. (2006) developed a modeling methodology for riparian hydrological processes using the random walk particle method. The model was used to assess fundamental hydrological processes such as pre-event and event storm runoff, and reversals of flow in the floodplain. Govindaraju et al. (2006) proposed a semi-analytical model of expected areal-average infiltration, given the spatial heterogeneity of rainfall and soil saturated hydraulic conductivity. The model was reliable both with coupled spatial variability of rainfall rate and hydraulic conductivity, and when only one variable is spatially heterogeneous while the other is uniform. Meng et al. (2006) performed a scaling analysis of space-time infiltration using a universal multifractal model. Major findings included: (1) rainfall spatial characteristics affected infiltration only early in the runoff event; (2) saturated hydraulic conductivity determined if the resulting infiltration field displays scaling behavior, (3) the heterogeneity of the rainfall and lack of a saturated hydraulic conductivity field impacted infiltration, and (4) infiltration is statistically heterogeneous.

Chen et al. (2006c) compared SWMM4 and SWMM5 to flow monitoring data. Both versions of the model agreed with each other and generally matched the field data. Lin et al. (2006) integrated “legacy” components, such as SWMM, into a storm sewer simulation. The results showed that multi-thread technology could be used to integrate legacy models into newer simulation schemes.

Galster et al. (2006) investigated the impacts of urbanization on watershed hydrology through the scaling of discharge to drainage area. The researchers found that scaling was nonlinear for peak flows in urban areas. Real-time flood forecasting in Rome (from the Tiber River) was investigated by Calvo and Savi (2006). Linear regression models were shown to better fit the data, and a Bayesian decision model was used to determine threshold discharges for activating the warning system. The influence of hydraulic rating curve uncertainty on daily rainfall-runoff model predictions was explored by Aronica et al. (2006) in Sicily. The final results showed the most significant uncertainties associated with overestimated rating curves than underestimated ones. Mouelhi et al. (2006) linked stream flow to rainfall using an annual time step using the Manabe bucket model. This model was not predictive and the authors proposed a new, simplified model that outperformed the Manabe bucket model. Wang et al. (2006a) examined a modified Hortonian overland flow model through laboratory data. A regression equation was presented, which provided both the theoretical and experimental basis to modify the time delay of peak flow for a distributed rainfall-runoff modeling.

Hammond and Han (2006) proposed using a nonlinear recession curve for hydrographs to aid storm separation. This model would be applicable to maritime climates where frequent rainfall events cause the flows to rise before the previous storm has receded to baseflow levels. Boughton and Chiew (2006) described multiple linear regressions used to estimate runoff from ungauged catchments in Australia. The model incorporates average annual runoff and areal potential evapotranspiration in its calculations.

Brath et al. (2006) assessed the effect of land-use change on flood frequency. They found that the sensitivity of the flood regime decreased with increasing return period for the modeled flow. Jayawardena et al. (2006) comparatively analyzed data-driven and GIS-based rainfall-runoff models. The results for a steeply-sloped catchment in Hong Kong showed that the conceptual model outperformed the data-driven model, whereas for other catchments, the data-driven model performed better. Koutsoyiannis (2006) showed that the careful application of the concepts of dynamic systems provided

strong indications that hydrological processes cannot be deterministically chaotic. Further investigations showed that real-world hydrometeorological series did not contain chaos. Liu and Shao (2006) simulated rainfall runoff in urban districts in China. A model was established based on the St. Venant equation. Purcell (2006) presented the physical analog of the linear reservoir that is used to conceptually model the rainfall-runoff process. A laboratory-scale model of this physical analog was constructed and used to illustrate the concepts to students.

Fleurant et al. (2006) presented an analytical model for a geomorphological instantaneous unit hydrograph (GIUH). The model parameters are based on real geomorphological data and do not require calibration. Guo (2006b) theoretically derived a dimensionless unit hydrograph using the kinematic wave approach. This hydrograph was applicable to urban catchments with drainage areas smaller than 120 ac. Saghafian (2006) described a nonlinear transform of a unit hydrograph used for flood hydrograph estimation. The authors suggested that the nonlinear transformation was a major step in breaching the gap between physically-based and traditional unit hydrographs.

Quader and Guo (2006) estimated peak discharges using analytical probabilistic and design storm approaches. The peak discharge estimates were comparable for the design case, as were the discrepancies caused by subcatchment aggregation and by the differences in meteorologic data analysis. Wu et al. (2006a) described the use of HydroCA, which incorporates GIS and cellular automation, to route flow through a watershed. A study in China showed that the HydroCA model could simulate the watershed runoff routing. Wyatt and Franks (2006) introduced the Multi-Model approach to rainfall-runoff modeling. This new lumped method incorporated numerous alternative process descriptions for the dominant processes within a catchment that affect the streamflow response to climatic forcing conditions.

Tsheko (2006) compared the NRCS CN and two other models (Pitman and Monash models) with gauged runoff to determine which model best estimated rainfall-runoff in southeastern Botswana. The modeling results were inconclusive. Jain et al. (2006a) reviewed the initial abstraction-maximum storage relation employed in the NRCS curve number methods and found that a new model outperformed the traditional simple linear model. The evaluation also showed that the NRCS CN model results were antecedent-moisture-condition dependent (Jain et al. 2006b). They found that the existing curve number model is more suitable for agricultural watersheds with high runoff than for mixed land use sites, whereas the Mishra-Singh model worked well in mixed land use areas. Jain et al. (2006c) discussed an enhanced curve number model that incorporates storm duration and a nonlinear initial abstraction-storage relationship. Their statistical analysis showed that the new model outperformed the existing models. Mishra et al. (2006b) applied curve number modeling to sediment yield analyses using the universal soil loss equation (USLE). The model was tested against urban, agricultural and forest watersheds.

Nachabe (2006) compared the TOPMODEL and curve number methods to predict variable runoff source areas. This approach provides a clear physical meaning for the maximum storage, allowing for a better estimation of that parameter. Kalin and Hantush (2006a) comparatively assessed two distributed watershed models applied to a small watershed. The two models, the Kinematic Runoff and Erosion (KINEROS-2) and the Gridded Surface Subsurface Hydrologic Analysis (GSSHA), performed similarly in the same watershed when evaluated over a 1-month simulation period. Fang and Su (2006) presented an integrated 1-D and 2-D urban stormwater flood simulation model. The model was applied to Beaumont, Texas and validated using data from Tropical Storm Allison.

Wurbs (2006) compared methods for developing monthly flows at gauged and ungauged sites in Texas. The methodologies for developing naturalized flows at gauged and ungauged sites incorporated in the Texas water availability modeling system were generally applicable for similar modeling applications in other places. Young et al. (2006) researched the prediction of low flows in ungauged basins. The model structure and regionalization strategy was not significant in limiting the performance of regionalized models. Ludwig and Schneider (2006) validated DEMs from SRTM X-SAR for use in hydrological modeling. This method was able to develop data sets sufficient for incorporation in modeling, although accuracy was reduced in mountainous terrain.

Wong and Lim (2006) evaluated the effect of a loss model on Manning's roughness coefficient in a concrete catchment. Losses in concrete had minimal effects on the Manning's  $n$  back-calculated from field measurements.

Pervious areas can be an important component of runoff generation within an urban watershed. Berthier et al. (2002) explored the role of urban soils in urban hydrology and presented a model capable of explicitly incorporating urban soil



and its characteristics. The model was applied to the Rezé catchment and found to predict flow rates at the catchment outlet fairly well. Simulations indicated that on average 11% of the outflow volume during the rainfall events studied were contributed from soil areas. Storm water infiltration into fractured-rock aquifers is difficult to simulate accurately with mechanistic models. Hong and Rosen (2002) presented an alternative approach using genetic programming (GP) to perform automatic model evolution to model dynamic behavior of groundwater level fluctuations affected by storm water infiltration. Simulation results showed that GP is capable of predicting groundwater level fluctuations due to storm water infiltration and also provides insight into the dynamic behavior of a relatively unknown urban fractured-rock aquifer system. In related work, Hong et al. (2002) proposed the application of a dynamic fuzzy modeling approach to predict groundwater level fluctuations.

Wong et al. (2002) described the Model for Urban Stormwater Improvement Conceptualization (MUSIC) developed by the Cooperative Research Centre for Catchment Hydrology (CRCCH). MUSIC was designed to be a decision support system (DSS) for urban catchment managers to facilitate the preparation of a stormwater treatment strategy and to simulate the performance of the strategy using continuous simulation. Detailed monitoring of a typical urban catchment in Canberra, Australia led Goyen (2002) to a modified modeling approach that incorporated lot scale process definition. Through accumulation, the lot scale processes are scalable to larger watershed areas. Goyen et al. (2002) developed analytical/numerical modeling tools to test the effects of mixed allotment scale and larger public drainage storage, infiltration/evapotranspiration, and water reuse systems throughout a 110 km<sup>2</sup> urban catchment in Australia.

The need to reduce run times in detailed hydrodynamic modeling of storage and conveyance in combined sewer systems prompted van Heeringen et al. (2002) to attempt hydrodynamic simulations with SOBEK using parallel processing machines. Tests of the parallel processing approach found that substantial reductions in the turn around time of simulations could be achieved. Jin et al. (2002) developed a one-dimensional hydrodynamic numerical model that implements an implicit four-point, finite difference solution technique to solve the one-dimensional Saint-Venant equations. The hydrodynamic model has been incorporated into the Haestad Methods hydraulics software to model unsteady flows in urban drainage systems. Crowder and Diplas (2002) presented a conceptual model for using two-dimensional hydraulic models to evaluate the impacts of flow regime changes caused by watershed changes (e.g., urbanization) on river flood levels, sediment transport rates, and habitat conditions. Hsu et al. (2002) developed an urban inundation model by coupling a two-dimensional non-inertia overland flow model with a storm water management model.

Smullen (2002) presented a two-tiered modeling approach for use in large-scale, comprehensive planning studies for complex urban watersheds. The first tier implements models to represent in detail the important hydraulic elements with a simplified representation of watershed hydrology. The second tier implements a more complete representation of hydraulic elements and basin hydrology. Performance of urban drainage practices has traditionally been expressed in terms that relate to local engineering design criteria, which has resulted in limited standardization of the process (Cardoso et al., 2002). A sewer system modeling post-processor was developed by Cardoso et al. (2002) to assess the performance of urban drainage systems and make recommendations for system design, diagnosis, operation, and rehabilitation.

Rangarajan et al. (2002) presented the general verification protocol being used to evaluate wet weather flow simulation models as part of the U.S. EPA Environmental Technology Verification (ETV) program. The protocol is designed to ensure that verification is carried out in a consistent and objective manner to confirm the specific capabilities and features of a model as depicted in its product literature. Hackett et al. (2002) applied the verification protocol to evaluate the XP-SWMM software package. Existing software used for hydraulic modeling often does not provide optimal or sufficiently detailed information to help the modeler in the analyses (Rivard and Dupuis, 2002). Rivard and Dupuis (2002) introduced a set of tools combining computational hydraulic modeling and information technology with a clear focus on problem solving. James (2002b) described the evaluation of a web instructional use of a group decision support system (GDSS) for the design of urban water systems. Experience has shown that achievable model accuracy is more a product of user quality and effort than on model structure. The use of the GDSS concept in urban drainage design was tested using nineteen graduate students and five professors from four Universities during the spring of 2000. The conclusion of the educational experiment was that a GDSS could be used to enhance user performance. Hatchett et al. (2002) introduced an automated storm sewer design procedure after discussing the differences between available storm sewer design models.

### **Water quality modeling and pollutant transport**

Chen and Adams (2006a) presented the theoretical framework for urban stormwater modeling and control analysis using

models. Chen and Adams (2006b) presented a methodology for developing analytical stormwater quality models using probability distribution theory for three processes – the rainfall-runoff transformation, pollutant buildup, and washoff. A case study showed that the analytical models were able to recreate the observed field data. Wang et al. (2006c) described a power function decay of hydraulic conductivity in the TOPMODEL-based infiltration routine. The advantages of the power function infiltration routine were replication of field-observed processes in urbanized areas and numerical consistency with power function decay of baseflow and topographic index distributions. Wong et al. (2006) modeled urban stormwater treatment using a first-order kinetic decay model in combination with a continuously-stirred tank reactor. Kanso et al. (2006) applied the MCMC-GSA model calibration method to runoff water quality modeling. The Metropolis algorithm was able to assess the uncertainties inherent in some parameters, as well as their interaction structure.

Garcia-Salas and Chocat (2006) assessed the uncertainties in modeling CSOs as a result of describing special structures in the model. Wride et al. (2006) used a system-wide computer model for the Greater Cincinnati Metropolitan Sewer District and calibrated using SWMM 4. The tool compared the up-to-date GIS data with current stormwater management data, documented differences, allowed for visualization of the difference locations in the system, provided a mechanism to methodically evaluate the differences, documented the decision making process, and created updated model data formatted for the model input files.

Sediment yield was simulated using a physiographic soil erosion-deposition (PSED) model. PSED was effective at estimating the sediment yield within a reasonable range (Chen et al. (2006a)). The Areal Non Point Source Watershed Environment Response Simulation (ANSWERS) model was modified to improve prediction of overland sediment transport capacity. The model simulations showed that soil moisture conditions, rainfall depth and intensity affect the model predictions (Ahmadi et al. 2006).

Maglionico and Barausse (2002) developed a water quality model to evaluate the response of natural streams to sewer overflows. Fang and Yang (2002) developed a two-dimensional depth-averaged mathematical model to simulate the hydrodynamics and sediment deposition from stormwater entering urban lakes. The model takes into account the wind and Coriolis forces and solves the governing equations on triangular grids using the time-split hybrid scheme. Application of the model to Lake Dian in China indicated that the most sedimentation occurred near the stormwater outfalls into the lake, as expected. Overall, the model predicted reasonably well. Garcia-Barcina et al. (2002) simulated the effect of fecal coliform pollution on the water quality of Bilboa Estuary in North Spain arising from CSO. Results suggested disinfection of the discharges might be needed. Harris et al. (2002) described, in general, models used for flow and water quality predictions in coastal and inland water bodies and discussed the limitations and restrictions of both physical and numerical models. They also described the development of a three-dimensional layer-integrated model to predict water elevations, layer-average velocity components, and the distribution of water quality indicators within Cardiff Bay, Wales. Kashefipour et al. (2002) developed a numerical model combining a depth integrated two-dimensional coastal model and a cross-sectionally integrated one-dimensional river model to predict water surface elevations, velocity fields, and fecal coliform concentration distributions across the entire model domain for the Ribble Estuary system along the northwest coast of England. Ahern and Hazelton (2002) reported on an extensive field data collection effort in the Lower Savannah River Estuary in support of the development of a three-dimensional hydrodynamic and water quality model of the estuary.

Linker et al. (2002) summarized the history of linked airshed, watershed, and water body modeling of the Chesapeake Bay. The first version of the Chesapeake Bay Watershed Model was completed in 1982, and then in progressive phases the watershed model was refined and linked with an estuarine model and to an airshed model. Recent work has incorporated the simulations of underwater grasses in the Chesapeake. These cross-media models have been used to estimate nutrient waste loads and set waste load allocations for major basins of the Chesapeake. The next generation of models will be developed as “community models” with source codes and model preprocessors and postprocessors freely available over the web.

Besides the Chesapeake Bay modeling activities, other regional integrated modeling systems have been initiated. Hussein et al. (2002) described the expansion of the capabilities of the next generation regional model for managing water resources in South Florida to include simulation of the fate and transport of dissolved constituents. Moskus et al. (2002) reported on the development and application of linked watershed (Generalized Watershed Loading Function) and water quality model (WASP) for the Pumpkinvine Creek watershed in Georgia. David and Matos (2002) used deterministic

water quality modeling integrated with urban stormwater modeling to assess impacts of stormwater discharges on ephemeral watercourses.

Faulkner and Lyon (2002) introduced a new screening model to predict the fate and transport of viruses in percolating water. The leaching fraction model has been implemented in the EPA VirMod computer program. The leaching fraction model can be integrated with GIS to easily incorporate spatial data layers and visualize model output. Schneiderman et al. (2002) updated previous estimates of nutrient and sediment loads to the Cannonsville Reservoir using a revision of the Generalized Watershed Loading Functions (GWLF) model of the West Branch Delaware River watershed.

Brezonik and Stadelmann (2002) compiled a large database of urban runoff data for the twin cities metropolitan area in Minnesota. Relationships between runoff variables and storm and watershed characteristics were examined. Results of the data analysis indicated that median EMCs tended to be higher in snowmelt runoff than in rainfall runoff and simple correlations between explanatory variables and stormwater loads and EMCs were weak. Rainfall amount and intensity and drainage area were the most important variables in multiple linear regression models to predict event loads, but uncertainty was high.

Sutherland and Jelen (2002) presented a technique to more accurately estimate urban runoff loads. The load estimation procedure involved selecting and monitoring specific pilot test areas that are representative of the various land uses found within the watershed. Instead of the costly monitoring of actual stormwater quality at each test area, the load estimation procedure called for the intensive monitoring of the accumulation and physical/chemical characteristics of the sediment found on the streets or parking lots and within the catchbasins of a given land use. This data along with monitored rainfall was then used to calibrate a stormwater quality model called SIMPTM. Once the model was calibrated to the various monitoring periods, an average or representative rainfall year was used to evaluate various street and catchbasin cleaning practices.

#### **Watershed model water balance**

Snowmelt prediction is often lacking in urban hydrologic models. Matheussen and Thorolfsson (2002) developed the lumped Risvollan Urban Hydrological Model (RUHM) that solves the full mass and energy balance equations when calculating snowmelt, evapotranspiration, infiltration, and runoff within a watershed. RUHM was applied to the Risvollan urban watershed in Trondheim, Norway and found to predict both runoff, water balance, and snow water equivalent with reasonable agreement.

Many enhancements have been made to the EPA SWMM model since the last official EPA release in 1994 (Huber et al. 2000). These have included improvements to the model engine, enhancements to input/output options, and “hooks” for easier interfacing with graphical user interfaces and ancillary software. The U.S. EPA Office of Research and Development (ORD) Urban Watershed Management Branch (UWMB) has identified two major objectives for urban modeling research: to develop a standard operating procedure for the user community, and to develop a BASINS-compatible SWMM – GIS interface (Kousta 2000). Kousta provided the SWMM-user community with a description of the UWMB approach to urban watershed modeling research and provided an update on ORD SWMM-related projects.

Distributed models were more and more used in regional hydrology. One of the main reasons was their essential compatibility with raster data in Geographical Information Systems. Zech and Escarmelle (1999) investigated the possibility of using other kinds of databases designed more specifically for cartography. Casser and Verworm (1999) described the upgrading of the existing hydrodynamic rainfall runoff model HYSTEM/EXTRAN and the decision finding model INTL for real time performance, their implementation on a network of UNIX stations and the experiences from running them within an urban drainage real time control project. The main focus was not on what the models do but how they were put into action and made to run smoothly embedded in all the processes necessary in operational real time control.

Modelers were often faced with data gaps and other problems which may not even come to light until well into the modeling process. Greer (1999) addressed these issues in the context of a case study of a watershed management project conducted in Silver Lake Watershed in central Delaware. A suite of hydrologic, sewer system and riverine water quality models have been used to address technical questions that have been asked in Rouge River Watershed (Michigan) planning (Kluitenberg et al., 1999).

Zug et al. (1999) described modeling efforts to address both flood control and pollution prevention at Gentilly, France. A mathematical model was satisfactorily calibrated and validated and was now being used to simulate the operation of the

catchment area and its associated sewerage system.

Schlater and Koehler (1998) asserted that expectations between owner and consultant regarding model applicability and associated development cost are misaligned and that matter-of-fact information concerning what a typical model can and cannot do needs to be clear in the minds of both parties. A checklist is provided to address what an owner needs to know about model development but does not know how to ask. Ahyerre *et al.* (1998) examined stormwater runoff quality models to determine why no model has achieved widespread use and indicate that the generation and transport of polluted runoff in an urban setting is complex, involves many media and many time and space scales, which renders stormwater quality models difficult and expensive to utilize. The authors suggested that a clear distinction should be made between management tools and research models. Gaume *et al.* (1998) studied the estimation and interpretation of the parameter uncertainties of conceptual models used in hydrology using a global approach. They concluded that the lack of measured data and its relative redundancy cause a significant interaction between the parameters which hinders calibration and that the data available in hydrology are only sufficient to support the development of models with limited complexity.

The Stormwater and Water Quality Management Modeling Conference, held in Toronto, Ont., Can. in February 1996 yielded a collection of articles which addressed a wide range of modeling applications for WWF impacts management. This accumulation of articles is the fifth in a series of monographs published and includes presented information on methods for urban- watershed management and planning; modeling stormwater quality; storage and treatment practices; and a stormwater-system evaluation (James, 1997).

Within the United States, users continue to rely on existing urban-stormwater models. TenBroek and Brink (1996) compared several continuous-stormwater-simulation models including STORM and SWMM. Donigian *et al.* (1996) compared the attributes of six urban- and seven nonurban-stormwater models. Mercer *et al.* (1996) summarized the use of a variety of stormwater models including SWMM, WASP, the Watershed Management Model, and P8 as part of the Rouge Project in the Detroit, MI area. Donahue *et al.* (1996) summarized the use of modeling and evaluation tools to select a cost-effective CSO-control plan within a watershed perspective. The attributes of six stormwater models are compared by Shoemaker *et al.* (1996). Swarner and Thompson (1996) presented the results of extensive measurements and modeling of SSO problems in Seattle, WA. The results of an extensive SSO evaluation using XP SWMM for the Miami, FL sewer system are described by Walch *et al.* (1996). Kachalsky *et al.* (1996) described modeling and evaluation methods of optimizing CSO control in New York, NY. Herrmann and Klaus (1996) did general water and nutrient budgets for urban-water systems including stormwater.

A variety of international urban-stormwater models have been released in recent years. Neylen *et al.* (1996) described the first version of the HydroWorks-stormwater-quality-management model being developed by Wallingford Software in the United Kingdom. Foller *et al.* (1996) showed how MOUSE can be used to optimize a combined-sewer system in East Germany. Dempsey *et al.* (1996) described SIMPOL, a simplified urban-pollution-modeling tool developed as part of the United Kingdom's Urban Pollution Management Research Program. SIMPOL models the stormwater system as series of tanks. Bente and Schilling (1996) proposed an object-oriented approach for an urban-hydrologic-simulation system. Davies (1996) discussed the importance of the appropriate blend of modeling and data for SSO evaluations including a discussion of the advantages and disadvantages of SWMM and HydroWorks. A very extensive evaluation of the Sydney, Australia SSO problem was done with MOUSENAM and SEEKER to simulate and optimize control options (Hayes, 1996). Ji *et al.* (1996) describe a fast model for evaluating the hydraulics of sewers and open channels. This work showed the implicit-solution scheme in the SUPERLINK model to be much faster than EXTRAN's explicit solution. Gent *et al.* (1996) surveyed models that can simulate solid deposition and resuspension in sewers. MOUSETRAP and HydroWorks QM that supersedes WALLRUS and MOSQUITO were described. Jack *et al.* (1996) described several models for characterizing sewer sediments. Brief descriptions of the WALLRUS/HydroWorks PM hydraulics model, the STOAT wastewater-treatment-performance model, and the MOSQUITO, HydroWorks-DM and MOUSETRAP sewer-flow-water-quality models were provided. Imbe *et al.* (1996) used a water budget to establish the effect of urbanization on the hydrological cycle of a new development near Tokyo, Japan. This development is trying to reduce hydrologic impacts by encouraging infiltration systems and storing rainwater. Mitchell *et al.* (1996) described a water-budget approach to integrated-water management in Australia. Budgeting is done at the individual parcel, neighborhood, and wider catchment scale. A current gap in urban stormwater modeling is the inability to properly incorporate the impact of rainfall on frozen surfaces in urban areas. Thorolfsson and Brandt (1996) described Norwegian experience in which "worst case" conditions occur during these winter periods. The development of new mathematical models to handle this special case were recommended.

## ***Model Applications***

Rossman et al. (2003) reported on the update/conversion of the EPA Storm Water Management Model (SWMM) to an object-based approach. In addition, the numerical stability of SWMM's dynamic wave flow routing was enhanced.

An integrated system in Flanders consisting of a sewer, a wastewater treatment plant and a river component was selected for a modelling project (Fronteau and Bauwens 1999). The purpose of that project was to assess the impact of CSO on the receiving water and to investigate on the effects of different operating scenarios within the sewer system. Commercial mathematical models were used, i.e. both the sewer network and the WWTP were modelled with Kosim, while Isis was used to represent the river system. An overview of extended stormwater treatment alternatives is discussed and as well as the possibility of including these practices in simulation models (Mehler and Ostrowski, 1998).

Watanabe et al. (1999a) described a distributed simulation model of water quality and stormwater runoff, which can simulate both open-channel and surcharged flows and at a temporal and spatial variation of runoff-water quality in the pipe systems. The proposed model consists of two models: one was PWRI (the Public Works Research Institute, the Ministry of Construction, Japan) Model for water quality simulations; the other was the SLOT Model for stormwater runoff simulations.

The distributed parameter (grid cell) agricultural nonpoint source runoff (AGNPS) model compared stormwater-runoff volumes, flowrates, and sediment loads from a forested watershed and urbanized watershed for ten simulated rainfall events and included the effects of impervious surfaces on runoff and sediment transport. The rainfall volume to runoff volume ratio was 14.5% higher in the urban watershed with the maximum differences occurring at rainfall depths < 75 mm (Corbett *et al.*, 1997). A complex watershed-scale water-quality-simulation model, the Hydrological Simulation Program-FORTRAN (HSPF) model, was calibrated for a 16 km<sup>2</sup> catchment. It was necessary to apply a critical process that included sensitivity analysis, numerical optimization, and testing of derived-model-parameter sets to evaluate their performance for periods other than those for which they were determined (Jacomino and Fields, 1997). Runoff depth and pollutant loadings for BOD, SS, Total Kjeldahl Nitrogen (TKN) and Pb computations, respectively for four small sites (i.e., 14.7 acres — 58.3 acres) in South Florida were respectively performed using the Soil Conservation Service (SCS) hydrology method and empirical equations developed by the U.S. EPA. Comparisons of predicted versus measured data for both hydrographs and pollutant loadings were reported (Tsihrintzis and Hamid, 1997). The Extended Transport block (EXTRAN) of the Storm Water Management Model (SWMM) Version IV was modified to include the effect of variable roughness for circular pipes on routed hydrograph attenuation and lag time (Zaghloul, 1997). Routing simulations using variable roughness resulted in hydrographs with significant peak-flow attenuation and lag time.

### **Rainfall variability and effects on modeling.**

Rainfall data are generally recognized as the most important input for hydrologic prediction.

Kalin and Hantush (2006b) modeled, using the Soil Water Assessment Tool (SWAT), an eastern Pennsylvania watershed using NEXRAD and rain gauge data. The purpose of the modeling was to predict impacts of future development on base flow and peak runoff. The spatial representation of precipitation did not improve model performance when stream flow at the watershed outlet was the required output. However, the use of NEXRAD technology appears to offer a promising source of precipitation data. Berthier et al. (2006) compared two evapotranspiration models/schemes using data from an instrumented suburban site. The results illustrated the uncertainties in evapotranspiration estimation in urban areas. De Figueriredo and Bathurst (2006) analyzed the effects of rainfall variability and land-use change on sediment yield simulated by the SHETRAN model. Sediment yield increased as rainfall progressed from dry to normal and as land-use changed from forest.

Accurate data with proper spatial and temporal resolution is critical to produce accurate rainfall-runoff predictions. Maskey et al. (2004) presented a methodology for propagating the precipitation uncertainty through a deterministic rainfall-runoff-routing model for flood forecasting.

The application of radar rainfall data is becoming more common as the technology to measure rainfall rates with radar and to ingest the data into runoff models improves. Vallabhaneni et al. (2004) described the basic steps of integrating gauge and radar measurements of rainfall into hydrologic and hydraulic models. Zhang et al. (2004) reviewed an approach using NEXRAD radar data and streamflow data for a river basin to determine the potential usefulness of applying a distributed model. Testing of the method using three test basins in the Arkansas-Red River basin demonstrated the validity of the technique.

Durrans et al. (2004) introduced a method to enhance the temporal resolution of an archived time series of incremental precipitation depths by perturbing cumulative totals of the coarsely resolved archival data to represent them at a finer degree of resolution. The testing of the enhancement demonstrated that the enhanced precipitation depths were a much less biased representation of true depths than were the coarsely resolved data.

Design storms continue to be applied for various applications at a range of scales. Smithers and Schulze (2004) derived scaling characteristics of South African extreme rainfall and implemented a regional approach to estimate design rainfalls in South Africa for durations ranging from 5 min to 7 days. Dinpashoh et al. (2004) presented a study of the regionalization of Iran's precipitation. Twelve variables were used to regionalize Iran's precipitation using factor analysis and clustering techniques. The country was divided into six homogeneous regions and a single heterogeneous region.

Issues associated with forecasting adverse weather in the Baltimore – Washington, DC metropolitan area were discussed by Zubrick (2004). Recent advances in observing technology have improved predictions. Better understanding of these issues will improve planning, management, and design of urban transportation and drainage infrastructure.

Asquith et al. (2003) developed a triangular dimensionless model of rainfall hyetographs in Texas in order to enhance watershed design practice in the applicable parts of Texas. Kim et al. (2003) used Thiessen polygons and spatially-distributed rainfall data to predict grid-based dam inflows on a large river basin. In a narrow elongated watershed width, there were large temporal and spatial discharge differences depending on the rainfall orientation. Mendez et al. (2003) reviewed rainfall point intensities in an air mass thunderstorm environment since point rainfall intensities are used to formulate design storms for rainfall-runoff models. When the rainfall data record was 35 years and 20 stations, accuracy of the maximum intensities were close to the rainfall measurements, but errors increased as the return period increased. Tachikawa et al. (2003) presented an error structure for real-time rainfall prediction by a translation model.

Ishidaira et al. (2003) investigated the effect of spatial and temporal resolution of precipitation data on the accuracy of long-term runoff simulation in the Fuji River basin. The difference between the simulated daily hydrographs using original precipitation and the averaged ones was investigated through the comparison of the Nash efficiency for each simulation. Wride et al. (2003) used radar-generated rainfall estimates to improve the characterization and therefore the modeling of I/I response in the sewer system. Radar-rainfall data, calibrated with a network of ground rain gages, were used to account for the spatial variability of rainfall across the study area. Wu et al. (2003) presented a Calibrated High-Resolution Precipitation Database (CHPD) for TMDL models, as well as other models that require precipitation input. The limitation is similar to that of other methods – the method does not address rainfall estimates between weather stations. In addition, this method can not give the true rainfall distribution for an isolated or fast moving storm.

Abebe and Price (2003) approached handling the uncertainties in conceptual rainfall-runoff modeling as an error modeling program, based on a parallel data-driven model that uses available measured data and previous model errors at specific time steps to forecast the errors of the conceptual model. The parallel data-driven model complemented the conceptual model and produced much better runoff predictions compared to the conceptual model alone. Meeneghan et al. (2003) evaluated whether improving the accuracy of the rainfall measurement translated into improved flow simulation performance from hydraulic/hydrologic models using a case study in Pittsburgh, PA. Four rainfall data sources were input and subsequently evaluated: the regional long-term record gauge; the nearest short-term gauge; a dense network of 5 gauges located in and around the study watershed; and a calibrated radar-rainfall system, with a pixel resolution of 1 km<sup>2</sup>.

Koussis et al. (2003) described a system for forecasting flood risk in the largely urban Kifissos Basin (Athens, Greece). Rainfall was forecast, on a 6 km grid, with a chain of nested numerical weather prediction models that were initialized with results of a global circulation model. Flood risk was assessed by driving a hydrologic model with the forecasted rainfall.

James (2002c) investigated the robustness of an algorithm for storm direction and speed used in the Rainpak utility of PCSWMM. An extensive sensitivity analysis indicated that standard data collection time steps of 1 or 5 minutes were sufficient for resolving storm dynamics and highlighted the importance of more rain gauges and the arrangement of rain gauge networks for describing storm event dynamics. Willems and Berlamont (2002a) evaluated the influence of the spatial variability of rainfall on the results of urban hydrologic models. Results of the study included a combination of

unified IDF relationships, spatial correction factors, a stochastic simulation model for spatial rainfall, and a methodology for improving the spatial correction factors in a case-specific way by performing simulations with the model.

One common problem encountered when performing continuous simulation is the availability of rainfall data at the location of interest and with an appropriate time increment. One solution to the time increment problem is to perform a temporal disaggregation step to produce a rainfall record with finer time resolution from a coarser resolution dataset. Burian and Durrans (2002) compared a quadratic spline and a quadratic polynomial technique, a method based on geometric similarity, a uniform distribution approach, and an artificial neural network method to disaggregate hourly rainfall records to sub-hourly increments. The methods were evaluated based on their ability to accurately disaggregate hourly rainfall data from Alabama and Arkansas to 15-minute and 5-minute increments and results indicated the artificial neural network approach and geometric similarity technique provided the most accurate disaggregation. In addition to the disaggregation of recorded rainfall data, stochastic generation of rainfall is a viable option to provide input data with adequate time resolution for wet weather flow simulation models. Hingray et al. (2002) presented a comprehensive detention facility-design modeling framework including a stochastic component to generate long-term rainfall series with short time step, a rainfall-runoff model to transform the rainfall series into a runoff series with a short time step, and a model to describe the hydraulics of the detention facility.

The evaluation of radar rainfall data products for use in wet weather flow modeling has expanded considerably as the technology continues to develop. Koran et al. (2002) described the use of radar rainfall technology in the development and calibration of the System Wide Model for the collection system of the Metropolitan Sewer District of Greater Cincinnati. Quirmbach and Schultz (2002) evaluated the suitability of using radar data versus rain gauge data for urban rainfall-runoff modeling. Results indicated that radar data should be used in urban hydrology if distances between rain gauges exceed 4 km and if rain gauge density for a catchment is less than 1 gauge/16 km<sup>2</sup>.

NEXRAD (WSR-88D) radars have made spatially distributed rainfall data available in an operational environment (Carpenter et al., 2001). The present study addressed the use of NEXRAD data using a Monte-Carlo sensitivity analysis of event streamflow to parameter and radar input for the Illinois River basin in Oklahoma and Arkansas. The main conclusion was that the distributed model forced by NEXRAD data produces results comparable to those produced by the operational spatially-lumped models using raingage data. Detection of rain/no-rain condition on the ground is needed to apply radar rainfall algorithms to hydrological models (Lui et al., 2001d). A radial basis function (RBF) neural network-based scheme for rain/no-rain determination on the ground using vertical profiles of radar data was described in this paper. Evaluation based on WSR-88D radar over central Florida indicates that rain/no-rain condition could be inferred fairly accurately. Lui et al. (2001e) presented a novel scheme for adaptively updating the structure and parameters of the neural network for rainfall estimation. The network can account for any variability in the relationship between radar measurements and precipitation estimation and also incorporate new information to the network without retraining the complete network from the beginning. To make the monthly satellite data useful for hydrological applications (i.e. water balance studies, rainfall-runoff modeling, etc.), the monthly precipitation estimates must be disaggregated into shorter time intervals (Margulis and Entekhabi 2001). In this study, two simple statistical disaggregation schemes were developed for use with monthly precipitation estimates from satellites. Results suggested that one of the proposed disaggregation schemes could be used in hydrological applications without introducing significant error.

Rainfall data collected since the publication of NWS' Technical Paper 40 and HYDRO-35, and NOAA's Atlas 2, and the development of improved statistical methods, motivated several states to initiate update studies of precipitation distributions (Durrans and Brown 2001). Results of the Alabama study were disseminated via an Internet-based graphical user interface, which permits users to interactively point and click on a location of interest and have IDF curves or storm hyetographs returned on demand. The study by Kim and Barros (2001) modified the existing ANN model to include the evolving structure and frequency of intense weather systems in the mid-Atlantic region of the US for improved flood forecasting. Besides using radiosonde and rainfall data, the model also used the satellite-derived characteristics of storm systems such as tropical cyclones, mesoscale convective complex systems, and convective cloud clusters as input. The results from the application of the quantitative flood forecasting model in four watersheds on the leeward side of the Appalachian mountains in the mid-Atlantic region were presented.

Aerial variations in rainfall were investigated by Balascio (2001), using unbiased multiquadric analyses to reduce the problem of negative rain gauge weighting when determining the representative rain depth for an area. Willems (2001) developed a stochastic spatial rainfall generator for use in small urban catchments. For applications at small scales, the

individual rain cells need detailed descriptions. Data from a dense network of rain gauges at Antwerp were used for verification of the process. Cameron et al. (2001) successfully modeled extreme rainfalls using a generalized Pareto distribution to represent the rain depths of high intensity rain cells. Trefryl et al. (2001) used a partial duration series/generalized Pareto regional index-flood procedure for updating rainfall intensity-duration-frequency estimates for the State of Michigan. Porras and Porras (2001) examined all series of extreme rainfall depths to produce less ambiguous depth-duration-frequency and intensity-duration-frequency curves for Venezuela. Cheng et al. (2001) used a simple scaling property of rainfall to guarantee that the normalized rainfall rates of different storm durations are identically distributed. They proposed a nonstationary Gauss-Markov model, based on the annual maximum events that arise from the dominant storm type to obtain the most likely hyetograph. This method allows translating hyetographs between storms of different durations. Koutsoyiannis and Onof (2001) developed a rainfall disaggregation method using adjusting procedures on a Poisson cluster model. This method allows the possible extension of a short hourly time-series with the use of longer-term daily rain data.

The National Weather Service's WSR-88D radar (NEXRAD) was used to estimate the spatial distribution of rainfall for three storms over the Brays Bayou watershed in Houston for hydrologic modeling purposes (Bedient et al. 2000). The results from the radar proved to be as accurate, and in some cases more accurate, than the rain gauge model when predicting runoff volume, peak flow, and peak time. Chan (2000) explored the spectral behavior of rainfall of various temporal resolutions and presented a method of generating rainfall data that combined the approaches of stochastic modeling with a disaggregation goal. The total rainfall volumes of the generated data compared well with observed values but tended to produce lower rainfall intensities and longer rainfall durations per event.

Sempere-Torres et al. (1999) presented a case study where the use of rainfall estimates from weather radar pictures was compared with the use of a rain-gauge network in terms of the ability to predict sewer flows in an urban basin in Barcelona, Spain. The results showed that the use of radar data enables the combined sewer systems model to better simulate observed flows, and provide support for the idea that the spatial description of rainfall was a key problem in modeling the events giving rise to CSO.

Luk et al. (1999) described a rainfall forecasting model that integrates an artificial neural network (ANN) with a GIS. The ANN was trained to recognize historical rainfall patterns recorded from a number of gauge of the study catchment and to make point forecasts of rainfall. The GIS was used to spatially distribute the point rainfall forecasts produced by the ANN. Mikkelsen et al. (1999) used regional modeling of a range of rainfall variable statistics to assess the performance of different historical rain time series. Sufficiently long rain series were rarely available from the exact catchment in question and for this reason simulations were often based on available rain series from other locations. Nnadi et al. (1999) tested the ability of various design storm distributions to simulate the actual rainfall pattern and to compare the runoff rates used in the design of stormwater management devices in the State of Florida using continuous simulation. Peak-runoff rates from design storms based on the various distributions were compared to those that would result from actual rainfall events. The results show that the behavior of the design storm distributions varies across the state.

Willems (1999) reported on data collected from a dense network of rain-gauges in Antwerp, Belgium to study the stochastic structure of spatial rainfall at the small spatial scale of small hydrographic or urban catchments. The derived spatial rainfall model contains two structures: a deterministic structure for the physical description of individual rain cells and cell clusters, and a stochastic structure for the description of the intrinsic randomness in the sequence of different rain events. Durrans et al. (1999) compared a number of approaches to the problem of how to disaggregate rainfall time series using polynomial approximating functions. Results of these evaluations indicate that a disaggregation method presented by Ormsbee was a relatively good performer when storm durations were short (2 h), and that a quadratic spline-based approach was a good choice for longer-duration storms. Most hydrologic/water quality (H/WQ) models that use rainfall as input assume spatial homogeneity of rainfall. Under this assumption this study assesses the variability induced in calibrated model parameters solely due to rainfall spatial variability. A large uncertainty in estimated model parameters could be expected if detailed variations in the input rainfall were not taken into account (Chaubey et al., 1999).

Useful variables for defining the state and evolution of a rain system include rainfall rate, vertically integrated rainwater content and advection velocity. The forecast model proposed in this work complements recent dynamical formulations by focusing on a formulation incorporating these variables using volumetric radar data to define the model state variables, determining the rainfall source term directly from multi-scan radar data, explicitly accounting for orographic enhancement, and explicitly incorporating the dynamical model components in an advection-diffusion scheme. An evaluation of this model was presented for four rain events collected in the south of France and in the northeast of Italy



(Dolcine et al., 1999). A procedure to generate rainfall input for the EUROpean Soil Erosion Model was presented. To develop such a procedure, first of all the influence of rainfall event amount, rainfall event duration, and time to peak intensity of event rainfall on soil losses, calculated with EUROSEM, has been tested for several rainfall stations. It seems possible to produce site specific appropriate rainfall input for EUROSEM, only with the knowledge of distributions for the investigated basic rainfall parameters; however, to improve the procedure and make it practically useful, it will be necessary to account for seasonal changes of distributions of basic rainfall event parameters (Strauss et al., 1999).

Data from a dense network of rain gauges in the city of Antwerp (Belgium) has been used to study the stochastic structure of spacial rainfall at the small spatial scale of small hydrographic or urban catchments. The derived spatial rainfall model contains two structures: a deterministic structure for the physical description of individual rain cells and cell clusters, and a stochastic structure for the description of the intrinsic randomness in the sequence of different rain events. Such a model forms the basis of the stochastic generation of spatial rainfall for urban catchments (Willems, 1999). Gyasi-Agyei and Willgoose (1999) presented a generalized hybrid model to generate point rainfall for a wide range of aggregation levels. The rainfall process was expressed as a product of a binary chain model which preserves the dry and wet sequences as well as the mean, and a correlated jitter, a second-order autoregressive Gaussian process, used to improve the deficiencies in the second-order properties of the binary chain. Two possible binary chain models were analysed, a non-randomized Bartlett-Lewis model and a Markov chain.

Daily rainfall records for durations of 30, 20, 10, 5, 4, 3, 2, and 1 years from six stations were analyzed revealing positive evidence of the existence of chaotic behavior in daily rainfall data for Singapore (Sivakumar et al., 1998). Results also suggested that the attractor dimensions of rainfall data of longer time periods are higher than that of shorter time periods. DeGaetano (1998) developed a clustering algorithm to form regions with similar extreme rainfall cumulative distribution function (CDF) characteristics and applied it to extreme rainfall data from W.V. Lambert and Kuczera (1998) modeled interstorm and storm durations for several Australian state capitals, illustrated practical issues in calibration and identification, and concluded that a generalized exponential model can replace 12 monthly models to describe the seasonal stochastic variation of interstorm time. Data from four rain gauge stations were analyzed by the fuzzy mode recognition method. The distributive character of a rainfall pattern for a short duration storm was given and the design-storm pattern was satisfied for the urban drainage by simulation and comparison (Cen et al., 1998).

Hromadka (1997) used a set of realizations of error data from rainfall-runoff hydrological models and generated a set of error transfer function realizations to equate to the original data using a four-section algorithm. Fernando and Jayawardena (1998) used artificial neural networks (ANN) to model the rainfall-runoff process. The radial basis function type of ANN saved considerable modeling time and effort.

#### **Rainfall-runoff quantity models.**

Al-Soufi (2006) applied the Soil and Water Assessment Tool (SWAT) to the Mekong Basin to evaluate the human impact on basin health as it relates to the basin hydrology. Kling et al. (2006) used a seasonal, spatially-distributed model of accumulation and melt of snow to compute runoff in a large-basin water balance model. The model performed best in high and medium mountainous catchments. Lower model performances were achieved in lowland catchments, where the contribution of snowmelt to river runoff decreases.

Sample and Heaney (2006) discussed the integrated management of irrigation and urban stormwater infiltration. They presented a modeling approach that incorporates decentralized options for stormwater management and urban water supply. Chen and Young (2006) discussed the application of the Green-Ampt infiltration model on sloping surfaces. The model was generally applicable to isotropic and mildly anisotropic soils, although nonvertical rainfall could increase runoff with increasing slope angle. Loaiciga and Huang (2006) analyzed ponding with Green-Ampt infiltration. The maximum depth of ponded water and the duration of ponding are among the variables that can be calculated with the method presented in this paper. Geurink and Ross (2006) examined the time-step dependency of infiltration errors when applied in the HSPF model. Recommendations for time-step selections were provided for shallow depth-to-water-table conditions, which can have implications for spatial discretization in the model. Struthers et al. (2006) presented a multiple wetting front gravitational infiltration and redistribution model for water balances. The model compared well with the numerical Richards equation. The model could differentiate between drainage response time and the age of draining water, which gives the approach general applicability.

Danger analysis techniques were applied to urban runoff using a numerical and experimental approach by Nania-Escobar et al. (2006). The present model was useful in studying flow in street networks, in analyzing the risk according to various

criteria, and in determining the influence of the number of gutters. The SWMM model was used by Kalaba et al. (2006) to predict the hydrology from composting sites in the United States. SWMM outperformed the rational method in predicting volume requirements for on-site detention facilities.

Kim et al. (2006c) combined rainfall-runoff outputs to improving streamflow prediction. Among the tested combining methods, sum of squared error (SSE), a combining method using time-varying weights, performed best with respect to the root mean square error. When SSE was coupled with optimal linear correction (OLC) [SSE/OLC], its bias became approached zero. Hu et al. (2006) applied the distributed snow process model and HEC-HMS in gridded snowmelt and rainfall-runoff modeling for reservoir operations. The paper focused on the information requirements and how to practically gather that information. Thorndahl et al. (2006) assessed the contributing catchment areas to runoff through modeling. This paper presented an inconsistency between calculations of the hydrological reduction factor, based on measurements of rainfall and runoff, and published recommended literature values for residential areas. Liu et al. (2006c) predicted stormwater runoff from different land-use classes using a GIS-based distributed hydrological model (WetSpa). The simulation results showed that urban runoff dominates the watershed outflow, especially in a flood event. Lim et al. (2006) evaluated the effects of initial abstraction and urbanization on runoff estimations using the curve number procedure. The results indicated that using a 5% initial abstraction-to-maximum storage, modified curve numbers and a D soil could improve long-term direct runoff prediction.

Peterson and Wicks (2006) assessed the importance of karst “conduit” geometry and other physical parameters in karst aquifer systems using SWMM. The model was minimally sensitive to slope and infiltration rates, and more sensitive to Manning’s roughness.

Jin and Shepherd (2005) review the parameters required to effectively include urban landscape in climate models. The parameters of most importance were the large fraction of heat-trapping impervious surfaces, the potential irrigation of urban plants, and the urban transport patterns affected by buildings and vegetation. Kim et al. (2005e) applied a grid-based model to assess the impact of landuse on streamflow. The watershed of interest was urbanizing, with some paddy fields still in operation. Paddy fields were found to greatly impact the amount of runoff discharged to the stream.

Yeo et al. (2005) used a multistage hierarchical optimization for land use allocations to control nonpoint source water pollution. Controlling the land-use pattern changes showed reductions in peak discharge rate. The sensitivity analyses suggested that maintaining at least 30% of the land in a conservation state. Xiong and Melching (2005) compared kinematic wave and nonlinear reservoir routing as they applied to urban watershed runoff. The authors proposed that, while the reservoir routing equations worked well with storms whose durations were longer than the watershed time of concentration, the kinematic-wave model was better able to predict the runoff across all storm events, including those whose duration was less than the time of concentration.

Modeling was used by Moramarco et al. (2005) to assess the causes of flooding in an urbanized ungauged basin in Italy. The results showed that the flooding volume and lag time parameters required special evaluation. The bridge was modeled as a hydraulic obstruction. These obstructions must be incorporated into any model of urban flooding, according to the authors. Nielsen (2005) used Mike Urban Flood to model the pipes and canals in a traditional storm sewer system and to model a dynamic overland flow model. The overland flow model was used to describe the street flooding. Rainfall-runoff process models for initial abstraction were reviewed by Anderson et al. (2005). In the urbanized areas, four land treatment types (natural, irrigated lawns, compacted soil, and impervious) were used to define surface infiltration conditions. The initial abstraction/uniform infiltration (IA/INF) techniques appeared to produce superior results over the CN method for the measured rainfall events. Rodriguez et al. (2005b) developed a distributed hydrological model based on urban databanks. The model considered the spatial variability of land use and can model evapotranspiration and infiltration.

Singh (2005) compared Clark’s and Espey’s unit hydrograph to the gamma unit hydrograph in terms of recession characteristics and time-area curves. The gamma unit hydrograph was better able to represent the hydrograph recession and both the Clark and Espey unit hydrograph could easily be converted into gamma unit hydrographs. The NRCS Unit Hydrograph Method was adapted for LID modeling in the Milwaukee (Wisconsin) area (Koch 2005). The LID retention volume was aggregated across the site and treated that volume as a depth of runoff that had to be exceeded before runoff appeared. Moore and Barrack (2005) presented new LID modeling techniques that can be used to evaluate its benefits. The modeling procedures were used in the SWMM RUNOFF and TRANSPORT models. These techniques were demonstrated in the Cub Run Watershed.

Mourad et al. (2005a and c) evaluated the optimal size and characteristics of datasets that were used to calibrate and validate stormwater regression models. The results showed that models were most sensitive to calibration data and that more of the dataset should be used in the calibration activity.

The rainwater harvesting information system in Chennai City, India was outlined by Ravikumar et al. (2005). The methodology and analysis created an output from GIS overlay analysis that could be used as a utility map for rainwater harvesting.

Rodriguez et al. (2005a) compared three complementary methods for determining urban unit hydrographs from catchment morphology. All three methods showed a variability of the unit hydrographs with rainfall intensity, as should be expected.

The development and application of distributed hydrologic models continues to evolve as spatial data becomes more available and easier to process (Vieux 2004). Brath et al. (2004) analyzed several aspects of distributed model applications including calibration period required for efficient parameterization, spatial resolution of rainfall data for model calibration, and the reliability of model parameters for application to ungauged watersheds. Results suggest the need for at least three months of calibration data and sufficient rain gage network density to produce acceptable simulation results. The distributed model was also found to provide reliable simulations of ungauged internal river sections. Meselhe et al. (2004) compared the performance of a physically-based hydrologic model (MIKE SHE) and a lumped hydrologic model (HEC-HMS) in terms of ability to predict time and magnitude of peak discharges and runoff volume. Vieux and Bedient (2004) described the development of a new testbed network of radars to measure rainfall for real-time flood forecasting applications implementing physics-based distributed modeling.

Freer et al. (2004) applied the dynamic TOPMODEL using rainfall-runoff and water table information in the calibration. The water table predictions from TOPMODEL were constrained using a fuzzy rule based performance measures derived from analysis of water table depth measurements. The analysis indicated that many possible combinations of parameter values were possible to simulate the rainfall-runoff data. Constraining the water table depths reduced the number of behavioral parameter sets. Also working with TOPMODEL, Xiong and Guo (2004) assessed the effects of the catchment runoff coefficient on rainfall-runoff relationships in an attempt to improve simulations of catchments with low runoff coefficients. Working with the networked version of TOPMODEL, Bandaragoda et al. (2004) applied TOPNET as part of the Distributed Model Intercomparison Project (DMIP). After calibration, the predictions were found to be relatively good, even for streamflow from smaller interior watersheds not used in calibration. Vieux et al. (2004) provided another contribution to the DMIP by applying the `r.water.fea` physics-based rainfall-runoff model.

Ivanov et al. (2004a, 2004b) reviewed various aspects of the continuous simulation capabilities of a fully-distributed, triangular irregular network (TIN) hydrologic model, the TIN-based Real-time Integrated Basin Simulator (tRIBS). Computational effort was assessed and results were compared to streamflow observations at basin outlet and interior gauging stations. Acceptable prediction accuracy coupled with modeling distributed hydrologic processes over the computational domain in an efficient manner (5-10% of the original grid nodes) demonstrated the potential for using fully-distributed models at the scales of operational hydrologic forecasting. Bathurst et al. (2004) evaluated the capability of the physically-based, distributed catchment modeling system (SHETRAN) for predictive modeling of hypothetical future catchments. Results from internal and outlet responses verified SHETRAN passed eight of the ten specified success criteria, constituting a successful validation.

Furuichi et al. (2004) described the use of Infoworks to simulate flood flows and inundations in urban zones and the creation of a hazard map showing flooded areas during extreme rainfall events. Joubert (2004) presented a modeling analysis comparing the results of a simple stormwater model with a more complex model. Prior to calibration, the simple model provided a better prediction of observed streamflows for the test event. The channel roughness coefficient in the complex model was determined to have the most significant uncertainty and adjusting the value improved the prediction substantially. The simple model was shown to be useful to help understand the complex system and identify adjustments needed in the more complex model. The author concluded that complex systems do not necessarily require complex modeling and estimation of channel roughness coefficients is important.

An improved method to perform automated calibration of a stormwater model was introduced by Dent et al. (2004). They developed a link between SWMM and the Palisade's Evolver software and tested the approach using an infiltration and inflow simulation study. Mazi et al. (2004) presented an approach to calibrate a hydrologic model using groundwater

data. An approach using groundwater can be used when the runoff in the basin is intermittent, a common case in the semi-arid regions, or perhaps in situations lacking river flow measurements. Although the study suggested that using groundwater data to calibrate a hydrologic model may be useful, the automated calibration approach was not successful. Yang et al. (2004) applied a fuzzy multiobjective function approach to calibrate single-event rainfall-runoff models using the time-to-peak, peak flow, and total runoff volume characteristics of the hydrograph.

Vieux and Bedient (2004) reviewed the use of event reconstruction to develop achievable model accuracy for urban flood prediction. The analysis indicated that once the radar data was gauge-corrected, remaining random error does not correlate strongly with the error in streamflow predictions, indicating that the random error measured by radar-gauge comparison is diminished when simulated runoff is compared to observed streamflow. Furthermore, bias adjustment of radar in real-time was noted as necessary to achieve acceptable accuracies.

Catchment scale water balance models have been the focus of recent work in Australia (Boughton 2004a). Using water balance models is a mature technology in Australia for agricultural and urban water supply, flood estimation, management of rural water resources, stormwater, and wastewater, and management of aquatic ecosystems. Nearly all water balance models in Australia are applied where streamflow data are available for calibration. Boughton (2004b) described the Australian water balance model and illustrated the application of the model using data from 19 catchments located across Australia.

Heineman (2004) introduced NetSTORM, a computer program that updates the HEC-STORM concepts to simulate rainfall-runoff and incorporate precipitation analysis routines. NetSTORM improves the STORM methodology by providing a modern interface and adding capability to simulate linked structures in a complex collection system, perform rainfall frequency analysis, and temporally disaggregate hourly and daily precipitation data.

Gautam et al. (2004) presented a study involving analysis of hydrogeological data and an artificial neural network model of surface and subsurface flow conditions to predict the effect of bridge construction on channel hydraulics. The modeling results indicated the construction of the bridge would have a significant impact on flood flow hydraulics.

Croke and Jakeman (2004) described a modification of the IHACRES rainfall-runoff model with a revised version of the non-linear loss module to calculate the effective rainfall. The new module has only three parameters and has significantly less correlation between parameters. O'Brien and Zhao (2004) presented an application of a two-dimensional flood routing model (FLO-2D) using interpolated rainfall data from rain gauge networks or radar. The use of spatially and temporally variable rainfall enables not only monitored rainfall and design storms to be simulated, but also real-time systems potentially leading to applications in predictive early flood warning systems.

Simulating the surface and subsurface flows and their interaction continues to evolve as surface and subsurface models mature. Rivard et al. (2004) reviewed an application of PCSWMM to simulate surface flows and MODFLOW to simulate subsurface flows. They discussed several different approaches to integrate the two models.

A methodology to determine the relation between accumulated storm depth and corresponding flow to a stormwater treatment device for small, urban watersheds was presented by Ahlfield and Minihane (2004). The derived relationship can be used to determine the flow rate to a treatment device that will meet a specified return period for a first-flush depth.

Rodriguez et al. (2003) derived urban unit hydrographs (URBS-UHs) from data on three urban catchments. The shape and the scale of the URBS-UH were primarily influenced by catchment morphology, channel roughness and rainfall return period, but were similar in shape and scale to the unit hydrographs in the other catchments, indicating that the transfer function was not unique but rather dependant on rainfall characteristics. Muzik (2003) reviewed an asymptotic method of estimating the curve number CN and initial abstraction  $f$  for a watershed from observed rainfall and runoff events. The estimated values would approach the "true" values as the number of observations increased. Bardsley and Liu (2003) demonstrated an approach to creating lumped-parameter rainfall-runoff models for drainage basins undergoing land-use changes. The model-constructing approach leads to calibration/recalibration using a hybrid of manual and automated methods. Aubert et al. (2003) investigated the sequential assimilation of soil moisture and streamflow data into a conceptual rainfall-runoff model. A sequential assimilation procedure, based on an extended Kalman filter, was coupled with a lumped conceptual rainfall-runoff model. The model updates the internal states of the model (soil and routing reservoirs) by assimilating daily soil moisture and streamflow data.

Mosini et al. (2003) performed a sensitivity analysis for input parameters to the “CANOE” rainfall-runoff model on a Nantes area catchment basin. The results showed that the choice of runoff coefficient type exerted a significant impact on the results obtained. Sun et al. (2003) presented digital evaluation hydrological modeling for a small catchment in South Australia. Improved runoff predictions were obtained as a result of the improvement in spatial data input and spatial soil moisture representation.

Davidson et al. (2003) described a method for creating polynomial regression models and compared it with stepwise and symbolic regression models. The applications were rainfall-runoff modeling and approximating the Colebrook-White equation. Ducharme et al. (2003) developed a high-resolution runoff routing model RiTHM and its calibration and application to assess runoff. Blazejewski and Murat-Blazejewski (2003) presented analytical solutions for a routing of stormwater flowing through a linear reservoir based on the assumption of a trapezoidal-shaped inflow hydrograph. The maximum ponded (water) depth in the detention basin was the main design criterion.

Ducrot et al. (2003) proposed a multi-agent model to represent the relationships between urbanization dynamics and land and water management in a peri-urban areas. The combined use of cellular automata, spatialized passive entities and communicating agents enhanced the connections between hydrological processes (water cycle, pollution), land-use changes and urbanization. Jones et al. (2003) used annual hydrographs to determine impervious area and to improve the control of impervious area as development increases. An annual hydrograph method is proposed to determine effective impervious area. Arthur-Hartranft et al. (2003) used satellite and ground-based microclimate and hydrologic analyses coupled with a regional urban growth model to predict site-specific climate and hydrology based on land-use changes. The model application will be improving land-use management decisions. Ierotheos et al. (2003) coupled remote sensing and hydrologic models to estimate the impacts on wetlands due to land use changes. The modeling results illustrated significant variations in the hydrological regime caused mainly by the considerable increase of agricultural land and urban areas that posed adverse effects on the regional wetlands.

Forbes (2003) focused on the selection of an appropriate design storm when performing an evaluation of a collection system and presented a case study that demonstrated the process of selecting a design storm and how this selection can and will impact the cost of regulatory compliance. The case study demonstrated that variation interpretations of what comprises a particular design storm existed.

Kojima and Takara (2003) introduced a grid cell-based kinematic wave runoff (GC-KWR) model, and discussed the effect of spatial resolution of the grid cell based distribution runoff model. They also compared the distributed runoff model with two models conventionally used in Japan: the storage function model and the slope-channel system KWR (SC-KWR) model. Lu and Hayakawa (2003) analyzed runoff in the Uono River basin, a tributary of the Shinano River, using a distributed hydrological model based the authors’ distributed hydrological modelling system.

Dye and Croke (2003) evaluated streamflow predictions by the IHACRES rainfall-runoff model in two South African catchments. IHACRES tended to underestimate quick flow events, especially at times when the greater part of a catchment is dry, but showed potential in linking proposed land-use change to altered flow regimes and efficiently describing the flow characteristics within catchments.

Tucci et al. (2003) compared flow forecasts from runoff models using a case study in southern Brazil. The results showed that it was necessary to apply a statistical correction to eliminate a spatial trend in predicted rainfall. Results show that the combined use of models of climate and river-basin response were successful for the River Uruguay basin. Boughton and Droop (2003) reviewed the use of continuous simulation for design flood estimation, ranging from the simple to the very complex. Kuchment et al. (2003) used a physically-based runoff model coupled with a Monte Carlo simulation of model inputs to estimate flood peak frequency distributions. The Monte Carlo simulations of snowmelt runoff were based on stochastic models of daily precipitation series, daily air temperature and daily air humidity deficit (for continuous simulations during autumn-winter-spring seasons) or statistical distributions of snow water equivalent, depth of frozen soil, and soil moisture content before snowmelt (for simulations only during snowmelt flood events).

Ostrowski (2002) discussed the issues of spatial and temporal scales in urban drainage modeling. The focus of the discussion was the effect of urbanization on floods, in particular the effect of source control measures for controlling floods in large river basins. Working at the lot scale, Huber and Cannon (2002) used SWMM to simulate runoff from a residential neighborhood in Portland, Oregon for low impact development alternatives. Both an aggregated model representation and a disaggregated model representation were tested. The simulation results showed the hypothetical LID

improvements at the lot scale would produce more than a 50% reduction in hydrograph peaks and volumes at the watershed outlet. At a larger scale, Schulte and Grace (2002) used SWMM to simulate runoff and storm drain hydraulics for a military base re-development project in San Diego. Overall, the drainage infrastructure was in poor condition and lacked hydraulic capacity to meet today's design standards. Additionally, the project required SWMM simulations to correlate closely with the Modified Rational Method. Several rules-of-thumb were developed to apply the Rational Method with SWMM.

Applying a calibrated SWMM model, Holder et al. (2002) simulated the catchment scale response of Harris Gully to Tropical Storm Allison. The simulation had to account for submerged conditions at the outlet into Brays Bayou that could reduce outflow capacity of the Harris Gully by 60-80%. The high water levels in Harris Gully for Tropical Storm Allison were successfully simulated with the model. A hydrodynamic model for the Nine Mile Run combined sewer system in Pittsburgh, Pennsylvania was coupled with a drainage model for the adjacent urban stream (Heineman and Meenaghan, 2002). The linked models were used to develop frequency-duration statistics for ecosystem restoration design purposes.

The detection of urbanization in hydrologic records and the representation of urbanization impacts on hydrological response require new data analysis approaches and the incorporation of additional data sources into modeling. Beighley and Moglen (2002) evaluated the use of an annual maximum discharge to precipitation ratio to detect nonstationary signals in stream gauge records. Using the discharge to precipitation ratio was found to reduce the climate signal present in the annual maximum discharge series. They also developed three threshold measures of urbanization to predict the existence of a significant trend in the flood series. A method was proposed by Chen and Wang (2002) to incorporate available meteorological data to define the degree of change in a runoff hydrograph for urbanizing basins. Simulation results for the Wu-Tu watershed in Taiwan indicated that three decades of urbanization had increased peak flow by 27% and reduced the time to peak by four hours.

Incorporating probability and uncertainty into modeling results is critical in order to effectively use the results for informed decision-making. A probabilistic modeling approach to stormwater management was tested by Kreikenbaum et al. (2002). Decision-making becomes more complex with the additional degree of freedom associated with the probability of the modeling results. Planners must be adequately trained to understand the uncertainties in order to effectively use probabilistic tools. Hauger et al. (2002) presented a model-based approach using long-term Monte Carlo simulations for risk assessment of different alternative control measures for wet weather flow control. The approach is elaborated for oxygen depletion in urban rivers caused by CSO.

Bergman et al. (2002) performed a calibration of storm loads in the South Prong watershed, Florida using BASINS/HSPF. Results included calibration of the hydrology and calibration of the individual storm loads. The hydrologic calibration was continuous over the period 1994 through 1999. Simulated storm runoff, storm loads, and event mean concentrations were compared with their corresponding observed values. The hydrologic calibration showed good results. The outcome of the individual storm calibrations was mixed. Overall, however, the simulated storm loads agreed reasonably well with measured loads for a majority of the storms. Barlage et al. (2002) reviewed the impacts of climate and land use change on runoff from a Great Lakes watershed. Model results showed that changing climate and changing land use will increase the percentage of precipitation that results in surface runoff from 17.1% to 21.4%. This 4.3% increase partitioned into a 2.5% increase due to climate change and a 1.6% increase due to land use change.

One can use regional regression equations or hydrologic modeling to estimate streamflows at ungauged sites. Bell and Wade (2002) evaluated the transfer method to estimate flows at an ungauged site using data from a gauged site, based on the proportionality of contributing drainage areas. The flow estimates using the transfer method are made at a gauged site to assess the predictions. Bledsoe (2002a) presented a process-oriented view of what is known about the physical response of streams to urbanization and stormwater controls, identified some critical information gaps, and suggested useful approaches and analysis tools for filling these gaps. In particular, variable responses to altered flow and sediment regimes across different stream types, riparian conditions, and spatio-temporal scales were considered.

Bledsoe (2002b) used hydrologic and sediment transport models to examine the effectiveness of typical stormwater management policies in reducing the potential for stream-channel erosion. The various sediment-transport relationships yielded widely diverging estimates of sediment-transport capacity and yet suggested detention volume requirements that agreed within 20%. Detention design for control of cumulative sediment load required a detention storage volume 61% greater than a peak control detention facility and resulted in an altered temporal distribution of sub-bank-full shear stress.

Design of stormwater facilities based on time-integrated sediment-transport capacity may inadvertently result in channel instability and substrate changes unless the approach accounts for the frequency distribution of sub-bank-full flows, the capacity to transport heterogeneous bed and bank materials, and potential shifts in inflowing sediment loads.

ANN methodology was applied to solve various problems concerned with hydrology and water resources engineering and planning, in particular the prediction of the index flood for several ungaged catchments in the UK (Dastorani and Wright 2001). A network with 7 inputs provided the best results. The Multi-Layer Perceptron network with three layers, Tanh function for hidden layer, and the Sigmoid function for output layer were the most accurate. The review by Dawson and Wilby (2001) considered the application of ANNs to rainfall-runoff modeling and flood forecasting, including the related themes of the division and preprocessing of data for model calibration/validation; data standardization techniques; and methods of evaluating ANN model performance. A template was proposed to assist the construction of future ANN rainfall-runoff models. ANNs was shown to be an efficient way to model the runoff process where explicit knowledge of the internal hydrology is not required (Ahmad and Simonovic 2001). ANN was used for the Red River in Manitoba, Canada to predict the peak flow, timing and shape of runoff hydrograph, based on the antecedent precipitation index, melt index, winter precipitation, spring precipitation, and timing. The percent error in simulated and observed peak flow and time of peak was 6 and 3.6 %, respectively.

A rainfall-runoff model was developed based on water balance equations (Abulohom et al., 2001). The model inputs were precipitation and potential evapotranspiration (both on monthly basis) and the output was the simulated runoff at the watershed outlet. The model was calibrated and tested for four watersheds, with a correlation coefficient between the simulated and measured data ranging between 77% and 93%. Croke and Jakeman (2001) assessed the model types available to improve the prediction of catchment flows and transport in Australia where the flows are typically peakier, base flows are of lower proportion, runoff coefficients are smaller, and dry periods are longer and more variable, than in European and North American catchments. Improvement of predictions relied on the following: more rigorous testing of models; the use of improved interpretation of spatial data; more and better monitoring of hydrological response; complementary use of conceptual and distributed models; and integration of modeling with other information.

The Garg and Sen (2001) study presented a physically based hydrologic model using derived watershed features to simulate rainfall-runoff response of a catchment. The finite-element concept was used to obtain the time-invariant weighting coefficients for estimating the rainfall on the cascade planes. Overland flow was simulated using a kinematic wave model. The fundamental premise of the AFDC approach is that maintenance of a stream's ecological integrity depends upon maintaining an appropriate flow regime (magnitude and frequency) (Good and Jacobs 2001). The AFDC provided a graphical tool to illustrate the quantity and frequency of streamflow available in a river basin and facilitated the simulation of the modified streamflow regime based on historic time series data. The AFDC methodology was illustrated in the lower Suwannee River basin in Florida. The Long-Term Hydrologic Impact Assessment (LTHIA) model run on a GIS is a relatively simple model that uses the Curve Number method to estimate changes in surface runoff between different stages of development (Grove et al., 2001). Application to a large, rapidly urbanizing watershed near Indianapolis, Indiana suggested that average annual runoff depths increased by more than 60% from 1973 to 1991. A sensitivity analysis showed that a precipitation record length of 15 years or more was required to produce consistent results with LTHIA.

Chen and Cai (2001) used the Kinematic Wave method to model the rainfall-runoff process in an idealized drainage basin. The simulation results showed that for basins with moderate to high rates of infiltration losses, the critical rainfall duration associated with the maximum peak discharge may be shorter than the time of concentration ( $t_c$ ) for the basin, implying that a storm with a spatial coverage of only part of the basin may generate the maximum peak discharge. For basins with low or negligible infiltration losses, the critical rainfall duration approaches  $t_c$ . The geomorphological instantaneous unit hydrograph (GIUH) was used to relate the shape and scale of the catchment transfer function to stream network topology and channel characteristics (Hall et al., 2001c). GIUH derivation depended on a series of assumptions, including the estimation of a "characteristic velocity." If this velocity is expressed in terms of the kinematic wave approximation, the peak and time-to-peak of the IUH may be expressed by a group of catchment and channel characteristics and by the intensity of rainfall excess. The study by Guo (2001a) expanded the rational method into the rational hydrograph method in which the time of concentration is considered the system memory and the contributing rainfall depth to the present runoff rate is defined as the accumulated precipitation over the past up to the time of concentration. Using this method, the complete runoff hydrograph could be generated under a continuous nonuniform hyetograph. A new formula for estimating the time of concentration was derived from 25 rainfall/runoff events in four urban watersheds and was confirmed in watersheds in Maryland and Colorado.

Neither the index antecedent precipitation index and the Natural Resource Conservation Service's antecedent moisture condition triad consistently characterized the runoff consequence of watershed moisture preceding a rainfall event (Heggen 2001). A normalized antecedent precipitation index that modified the conventional index in three ways (inclusion of antecedent precipitation earlier in the day of the event, normalization to the station mean, and normalization to the antecedent series length) was proposed. Initial results showed the proposed index outperformed single curve number-based results, even when the curve number is fit to historic rainfall-runoff records.

Kroll et al. (2001) tested whether the inclusion of new watershed characteristics improved the prediction of extreme hydrologic events, in particular, low streamflow prediction. Preliminary results indicated that regional regression models of low streamflow quantiles, which traditionally have very high model errors, might be improved in some regions by including topographic, climatic, and hydrogeologic statistics. Lee et al. (2001a) developed a stochastic differential equation (SDE) for a lumped rainfall-runoff model and applied it to a watershed that consisted of a number of subwatersheds in series in Taiwan. The development of the moment equations of simulated outflow was based on a SDE. The outflow hydrograph was obtained by applying the Laplace transform method to the equations that describe rainfall excess. A second paper by Lee et al. (2001b) presented a geomorphic and hydrologic information system for calculating the discharge in small and midsize ungaged watersheds. A compound module, based on a digital elevation model, frequency analysis theory, kinematic-wave approximations, and geomorphic-based runoff modeling, provided enough information for calculating the design discharge for different return periods. The stochastic-conceptual rainfall-runoff simulator (SCRSS) developed by Freeze in 1980 was used to demonstrate quantitatively the interplay of the factors that control overland flow by the Horton and Dunne mechanisms (Loague and Abrams 2001). The simulation domain and input data were abstracted from the R-5 catchment (Chickasha, OK) data sets. The SCRSS simulations showed that the Horton and Dunne processes can (i) occur simultaneously at different locations during a given rainfall event, (ii) change from one process to the other with time depending on the characteristics of the rainfall event, and (iii) be strongly dependent on the initial conditions.

Corrêa et al. (2001) presented the outcome of recent work for the cities of Springfield and Columbia, Missouri using high spatial resolution satellite data to enhance or effectively replace conventional data sources for mapping impervious and bare ground surfaces, and for determining runoff curve numbers (CNs) required by hydrologic and environmental computer models. The estimated accuracy of high-spatial resolution imagery was approximately 80%. Spatial data of primary importance to hydrologic modeling include Digital Elevation Models (DEM) for topography, imagery such as Digital Raster Graphics (DRG), hydrologic soil type, and land use for infiltration losses (Hartman and Nelson 2001). Other supporting data types may include Triangulated Irregular Networks (TIN), hydrography, precipitation, and stream stage. The GSDA website offered detailed explanations, tips, and direct links to hydrologic data sources. A case study modeling the Lost Creek watershed in Northeastern Utah provided an overview of the data acquisition process, and can also be found at the GSDA website. Land use changes over a 30 year period (1961-1990) were incorporated into a continuous simulation rainfall runoff model to investigate the effect of these changes on flood frequency in the Thames catchment at Kingston (Crooks and Davies 2001). Broad scale changes in land use over the last 120 years in the Thames catchment were determined from a variety of sources.

PCSWMM was used to calibrate the kernel function in the central rain-runoff algorithm in SWMM and to generate plots that were compared to the experimental results obtained from a laboratory rig whose impervious pavement had a 0.025 m/m/ slope over an area of 2.11 m<sup>2</sup> (James 2001). Results indicated that the RUNOFF algorithm produces reasonable results, even when supercritical laminar flow cases were included in the validation tests. Andreassian et al. (2001) proposed a new approach to sensitivity analysis for watershed models through a comparison between the efficiency ratings and parameter values of the models and the quality of rainfall input estimate (GORE and BALANCE indices). Although the watershed size was generally immaterial, smaller watersheds appeared to need more precise areal rainfall estimates to ensure good modeling results.

Engineering practice and works design requires the calculation of the "design flood" (Paoli et al., 2001). When there are no available records for the flood frequency analysis, different formulations, semi-empirical methods and hydrological simulation models have been used with the design storm then transformed into a maximum flow. This research concluded that the procedure to determine the design flood from frequency analysis of flow peaks (obtained of the transformation P-Q) provided better results than the one that transformed the storm design. Three indirect techniques for index flood estimation were analyzed in order to evaluate their applicability and effectiveness (Brath et al., 2001). The results showed that the statistical model had a better descriptive ability than the physically-based models. The results highlighted that



direct estimation techniques were advisable for catchments with peculiar geomorphoclimatic properties.

One-dimensional floodplain models of the proposed modifications to William Cannon Drive in Austin, Texas, indicated no significant upstream impact during the 100-year flood (Buechter 2001). Given the limitations of traditional one-dimensional tools in this application TxDOT decided that to model this project using two-dimensional floodplain modeling techniques. The two-dimensional model better identified the potential impacts associated with the proposed highway reconstruction. Radar-rainfall data, remotely-sensed land-use and land-cover data, measured streamflows, and meteorological data were incorporated into the distributed flood forecasting model WATFLOOD to synthesize runoff hydrographs for three significant rainfall events that occurred in 1995 in the Duffins Creek drainage basin in southern Ontario (Cranmer et al., 2001). These results indicated that WATFLOOD could accurately model the nonlinear rainfall-runoff processes for increasing rainfall intensities with respect to peak flow, basin lag, and time to peak flow. Iturbe et al. (2001) used the spatial structure of storms to enhance flood estimation using a rainfall runoff process. The results suggested that interpolation was insensitive to the variogram selection. The applications of the estimation error (and of the method in general) were discussed.

Bates and Campbell (2001) and Campbell and Bates (2001) used a Markov chain Monte Carlo procedure to select rainfall – runoff model parameters. Regionalization of the model parameters was accomplished for all parameters simultaneously via a regional function that links the posterior means to watershed characteristics. They demonstrated the methodology using an eight-parameter conceptual rainfall-runoff model and two case studies from southeastern Australia. Perrin et al. (2001a) questioned whether the use of large numbers of modeling parameters improve model performance. They conducted an extensive comparative assessment using 19 lumped models on 429 catchments, mostly in France, and with some located in the United States, Australia, the Ivory Coast, and Brazil. They found that the bulk treatment of the data showed that the complex models outperformed the simple models in the calibration mode, but not in the verification mode. They concluded that some simple models can yield promising results, although they are not able to handle all types of problems. Kokkonen and Jakeman (2001) also found that a model with less conceptualization could provide a more accurate reproduction of streamflow for some situations. They conclude that the more complexity one wants to include in the model structure, the more types of data and higher information content are required. When only rainfall-runoff data are available, it is difficult to justify substantial conceptualization of complex processes. Wagener et al. (2001) state that many existing hydrological models do not make the best use of available information, resulting in additional uncertainties in model structure and parameters, and a lack of detailed information regarding model behavior. They propose a framework for appropriate levels of model complexity as a function of available data, hydrological system characteristics, and modeling purpose.

Liong et al. (2001) utilized a Pareto front, or trade-off curve, to obtain the best overall calibration for different conditions. Ndiritu and Daniell (2001) used an improved genetic algorithm for rainfall-runoff model calibration. Zaghloul and Kiefa (2001) employed neural network procedures for the calibration of the Transport block in SWMM.

The Hydrologic Modeling System (HEC-HMS) is “next generation” software for precipitation-runoff simulation and will supersede the HEC-1 Flood Hydrograph Package. The program is a significant advancement over HEC-1 in terms of both hydrologic engineering and computer science (Scharffenberg and Feldman 2000). Current capabilities of the HEC-HMS program that are not found in HEC-1 are discussed. Nguyen et al. (2000a) applied two different optimization methods to calibrate the RUNOFF block of the SWMM model: the Downhill Simplex Method, and the Shuffled Complex Evolution (SCE) Approach. Better results were found using the SCE approach. A semi-distributed conceptual rainfall-runoff model for urban catchments was developed (Aronica and Cannarozzo 2000). The urban drainage network was idealized as a cascade of non-linear cells with kinematic wave routing. The results indicated that both the variation in the spatial representation of the rainfall and the variation in the spatial discretization of the catchment influence the outlet hydrographs.

New developments in information technology were proposed to estimate spatially variable parameters for hydrologic simulation systems (Ball 2000c and 2000d). Control parameter estimation philosophies were discussed, and techniques were demonstrated on the use of hydroinformatic systems in parameter estimation. The development of urban databases provided a convenient means of accessing information for the purpose of hydrological modeling (Rodriguez et al. 2000a). A recently developed model, 'SURF' (semi-urbanized runoff flow), was specifically designed to couple with a GIS. SURF was evaluated with a 7-year continuous data series and was shown to compare favorably to both measured data and results from URBAN, another urban hydrologic model.

Hydrologic losses were estimated on the basis of rainfall-runoff data recorded in 21 urban experimental catchments (Becciu and Paoletti 2000). From analysis of experimental data, the probability distribution function of the runoff coefficient was found to be approximately normal, and simple relationships for estimation of main moments were developed. The impact of grid-cell size on calibrated parameters and on the performance of a variable source area model intended for urbanizing catchments was examined by modifying TOPMODEL concepts to accommodate urban surfaces (Valeo and Moin 2000a). Results showed that in this integrated model of urban and rural areas, predicted processes based on calibrated parameters were dependent on grid resolution. The snow accumulation and melt routines of three drainage models that have been applied to urban settings were reviewed; two of these, MouseNAM and SWMM, were designed for urbanized catchments; the third, HBV, was a regional-scale model for rural catchments (Semádeni-Davies 2000). All contained a temperature index for melt – this method is shown to be theoretically unsound without modification for urban simulations. Literature on model development, validation, and application was found to be lacking.

In many cities of the world, urban cells may be hydraulically defined where built-up areas are highly subpartitioned into walled properties (Hicks et al. 2000). A method was proposed to quantify flood damage vulnerability based on hydraulic properties of the urban cell and on peak flow and time to peak. A flood inundation model was developed by combining a SWMM-based model of a storm sewer network and a two-dimensional (2D) overland-flow model (Hsu et al. 2000). SWMM was employed to solve the storm sewer flow component and to provide the surcharged flow hydrographs for surface runoff exceeding the capacity of the storm sewers.

The Object Watershed Link Simulation (OWLS) model was developed and used to simulate the hydrological processes within the BBWM. The OWLS model was a three-dimensional, vector-based, visualized, physically-based, distributed watershed hydrologic model. Simulation results provided a close examination of hydrologic processes of flow separations and Variable Source Areas (Chen and Beschta, 1999).

Donnelly-Makowecki et al. (1999) examined whether the quasi-distributed response function used in TOPMODEL provides superior performance for event simulation in small, temperate forested catchments, compared to lumped reservoir representations of runoff routing similar to those employed in many catchment hydrology models. The alternatives were a two-reservoir black-box model and a three-reservoir model structured to represent our perceptual model of runoff processes based on held observations. A second objective was to test the statistical significance of differences in model performance using a new approach that combines the Jackknife with analysis of variance (ANOVA).

A procedure was introduced for applying the statistical approach to water-table management models, e.g., DRAINMOD, a H/WQ model used to simulate lateral and deep seepage through the soil profile. In the evaluation procedure, probability distribution functions were developed for the most sensitive input parameters, output probability distribution functions were developed using Monte-Carlo simulation, and the output probability distribution functions were used to assess the model. DRAINMOD performed successfully in the evaluative procedure in predicting the runoff, subsurface drainage volume, and the water-table depth fluctuations, which were expected to be most susceptible to input uncertainty (Sabbagh and Fox, 1999).

Matheussen and Thorolfsson (1999) presented research on the simulation errors due to insufficient temporal resolution in urban snowmelt models. Storm-sewer overflow was calculated from an artificial overflow for all time resolution. Based on this research, the authors propose that snowmelt-produced runoff in urban areas should be measured and modeled with no more than a 1-hour time resolution.

Vertessy and Elsenbeer (1999) described a process-based storm-flow generation model, Topog SBM consisting of a simple bucket model for soil water accounting, a one-dimensional kinematic wave overland flow scheme, and a contour-based element network for routing surface and subsurface flows. Aside from topographic data and rainfall the model has only six input parameters: soil depth, saturated hydraulic conductivity at the soil surface, the rate of decay of saturated hydraulic conductivity at the soil surface with depth, the Manning surface roughness parameter, the maximum (saturated) soil water content, and the minimum (residual) soil water content. The model was applied to La Cuenca, a very small rainforest catchment in western Amazonia that has been well characterized in several hydrometric and hydrochemical investigations.

Ando et al. (1999) described how the effects of urbanization on the hydrological water cycle were estimated by using a simulation model to quantify the constituent elements of the hydrological-water cycle. A questionnaire survey was conducted among residents of the river basin to identify the problems that the residents wish to have resolved through the

restoration of the hydrological-water cycle in the Azuma River and to set target values for the desired improvements. Becker et al. (1999) presented a few examples where detailed field studies described the essential elements of runoff generation and thus help to achieve a more realistic representation of the underlying mechanisms within process-oriented rainfall-runoff models.

An approach was developed for incorporating the uncertainty of parameters for estimating runoff in the design of polder systems in ungaged watersheds. Monte-Carlos simulation was used to derive a set of realizations of streamflow hydrographs for a given design rainstorm using the SCS unit hydrograph model. This approach was demonstrated for the Pluit Polder flood protection system for the City of Jakarta, Indonesia. Although, the SCS model was limited to agricultural conditions, the approach presented herein may be applied to other flood control systems if appropriate storm-runoff models were selected (Yulianti and Lence, 1999).

A modified Rational Formula approach for designing urban storm sewer systems included the conventional detention pond and the double detention pond (Wu et al., 1998). This approach also estimated the hydrographs which may be applied to design the conventional detention pond or the double detention pond with results showing the double can hold up to 50% of the volume compared to the conventional. The calibration of the Soil Conservation Service (SCS) runoff equation using rainfall and runoff data from six storms in Fla. showed that the CN for impervious surfaces may differ from the value of 98 suggested by SCS, and in warm climates may be closer to 94 or 95 (Pandit and Regan, 1998). Due to the nonlinear behavior of sewer systems, hydrodynamic simulations using single storm events often do not lead to a good probability estimation of the overflows. Well calibrated, simplified models using long-time simulations give better results (Vaes and Berlamont, 1998). Guo and Adams (1998) derived closed-form analytical expressions for average annual runoff volume and runoff event volume return period based on an equation which describes the rainfall-runoff transformation on an event basis, and the exponential probability density functions of rainfall event characteristics. Guo and Adams (1998) also derived analytical expressions or probabilistic models for peak discharge rates that are proposed as an alternative to simulation modeling or regional analyses for the determination of flood frequencies for urban catchments.

Hromadka and Whitley (1999) developed a mathematical formalization of link-node hydrologic models using HEC-1. By subdividing a watershed into numerous subareas, and connecting the subareas by a network of links, a link-node model representation of the watershed was constructed. King et al. (1999) compared two methods of simulating excess rainfall on a large basin with multiple rain gages. The SCS daily curve number method (CN) was compared with the Green-Ampt, Mein-Larson (GAML) method on the Goodwin Creek Watershed. Li and Joksimovic (1999) presented a methodology to define the average conditions for urban drainage system modelling. The drainage system performance should be first analyzed in a cursory manner to identify the average conditions and the "typical rainfall year". A detailed analysis of the drainage system performance should then be conducted for the "average rainfall year" and the "typical rainfall year." If the discrepancy in performance was large, the "typical rainfall year" should be used in the analysis of average conditions of urban drainage systems. Loke et al. (1999) compared Artificial Neural Networks (ANN) and Grey-Box Models (GBM), implementing them in three practical urban storm drainage case studies. The advantages of ANN included good generalization, high fault tolerance, high execution speed, and the ability to adapt automatically without human intervention. However, ANN relied strongly on the availability of data examples, and they were not transparent and obstruct any direct analysis and interpretation of their performance. On this basis the GBM was superior, as it enables the user to get a better insight into the involved uncertainties. Mehlhorn and Leibundgut (1999) discussed the use of tracer time parameters to calibrate the baseflow time of concentration in a conceptual rainfall-runoff model. A comparison showed that the modeling approaches in tracer hydrology and rainfall-runoff modeling were mathematically equivalent. Therefore, it was assumed that tracer time parameters were suitable to calibrate baseflow runoff models. Coupling water age and turnover time made it possible to simulate the baseflow in more detail.

Milina et al. (1999) showed that, for Norwegian cities, large flood events have only been affected to a minor degree by urban development whereas short-term events occurring after dry-weather conditions show a significant increase in runoff. The effects of urbanization on runoff have been studied where many catchments have yielded maximum flow from autumn and winter frontal rains, often concurrent with snowmelt or rain on frozen ground. Morita and Yen (1999) presented further developments of the conjunctive urban runoff model and focus on the interaction between surface and subsurface flow components. This interaction was directly related to the estimation of effective rainfall or initial loss of hyetographs. The model reproduced the initiation of overland flow and initial loss process and enables the estimation of the effective rainfall reasonably and theoretically.

Nania et al. (1999) designed and conducted experiments on flow patterns at street crossings and intersections. A one-dimensional formulation was proposed in order to predict the dividing flow in street crossings. Rigby et al. (1999) developed a sophisticated event based urban hydrology model from very simple beginnings. It highlighted the capabilities of earlier models and how they have increased in complexity and functionality over the last two decades. Shen et al. (1999) proposed the fuzzy neural network model called "FUZZY STORMNET" to estimate volumetric flow from rainfall intensity. This model for flow estimation could be calibrated automatically by use of known storm events, and no knowledge on the field and the sewer system was needed. Smith (1999) presented a decision support system for drainage engineers involved in the design of stormwater management facilities. The runoff model was versatile and involved a variety of methods for storm description, rainfall loss estimation and overland flow routing. In addition to normal pipe and channel sizing, the design options include a number of detention devices for on-site controls such as rooftop and parking lot storage, in-line storage super-pipes and exfiltration trenches. Stephens and Kuczera (1999) tested the widely used time-area method at the parcel scale. The time of concentration for impervious areas at the allotment scale was found to be of the order of 2 min and not the 5 min as assumed in Australian practice. This result has implications for the design of sub-catchment scale pipes, storage basins and outflow control devices.

Terayama (1999) developed a stormwater runoff model based on the modified Road Research Laboratory method, to express the effects of on-site storage considering temporary storage of the effective rainfall and its disposal. An example application of this model in a local city, which has introduced the on-site storage facilities, was also presented. A nonlinear rainfall-runoff model was developed and applied to flood runoff analysis in Japan. Sugiyama et al. (1999) extended the model's applicability by developing practical equations for estimating model parameters that were appropriate on a regional basis. The utility of the estimating equations was tested by computing runoff hydrographs for lumped basins. Vaes and Berlamont (1999) showed that a well-calibrated reservoir model can predict CSO emissions as well as a detailed hydrodynamic model, taking into account the uncertainties in the input data. Such simplified models were ideal tools to perform quickly various scenario analyses. Physically based conceptual models give an optimal balance between model uncertainty and uncertainty in the input data.

Wong and Kho (1999) studied the increase of flood peaks due to urbanization. Four urbanization scenarios were simulated and subjected to the Singapore 2-year rainfall. The degree of urbanization was expressed in terms of the percentage of developed area and the percentage of channelized area. Their results showed that the patterns of the flood peak increase for the downstream to upstream and the inside to outside urbanization sequences were concave. Wong and Li (1999) reported on a conceptual study of the hydrological effects of urbanization. By considering urbanization on an overland plane as a process whereby a relatively rough, permeable surface was gradually replaced by a relatively smooth, less permeable surface, the effect of urbanization sequence on the flood peak was theoretically assessed by the kinematic wave method.

Yen et al. (1999) presented details of the runoff model ILUCAT. The model allowed temporally variable rainfall in incremental times as input to each catchment, and deducts abstractions to yield the rainfall excess to be routed through the urban catchment. Each catchment was divided into five types of areas, namely, direct impervious, direct pervious, supplemental impervious, supplemental pervious, and noncontributing areas. The rain excess was routed through two flow paths of the first four contributing areas using the time-area method to produce the runoff hydrograph. Cagiao et al. (1999) presented two different methodologies for a study of the runoff generated in an urban watershed with a separate sewer system during stormwater events. The first approach used a process simulator (SWMM), and a non-linear parameter estimation tool (PEST), while the second used artificial neural networks. A pilot project of a subcatchment in the city of Santiago de Compostela was studied. Campolo et al. (1999) used neural networks to forecast flow rates in the Arno River downstream of the city of Florence, Italy during low-flow conditions. The model used basin-averaged rainfall measurements, water level, and hydropower production data. Model predictions were found to be accurate with root-mean-square error on the predicted river flow rate, less than 8% over the entire time horizon of prediction. Chang and Hwang (1999) used the group method of data handling (GMDH) algorithm to evaluate complex rainfall-runoff processes in a heterogeneous watershed in Taiwan. Two versions of the revised GMDH model were implemented: a stepwise regression procedure and a recursive formula. The prediction results of the revised GMDH models and the instantaneous unit hydrograph (IUH) model were compared. Much better performance was obtained with the revised GMDH models.

Dinicola (1999) presented recent efforts to develop regionalized HSPF parameters for King and Snohomish Counties in Washington that were useful for urbanizing watersheds. Djordjevic et al. (1999) described a model for dual drainage - an approach to rainfall runoff simulation in which the numerical model takes into account not only the flow through the sewer system, but also the flow on the surface. The numerical model simultaneously handled the full dynamic equations

of flow through the sewer system and simplified equations of the surface flow. The surface excess water (due to the limited capacity of inlets or to the hydraulic head in the sewer system reaching the ground level) was routed to the neighbor subcatchment (not necessarily the one attached to the downstream network node), using surface retentions, if any. Edijatno et al. (1999) described a new empirical watershed model that involves only three free parameters. In spite of its crude simplicity, it achieved, on average, worthwhile results on a set of 140 French catchments and overwhelmingly outperformed a linear model involving 16 parameters. It performed roughly as well as a conceptual model with five free parameters, derived from the well-known TOPMODEL.

Escarameia and Swaffield (1999) summarized the results of research on monitoring and modeling stormwater runoff from roofs in the UK. This paper presented important new data for the design of rainwater systems and concludes that numerical simulations of unsteady flows were a useful tool for complementing the design recommendations in current design guides. Four simple conceptual daily rainfall-runoff models were applied to a 25-basin data set in the UK, covering a range of sizes, topographies, soils and climates (Houghton-Carr, 1999). Model performance was judged by a range of quantitative and qualitative measures of fit, applied to both the calibration and validation periods. These included efficiency, mean annual runoff, baseflow index, the synthetic monthly and daily flow regimes, and the flow duration curve. With increases in computing power of recent years, fully two dimensional, unsteady hydraulic modelling was becoming increasingly common for applications involving large, complex floodplains. Bishop et al. (1999) described the results of a recent study of a highly urbanized area along the Gold Coast, Queensland, Australia. With the increasing focus on ecologically sustainable development, and concerns regarding class actions by flood affected communities, many agencies in Australia were requiring that new proposed urban development have zero impact. With regard to flooding impacts, this requirement has resulted in the need for assessment of effects, in terms of water level changes, down to 1 cm or less accuracy. Details were provided on the requirements of and approach to full two dimensional flow modelling including the required grid definition and size, structure modelling, fine scale nesting and model stability and accuracy (Collins et al., 1999). A distributed, field-based rainfall-runoff model was developed for the 1400-km<sup>2</sup> arid catchment of Nahal Zin, Israel. No calibration with measured flow data was performed; the model used rainfall radar input applied over a catchment that was spatially disaggregated into different terrain types according to hydrologically relevant surface characteristics. In general, this study showed that field-based data on generation and losses of runoff may be incorporated into a distributed hydrologic model to overcome calibration with the poor data records of arid high-magnitude events (Lange et al., 1999).

Miles et al. (1999) presented a method of analyzing flow and rainfall monitoring data that has successfully documented rainfall dependent infiltration and inflow (RDI/I) reduction in Charlotte, North Carolina and Greenville, South Carolina. The method relies on scientific principles including good data quality control practices and the use of control areas to establish changes in RDI/I between monitoring periods because of environmental factors. Schultz et al. (1999) summarized research, conducted by a team of consultants and cooperating municipal agencies, which identified and tested eight major categories of rainfall derived infiltration and inflow (RDII) analysis methods in several diverse sewersheds. They identified metrics suitable for objective comparison of the RDII analyses, and concluded with recommendations for selecting RDII methods appropriate to a variety of applications. In the Netherlands, a very simple criterion for flooding was used to check the hydraulic behavior of a drainage system, whereas The European approach was more strict but not applicable. Therefore, van Luitelaar (1999) presented an alternative approach to eliminate hydraulic bottlenecks in drainage systems in flat and moderately sloped areas.

A topographic index predicted patterns of runoff, reproduced spatial patterns of subsurface-storm flow for a variety of prestorm conditions, and was used as a basis for a rainfall-runoff model (Woods *et al.*, 1997). Three conceptual rainfall-runoff models (i.e., GSFB, IHACRES, and LASCAM) were assessed and provided accurate predictions of rainfall-runoff relationships (Ye *et al.*, 1997). Tan *et al.* (1997) developed an algorithm for simulating tropical rainfall using a one-step-Markov-chain model. The results indicated that the synthetic-rainfall time series reproduces the characteristics of tropical rainfall. The model may also be capable of estimating extreme-annual rainfall. A geomorphology-based-unit hydrograph and a Runge-Kutta-time-discrete scheme were applied to predict direct-runoff volumes. The hydraulic-routing scheme presented was highly accurate in predicting runoff volumes and may be useful in managing major-rainfall storms (Sepulveda, 1997).

Nine flood-estimation models used for ungauged-urban watersheds were evaluated in Louisiana. Flood-quantile predictions from simple regression models calibrated by local data were found to be more reliable than those more complicated models or models with many parameters that may not be accurately estimated (Yu and Adrian, 1997). A newly digitized record of precipitation for 304 sites in the Midwest United States that extends back to 1901 challenged the

the assumption that extreme-rainfall time series are stationary and without trends. It was suggested that rainfall-frequency studies be updated on a regular basis for maximum usefulness because of observed changes in the annual maximum time series (Angel and Huff, 1997).

Hydrological studies of rainfall-runoff processes provided the basis for estimating design flows for urban-stormwater-drainage systems which control floods and the transport of sediments and pollutants. Oloughlin *et al.* (1997) summarized the theory of urban rainfall-runoff processes, the development of modeling practice, and the current use of computer models. Agbodo *et al.* (1997) reviewed HYDRA, HydroWorks, MOUSE, and XP-SWMM, which are widely used hydraulic-modeling tools utilized in determining optimum improvements of sanitary-sewer systems that have excessive I/I. Zhu and Schilling (1997) presented a method to predict errors of calculated mean-annual-overflow volume due to coarse temporal resolution of rainfall data that was used as input to rainfall-runoff models. Errors were quantified by comparison of overflow volumes based on rain-data series with different temporal resolution. The pattern of the temporal rainfall variation of the two data series were too different to derive error-prediction rules that were generally applicable for all rainfall regimes.

### **Hydraulic models**

Grum *et al.* (2006) examined the effect of climate change on urban drainage using regional climate model simulations. The results showed that the modeled impacts greatly rely on the model's suitability in describing extremes at time scales relevant to urban drainage. Afshar (2006b) used adaptive refinement to improve the efficiency of ant algorithms in storm sewer design. The method was able to find an optimal or near-optimal solution, independent of the discretization level and size of the colony. Afshar *et al.* (2006a) used the TRANSPORT component of SWMM to implement the simulations and the results were compared with literature values. Frost (2006) presented updates to the parameters used to calculate minor loss coefficients in storm drains in the SWMM model.

Niemann *et al.* (2002) examined the pump station modeling capability of EPANET, XP-SWMM, MOUSE, and INFOWORKS and presented considerations necessary for models to represent actual conditions and their projected impacts on the public and environment. Despotovic *et al.* (2002) developed and calibrated detailed BEMUS and Visual OTTHYMO models for a catchment served by combined sewers in Belgrade. The calibrated models were used to assess catchment flooding for design flows at four locations in the catchment. Yeboah *et al.* (2002) presented work evaluating a 500-cfs pumping station to address flooding problems in the South End neighborhood in Boston. They conducted a comprehensive flow-monitoring campaign, developed pump head-capacity curves, and created a SWMM model of the station. The calibrated model was successfully used as a tool to evaluate the facility planning alternatives. Vallabhaneni *et al.* (2002a) used SWMM RUNOFF and EXTRAN to simulate infiltration and inflow to sanitary sewer lines and the impact on sewer hydraulics. Sharek *et al.* (2002) described their efforts constructing and analyzing hydraulic models coupled with continuous infiltration and inflow models and specifically highlighted their work evaluating the alternatives for improving the performance of the Western Lake Superior Sanitation District East Service Area collection system.

### **Rainfall-runoff quality models.**

Behara and Adams (2006) presented the results of runoff quality analysis using probability density functions of rainfall characteristics, a runoff coefficient, and commonly-used pollutant buildup and washoff process representations. The verification results suggested that these analytical probabilistic models can be used during planning to assess runoff pollutant loads. Ahlman (2006) developed a modeling framework to analyze pollutant sources in urban stormwater runoff based on their origin (material corrosion, brake and tire wear, etc.). The goal was to aid designers in selecting appropriate source controls for the various pollutants.

Harris and Adams (2006) provided a probabilistic assessment of urban runoff erosion potential. Exceedence duration and peak channel velocity were demonstrated to affect the erosion potential. Sutherland *et al.* (2006) described the stormwater quality modeling performed for the cross-Israel highway. The SIMplified Particulate Transport Model (SIMPTM) was used to evaluate the potential stormwater effects and the benefits of highway cleaning. A specific cleaning technology was proposed. It involved a single vehicle with several high speed rotating jets to pressure wash the pavement and immediately recover the resulting runoff. Kang *et al.* (2006a) described the implications of a kinematic wave model for first flush treatment design. The simulation results showed that an optimum watershed size exists to maximize first flush. Owusu-Asante and Stephenson (2006) estimated storm runoff loads based on rainfall-related variables and power law models. Event loads were better estimated using power functions of storm-related variables.

Sheng et al. (2006) used the unit pollutograph concept to estimate solids loadings to a stormwater runoff treatment unit. Relationships between solids mass and hydrologic volume were based on relationships that expressed either a first-order or zero-order relationship between solids mass and volumetric transport. Ostendorf et al. (2006) described calibrated models of deicing agent solids, pavement texture and specific conductivity for highway runoff. The models were applied in southern Massachusetts to determine if first flush exists in highway runoff.

Shi (2005) presented a solution for the Streeter-Phelps model of one-dimensional stormwater quality. Simulation results showed that the approach gave good estimates of BOD and DO in stormwater. Ahyerre et al. (2005) evaluated the efficiency of three stormwater quality models on three suspended solids data sets encompassing 34 rain events. When the results were compared to the simple hydraulic approach, the results were similar; the advantage was that the models were able to represent the shape of the pollutographs.

A novel modeling approach for estimating first flush metal mass loading was proposed by Kim et al. (2005b, c). The new washoff model was designed to predict event mean concentrations, accounting for first flush loadings as well. Model parameters included average daily traffic, antecedent dry period, rain intensity, rain volume and runoff coefficient. Deng et al. (2005) proposed a fractional kinetic model to describe the first flush of stormwater pollutants.

Load quantification models were proposed by Hochedlinger et al. (2005) as a means of estimating the overflow loads of combined sewers. One input for these models is rainfall, and the paper focused on the corrections required for rainfall measurements from tipping bucket rain gauges. Simulations of the runoff and associated pollutant load from a highway drainage system were undertaken by Aryal et al. (2005b). The runoff results showed that when the rainfall was not continuous, part of the depression storage and initial abstraction were recovered and affected the peak of the later runoff. Single-event simulations did not accurately reflect the suspended solids concentration in the pipe; continuous simulation that accounted for the initial sediment condition in the pipe was required. A diffuse nitrate modeling tool (DNMT) was proposed by Liu et al. (2005b) as a means of evaluation of pollutant loads in urban areas. The model consists of three components – the hydrological module, the nitrogen cycle module and the nitrate transport module.

The numerical model developed by Dussaillant et al. (2005b) was used to simulate rain gardens for infiltration and groundwater recharge in various world climates. The model results demonstrate the ratio of the rain garden size to impervious area that maximizes recharge.

Borah and Bera (2004) conducted a review of watershed-scale hydrologic and nonpoint-source pollution models. Three (SWAT, HSPF, and DWSM) were selected for further evaluation by compiling references to model applications available in the literature. SWAT and HSPF were found suitable for predicting annual flow volumes and sediment and nutrient loads. Monthly predictions were generally good for all three models. Daily predictions were poor. Smith and Wheeler (2004) presented a simple phosphorus transfer model for a watershed. The model uses simple rainfall-runoff and routing components combined with land use based export coefficients.

Liu et al. (2003) researched integrating diffuse inputs into an integrated urban water quality model that is comprised of four modules: hydrology, contaminant point sources, nutrient cycling and leaching. The model was applied in the White Cart catchment (Glasgow). Vaze and Chiew (2003) performed a comparative evaluation of urban stormwater quality models, primarily regression equations and process-based water quality models. The results indicated that, once calibrated, both the regression equations and the process-based model could estimate event pollutant loads satisfactorily.

Ha et al. (2003) improved the parameter estimation procedure for SWMM using remote sensing and artificial intelligence techniques. The estimated total runoff, peak time, and pollutant generation varied considerably according to the classification accuracy and percentile unit load applied. Joksimovic et al. (2003) applied the model calibration unit of XP SWMM to a large urban sewer system (City of Ottawa, Canada) using radar precipitation information. In general, measured and modeled peak flows and event volumes matched well. Measured and modeled event volumes were within a 15% envelope. Sutherland and Jelen (2003) discussed the stormwater quality modeling improvements needed for SWMM. The modeling insights and improvements led to the development of the Simplified Particulate Transport Model which has been recently applied to projects in Michigan, Oregon and Washington.

Ha and Stenstrom (2003) used a neural network to couple land use with stormwater quality data. The neural model used a Bayesian network and had 10 water quality input variables, four neurons in the hidden layer, and five land-use target variables (commercial, industrial, residential, transportation, and vacant). Ichikawa et al. (2003) reviewed the

development of a distributed red soil runoff model for the Okinawa region of Japan that uses radar data as an input parameter. The model was based on a kinematic wave flow model and digital topographic model, but needs to account for land cover changes.

Ackerman and Schiff (2003) modeled stormwater mass emissions to the Southern California bight based on land use, rainfall, runoff volume and local water-quality information. Urbanized watersheds produced the majority of mass emissions, except for suspended solids, total DDT, and chlorpyrifos. Boulanger and Nikolaidis (2003) modeled managing copper runoff in urban watersheds. The model incorporated water quality characterization, watershed land use areas, hydrologic data, a statistical simulator, a biotic ligand binding model to characterize acute toxicity, and a statistical method for setting a watershed specific copper loading.

Cristina and Sansalone (2003) used a kinematic wave model for the runoff from an urban pavement subject to traffic loadings. The accurately captured the time to peak, total volume of flow and peak discharge from a 300-m<sup>2</sup> paved surface subject to traffic. The kinematic wave theory also gave predictions of the time of concentration that were more accurate than more common methods.

Burian et al. (2001b) investigated the suitability of integrating deterministic models to estimate the relative contributions of atmospheric dry and wet deposition by stormwater runoff. The CIT airshed model and the SWMM were linked to simulate the fate and transport of nitrogen species through the atmosphere and storm drainage system in Los Angeles, California, USA. Coupling CIT and SWMM involved defining and resolving five critical issues: (1) reconciling the different modeling domain sizes, (2) accounting for dry deposition due to plant uptake, (3) estimating the fraction of deposited contaminant available for washoff, (4) defining wet deposition inputs to SWMM, and (5) parameterizing the SWMM washoff algorithm.

A mass-balance model for calculation of annual metal loads to lakes dominated by diffuse inflow and urban runoff was presented by Lindstrom and Hakanson (2001). In the lake, the variations in runoff concentrations were smoothed, making it possible to get a more stable flow assessment. The model accounted for inflow, outflow and sediment interactions (sediment resuspension is modeled using new approaches) with the most important factors in the uncertainty of model predictions being the settling velocity of particulate matter, the percentage of accumulation areas for fine particles, and the dissolved fraction of the total metal concentration. High correlations between metal accumulation and phosphorous and nitrogen concentrations indicated that the autochthonous lake production was crucial. The sources, distribution and fate of fecal coliform populations in the North Fork of the New River in Fort Lauderdale, Florida were investigated by Scarlatos (2001). In order to facilitate field sampling, computer simulations using WASP were applied to assess the likelihood of the various possible pollution scenarios. WASP accurately simulated the water hydrodynamics and coliform concentrations within the North Fork, while the neural network identified correlations between fecal coliform and the other parameters.

Swanson and Ward (2001) presented a series of applications of WQMAP, an integrated model of the circulation and pollutant transport in estuarine and coastal waters, to Narragansett Bay. Applications included circulation and temperature distributions in Mt. Hope Bay; consideration of the effects of a once-through cooling water discharge from a fossil fueled power plant; circulation in the Providence River and Upper Narragansett Bay; fecal coliform transport from combined sewer overflow (CSO) loads; and a eutrophication study of the Providence River.

Sanders et al. (2001) developed a hydraulic model to examine the tidal transport of stormwater bacteria near the southern California network of flood control channels that drain to near-shore bathing waters. Yuan and Oldham (2001) prepared a model describing the accumulation and washoff of urban area particulates, specifically examining metal binding. They monitored 47 rain events with short time intervals and obtained good agreement for predicting lead transport. Zoppou (2001) compared several different stormwater models, including statistical, empirical, hydraulic and hydrological model types.

Whigham and Crapper (2001) provided the following definition: "Genetic programming is an inductive form of machine learning that evolves a computer program to perform a task defined by a set of presented (training) examples and has been successfully applied to problems that are complex, nonlinear and where the size, shape, and overall form of the solution are not explicitly known in advance." Genetic programming of rainfall-runoff model has also been used by Muttill and Liong (2001). Mathematical methods using linguistic variables (such as the application of fuzzy rule-based modeling), rather than conventional numerical variables, are starting to be used for hydrological studies (Hundecha et al., 2001).



Ozelkan and Duckstein (2001) also recently applied fuzzy logic to rainfall-runoff modeling.

The results of a number of investigations indicated that contaminant transport should consider the speciation of nutrients and metals in stormwater runoff (Ball 2000c). From the results of these studies, a new approach for the simulation of contaminant transport was presented which considers the speciation of the contaminants. Statistical models were proposed to predict the total mass of specific pollutants removed with stormwater runoff from an urban residential catchment (LeBoutillier et al. 2000). The models were based on analysis of data collected during an on-going research program in Saskatchewan. A method for predicting the thermal enhancement of stormwater runoff from paved surfaces was documented for a test facility in Kingston, Ontario, Canada (Van Buren et al. 2000b). Prediction of runoff temperature was based on TRMPAVE, a mathematical model that was developed using a thermal energy balance approach and the one-dimensional heat equation to predict the surface temperature and temperature gradient in asphalt during dry-weather and wet-weather periods. An export coefficient modeling approach was used to assess the influence of land use on phosphorus loading to a Southern Ontario stream (Winter and Duthie 2000). It was found that runoff from urban areas contributed most to the loading of phosphorus to the stream. An existing model of sediment wash-off from paved surfaces was extended to predict fine granular sediment inputs into drainage systems via roadside gully-pots (Deletic et al. 2000). The model was applied to two catchments in Dundee, Scotland where it was concluded that only two calibration parameters are required to estimate the input of fine granular sediment into storm drainage systems via gully-pots.

Tsanis (2000) developed a program named RUNMEAN (RUNOffMEAN) for estimating toxic-contaminant event mean concentrations (EMCs) in stormwater runoff.

Bent et al. (1999) evaluated the runoff and erosion response of two perennial grass species on simulated waste burial covers at Idaho National Engineering and Environmental Laboratory. The Agricultural Non-Point Source Model (AGNPS) permits the incorporation of important spatial information (soils, landuse, topography, hydrology) in simulating surface hydrology and NPS runoff. The AGNPS model was adapted for developed coastal watersheds by deriving urban coefficients that reflect urban landuse classes and the amount of impervious surface area (Choi and Blood, 1999).

Skipworth et al. (1999) described an experimental model investigating erosion and subsequent sediment transport of an in-pipe, fine-grained, organic, cohesive-like sediment deposit analogous to those found in sewers. The problem of optimal water distribution to a range of retention reservoirs in an urban sewer network during rainfall events was overflows and its impact on receiving waters. A multilayer control structure consisting of an adaptation, an optimization, and a direct control layer, was proposed for the solution of this complex problem (Marinaki et al., 1999). Watershed areas that generate NPS polluted runoff need to be identified prior to the design of basinwide water projects. The model TOPLATS simulates variable source area (VSA) hydrology and therefore provides an improvement to the current generation of NPS models for locating potential NPS-loading areas (Endreny and Wood, 1999).

Arnbjerg-Nielsen et al. (1999) compared trends in annual loads of pollutants to receiving waters in Denmark during the past decade. For N and COD, models were suggested that explain some of the variation between and during events. However, a large residual variation was identified and possible refinements of the model were discussed. Ball (1999) presented a new approach for simulation of the transport of the soluble contaminant in urban stormwater runoff. This modeling system was based on a decoupled solution of the kinematic wave equations for simulation of the surface flows and an advection-diffusion model for simulation of the contaminant motion. Use of deicing chemicals and abrasives to provide traffic safety during winter caused water quality problems for urban receiving waters (Bartosova and Novotny, 1999). Their model was calibrated using data from the Lincoln Creek watershed (Milwaukee, Wisconsin), and verified on 30th Avenue watershed (Edmonton, Alberta). The results of simulation for chlorides, suspended solids, and lead were presented.

Carr et al. (1999) discussed the benefits of a time series approach which provided the information necessary for design of water quality control structures and for assessment of ecological sustainability. An advantage of the time series approach was that it provides an integrated evaluation of performance during a variety of wet-weather conditions. Chiew and McMahon (1999) presented a simple approach for estimating long-term runoff and diffuse pollution loads in urban catchments, and discussed conceptual modeling methods for simulating daily runoff and pollution loads. The modeling results for several catchments in Australian capital cities were presented. The study indicated that long-term and daily runoff can be estimated reasonably accurately using simple approaches. However, the water quality characteristic can vary considerably between catchments.

Commonly measured fecal bacteria concentrations in water and rainfall data were utilized as inputs for training a neural network model to distinguish between urban and agricultural fecal contamination present in inputs to a drinking water reservoir (Brion and Lingireddy, 1999). A neural network model was written that used bacterial and weather data to differentiate between three site classifications: urban, agricultural and a mixture. The validity of the source identification, neural network model was verified through a case study. Roadside gully pots form a common and important part of many surface water drainage networks (Butler and Mernon, 1999). Their primary function was to retain larger solids from road runoff in order to minimize the problems associated with sediment deposition in downstream drainage structures and receiving waters. A dynamic water quality model has been developed to simulate these processes. Moulton et al. (1999) described NPDES monitoring for New Orleans, Louisiana. This paper asked the question, "How reliable were load estimates that were extrapolated from landuse based monitoring of small subcatchments?" The age of the developed areas was found to be responsible for differences in monitored nutrient loading from modeled runoff loads based on land use.

Several models related land use categories of urban, forest, agriculture, and wetland to in-stream concentrations of total nitrogen (N) and total P in eight low-order watersheds on the coastal plain of S.C. (Tufford et al., 1998). The models with highest predictive strength were those which used land closest to the stream channel. Vezjak et al. (1998) modeled the effects of eutrophication on plankton seasonal dynamics in lakes using state variables for the rates of change of phytoplankton, zooplankton, N and P. The influence of P concentration on eutrophication was one of the most important processes in the lake ecosystem. Bartolini et al. (1998) stressed the need for a complete rainfall-runoff model of the rainfall-runoff transformation that includes the underground portion of the hydrograph even if the maximum discharge during a flood is mainly due to the surface runoff. The proposed solution, taking into account the unknown time-lag between rainfalls and discharges as an extra parameter to be estimated in the calibration phase showed some benefits. An examination of several models for estimating stormwater pollutant loads from urban watersheds indicated that SS loads are largely a function of runoff volume, and that the use of a single event- mean concentration of SS for all urban land uses provided reasonable estimates of stormwater pollutant loads. Water quality data did not indicate a strong correlation between pollutant loads in runoff and the duration of the antecedent dry period (Charbeneau and Barrett, 1998).

The response of rain on ammonium loads for an urban sewer system using AQUASIM and MOUSE TRAP 3.0 was simulated. The study showed that a sewage storage tank performed better for the integrated load discharged into the system but a combined sewer storage tank would be more efficient in decreasing peak values and the duration of high concentrations in the river (Holzer and Krebs, 1998). A semi-empirical model quantified the hysteresis of river water constituents during a storm based on discharge data collected from several river sites over a storm hydrograph. Results showed that most constituents had higher concentrations during the rising limb of the hydrograph and lower concentrations during the falling limb (House and Warwick, 1998). The COD of a sewer network was modeled using a ratio of COD/SS as a function of the maximum rainfall intensity over a five minute period, SS and time. Simultaneous measurements of rainfall, hydraulics, SS and COD in three catchments with different characteristics and not used in the calibration phase validated the model (Zug et al., 1998). Osuch-Pajdzinska and Zawilski (1998) presented the results of calibration and verification of mathematical models for calculating hydrographs and pollutographs of urban stormwater based on results obtained from field studies for a mixed industrial and residential catchment. Tsihrintzis and Sidan (1998a) calibrated and verified the Santa Barbara Method for computing runoff hydrographs for small urban watersheds. The PC version of ILLUDAS was shown to predict hydrographs that compared well with measured hydrographs for small urban watersheds in Fla. (Tsihrintzis and Sidan, 1998b).

Mas (1998) used a relatively simplistic modeling approach to quantify the stormwater impacts of a proposed commercial development in southern N. Engl. A ten-year simulation assessed the impact of current and future nutrient loads and sediment runoff to a multipurpose reservoir scheduled to open in 1999 in Sarpy County, Nebr. and recommended BMP (Fowler et al., 1998). Brown et al. (1998) examined the interactions of land use, topography, soil, and surface water hydrology in modeling stormwater quality variations in subbasins of the Tijuana River watershed. Concentrations in Onondaga Lake, N.Y. of total Hg and MMHg in the water column, sediments and fish tissue are elevated due to industrial inputs, wastewater discharge and urban runoff. The steady-state Regional Mercury Cycling Model suggested that elimination of Hg inputs from wastewater effluent and drainage from a former chlor-alkali facility would decrease Hg concentrations in fish tissue (Gbondon-Tugbawa and Driscoll, 1998).

The South Africa Water Research Commission funded a project to adopt an existing urban-stormwater-runoff model to data from several catchments and showed that urban-stormwater runoff was highly polluted with nutrients, heavy metals, organics, and bacteria (Water Qual. Int., 1997a).

The spatial distribution of the water-quality equivalent of a snow cover on various landscapes were synthesized through log-normal distributions to predict snowmelt and runoff (Shook and Gray, 1997). When snow produces a significant portion of runoff, a smaller number of quality records could be more valuable for modeling than a much larger number of records of lower quality because the overall value of an operational-hydrometeorological network depends on the consistency and representativeness of average conditions of the collected records (Peck, 1997).

#### **Collection system, CSO and SSO models.**

A numeric and physical model was used to improve hydraulic operation of a CSO storage/treatment facility in Ontario, Canada. The model results showed that within the existing constraints, a few structural changes could increase the maximum treatment flow rate (He et al. 2006a). CSO performance evaluation was reassessed in terms of spatial variances in historical rainfall time series by De Toffol et al. (2006). Mean annual rain volume explained most of the variance for number of overflows and volume, while the spatial differences in the efficiency of the CSO structure was related to the maximum event with a 1-year return period. Stonehouse et al. (2006) described the benefits of modeling every sanitary sewer pipe in Ann Arbor (Michigan) using SWMM. The model aided the city in facilitating prioritization of footdrain disconnections and in evaluating new development.

The impacts of climate change on an urban catchment was investigated by Denault et al. (2006). The report stated that increases in short-duration rainfall intensity would not create severe impacts but equivalent levels of imperviousness could impact stream health. Moura et al. (2006) compared two methodologies for urban drainage decisions. The Brazilian and ELECTRE III methods produced equivalent results with low sensitivity and high robustness. Temprano et al. (2006) described a case study in northern Spain to calibrate SWMM to local conditions. The calibrated model simulated accurately the hydrograph's shape and the time of presentation of the peak flows. The validation for runoff quality was excellent for suspended solids and COD but less so for TKN. Sherman et al. (2006) reviewed a methodology for allocating rainfall-derived inflow and infiltration (RDII) using footdrain flow and other information. The chapter provided background information regarding the monitoring program.

Shen et al. (2006) applied a fuzzy neural network to estimate flow in sewer systems during wet weather and it compared it to the analysis of the same networks using the STORMNET neural network model. Compared with the neural network STORMNET, this method reduces the mean square error of the flow estimates by approximately 20%. Experimental results are reported herein. Leon et al. (2006) applied Godunov-type solutions to transient flows in sewers. These schemes were significantly faster to execute and the resolution of the shock fronts was superior to conventional modeling. Liu et al. (2006b) applied a moving-weighted least-square method to identify sanitary flow patterns. This method was superior to the parametric model in identifying flow patterns.

Edwini-Bonsu and Steffler (2006a, 2006b) investigated the dynamics of air flow in sewer conduit headspace. Mathematical formulas and curves as functions of longitudinal pressure gradient, wastewater velocity, and sewer headspace geometry were developed. The model accounts for combined wastewater drag and pressure-induced air flows, and manhole pressurization.

Ng et al. (2006) modeled serviceability deterioration of concrete stormwater pipes using genetic-algorithm trained neural networks. The robustness and generalization capability of this model, as compared to traditional statistical approaches, was demonstrated.

Djordjevic et al. (2005) presented a new model (SIPSON) that would be used to describe the conditions in a sewer pipe when the hydraulic capacity is exceeded. Validation of the model was performed in a catchment in Indore, India. Ettrich et al. (2005) proposed a new model for sewer flow that accounts for the bi-directional interactions of the surface and pipe flow. The model is data intensive but it was proposed that aerial photographs, etc., will reduce the amount of field data required. Nasello and Tucciarelli (2005) developed a dual, multilevel urban drainage model. The model consisted of two flow paths – a lower sewer network of closed conduits and an upper network of open channels. The purpose of the model was to predict water flow paths and rates, even when sewer pipes were flooded and unable to carry more water. Kamal and Bennis (2005) described a case of substituting simplified hydraulic modeling for detailed drainage system information when modeling urban runoff flows for a catchment. This paper focused on two transfer functions to obtain peak flow rates and time to peak from a global model and apply it to the more detailed basin model.

Vasconcelos and Wright (2005a) reviewed the applications and limitations of single-phase models to the description of the rapid-filling pipe problem, such as could be seen in storm sewers during intense rain events. The proposed model solves the Saint-Venant equations using a finite volume procedure. The modeling used by the City of Buffalo (New York) to assess the impacts of CSOs was reported by Irvine et al. (2005b). Metals loads from the CSOs were measurable but were several times less than the loads from the upper watershed. The CSOs were shown to be a source of fecal coliforms. The application of continuous simulation in separate sewer areas in Pittsburgh (Pennsylvania) was demonstrated by Loehlein et al. (2005). The model was able to account for rainfall-dependent inflow and infiltration and seasonal variations in responses to rainfall events. Korving and Clemens (2005) evaluated the impact of dimensional uncertainty and model calibration on sewer system assessments. CSO volumes were modeled using Monte Carlo simulations of the uncertainty and were found to vary greatly.

Kanso et al. (2005a) proposed a model for simulating the erosion of sediments in sewer pipes taking into account the increase in strength with depth in the weak layer of the sediment deposit. The model was validated from field studies, but concerns were raised about the level of data required to validate the model.

Portland's combined sewer system was modeled using an approach called Explicit Modeling that combined off-the-shelf modeling engines with database, GIS, and automation tools (Foreth and Mandilag 2004). The approach was demonstrated for basement flooding characterization, sewer design, and analysis in support of the need for a sewer inspection and maintenance project. A hydraulic model of the Massachusetts Water Resources Area (MWRA) service area was developed by Soucie et al. (2004) using InfoWorks. The framework for the model built upon existing MWRA GIS and oracle databases combined with information in previous SWMM models of the collection system to include all hydraulic structures. Calibration was performed to over 200 flow meter locations and more than 80 CSO locations using radar rainfall to characterize the storm events.

Wride et al. (2004) introduced wastewater treatment plant (WWTP) hydraulics into their collection system model using the SWMM EXTRAN model. Incorporating WWTP hydraulics effectively moved the downstream boundary condition to the plant outfalls permitting an improved understanding of collection system performance during wet-weather conditions.

An approach to select a time period for continuous simulation of collection systems that ensure both precipitation and runoff yield statistics that are representative of the long-term conditions of the study area was introduced by Yeboah and Heineman (2004). The methodology was demonstrated for a watershed in New Hampshire where five-year periods were identified for continuous simulation.

El-Din et al. (2004) introduced an artificial neural network approach to predict wastewater flows. The ANN model was used to make a short-term prediction of wastewater inflow rate to a treatment plant. Based on the positive results obtained, the ANN model was discussed as a potential real-time process control system.

Quantifying infiltration and inflow (I/I) to the collection system requires considerable data collection, management, and analysis effort. Pang and Morgan (2004) described the database created and modeling tools developed by King County in their regional I/I control program. More than 775 flow monitors, radar rainfall measurements, and 72 rain gauges distributed throughout the 420-square mile service area were used to collect data to use in the I/I modeling phase. The data analysis and modeling studies aided the identification of mini-basins that will be targeted for future I/I control improvements.

Collection systems may have flows transitioning from free surface to pressurized with the potential to generate hydraulic transients. Politano et al. (2004) introduced a numerical model of flow during the filling of tunnels, including transition from free-surface to pressurized flow. The code was tested using the CSO tunnel system in Atlanta. Vasconcelos and Wright (2004) compared two approaches to model the transition of free surface to pressurized flow. The first model followed the rigid column approach solved using the method of characteristics and the second model was based on the Preissmann Slot method. The models compared well to data collected using an experimental pipe setup.

Bishop and Scheckenberger (2003) demonstrated the practical execution of a design created in part through detailed modeling where the model acted as a bridge between the pre-design modeling and post-design modeling. Habimana et al. (2003) presented an overview of the numerical modeling that was performed during the design of Portland's West Side CSO Tunnel. The model was used to estimate the strains and additional loads in the pile-supported structures and to assess the efficiency of the proposed mitigation measures.

Burgess et al. (2003) reviewed the application of design storms in the analysis of sewer system capacity. The paper addressed (1) the range of design storms to be applied; (2) the approach to accounting for spatial variability in those storms; and (3) the assumed conditions for antecedent soil moisture to be applied with those storms. Steiss (2003) reviewed the development of a basement flood relief plan for the Dumoulin Combined Sewer District in the City of Winnipeg. The authors described the SWMM model development, calibration and verification, assessment of existing levels of basement flood protection and relief alternatives to upgrade the combined sewer system, and the economic analysis of proposed relief works.

Chen et al. (2003) presented simulations for the interactions between storm sewer and overland flows using a dynamic model that simulated the complex hydraulic process in urban areas. The model was verified by the Typhoon Xangsane event in Nov. 2000, and applied for simulating the Typhoon Nari event in Sep. 2001. The dynamic urban inundation model was suitable for the flood simulation of an urban area under high intensity of rainfall. Dempsey et al. (2003) described an integrated modeling study that was designed to improve the performance of the urban wastewater system of Belfast, Northern Ireland. The overall study concluded that the proposed sewer upgrading scheme would achieve the long-term environmental objectives for both the Blackstaff and the Lagan.

Harwood (2003) reviewed the use of computational fluid dynamics to assess the performance of CSO chambers. The model could assess the performance of existing and proposed structures and the performance of remedial measures retrofitted to unsatisfactory CSO chambers. Schluetter and Mark (2003) compared several methods for calculating annual pollutant loads for a given CSO. The results were then used to demonstrate how the different methods could impact the regulatory decisions regarding maximum loads.

O'Leary et al. (2003) applied a statistical model for rainfall-derived I/I (RDII) to actual flow and rainfall data series from wastewater basins in Tuscaloosa, Alabama. RDII volumes estimated as functions of time were compared to those calculated by traditional reading of hydrographs. The proposed methodology produced more stable estimates of RDII during rain events. Semadeni-Davies (2003) demonstrated the value of response surfaces for displaying multiple simulated responses to incremental changes in air temperature and precipitation using a case study of the Lycksele waste water treatment plant.

Harwood (2002) presented three strategies for the application of Computational Fluid Dynamics (CFD) to the modeling, design, and performance assessment of CSO chambers. Pollert and Stránský (2002) demonstrated the use of the one-dimensional MOUSE model and the three-dimensional FLUENT model for evaluation of separation efficiency of suspended solids in CSO. The 1D model simulated the runoff and pipe flow in the CSO catchment and the 3D model simulated the water flow and the dynamics of the suspended solids inside the CSO structure. Okamoto et al. (2002) used the Algebraic Slip Mixture model of the CFD code FLUENT-5 to predict the solids removal performance of a hydrodynamic vortex separator. Results from lab tests with a scaled model verified the model predictions of solids concentration at outlet points. Burt et al. (2002) described the application of CFD to simulate flows and suspended solids retention efficiencies in a high side weir CSO. Evaluation of three modeling approaches indicated that a multi-fluid, multiphase approach was found to be superior to coupling a single-phase flow calculation with Lagrangian particle tracking. van der Tak et al. (2002) developed and tested both a physical model and a CFD model of a CSO screening structure designed for CSO outfalls along the Hudson River in Hoboken, Weehawken, Union City, and West New York in New Jersey. Studies with the models were conducted to test a typical screening chamber and to optimize baffle and bar rack positions to minimize head loss, maximize the capture of solids/floatables, and facilitate maintenance of the chamber.

Stirrup and Marchant (2002) modeled the performance of a CSO storage tank in Hamilton, Ontario. When the simulated performance was compared to performance data collected by a SCADA system several limitations associated with their continuous simulation were identified and discussed. Vallabhaneni et al. (2002b) described the use of water billing records to establish base flow rates for dry-weather flow simulations in the Metropolitan Sewer District of Greater Cincinnati collection system computer model. After calibration and testing the authors concluded that the use of water billing records provided a reliable basis to establish base flow rates in sewer systems.

Huisman and Gujer (2002) presented a deterministic model for wastewater transformations in sewers, including activity in the wastewater and in the developed sewer wall biofilm. The model was based on the Activated Sludge Model No. 3 (ASM3). The resulting model described the oxygen concentration and wastewater respiration well and could easily be

linked with the WWTP Activated Sludge Model and the newly proposed River Water Quality Model No. 1. The use of a balanced scorecard model by Union City, California, and the City of Eugene, Oregon to implement improvement strategies for SSO reduction, treatment plant effectiveness and environmental management was described by Ruffier and Wies (2002). The paper described the model, the strategies where it has been used, the reasons why the balanced scorecard model was chosen. Korving and Clemens (2002) reviewed Bayesian decision analysis as a methodology for rational decision-making when evaluating the effects of CSOs on receiving waters. Bayes' rule was used to combine prior impressions with new observations to reduce the risks associated with the planning of sewer system reconstructions. The presentation by Korving et al. (2002) reviewed the use of single computations of CSO volumes using a time series of rainfall for system loads to make decisions on sewer system rehabilitation. The problem highlighted in the paper was that uncertainties in knowledge of sewer system dimension are not typically taken into account. Testing of this potential problem using Bayes factors regarding sewer system dimensions demonstrated that uncertainties in sewer system dimensions cause a considerable variability in return periods of calculated CSO volumes.

Modeling tools such as SWMM typically have been used to model I/I with sanitary collection systems (Czachorski and Van Pelt 2001). The hydrograph theory used by these models explicitly assumes that the system can be accurately modeled by linear dynamics; however, in general, this assumption is inaccurate. Nonlinear dynamics result from complex flow patterns and other transport mechanisms, but typically the dominant nonlinearity can be attributed to antecedent moisture effects. SWMM was used by Onondaga County, New York to simulate the hydrologic and hydraulic elements of its combined sewer system and to project the effects of a range of abatement alternatives (Davis et al., 2001c). The models successfully identified the maximum conveyance capacity of the collection system and showed that, following abatement, 85% of the combined sewage would be captured for primary treatment at the WWTP. To assist with hydraulic analysis for a Portland, Oregon project to reduce the potential for basement flooding, a detailed SWMM model of the basin using a suite of GIS and database tools was developed. The detailed GIS approach with virtual raingages produced model results that correlated very well with flow monitoring data. The detailed SWMM model identified the location of much of the system capacity problems. The City of Winnipeg initiated a basement flood relief program in the mid-1960s to provide a minimum five-year level of protection to the residents (Steiss and Watters 2001). Since 1977, this program has been modeled with SWMM, and to date, sewer relief works have been implemented in 21 of the City's combined sewer districts. The public notification method developed for the City of Detroit uses a continuous SWMM model for determining the occurrence and time of overflow and was approved as an interim reporting method until an instrumentation project currently under way is completed (Brink et al., 2001).

James and Young (2001b and c) developed new code for radial gates that was integrated into the Extended Transport (EXTRAN) module of SWMM. The new program, called RGEXTRAN, was capable of handling unsteady flow conditions occurring in real sewer systems with radial and regular sluice gates. The program also provided for dynamic control of the radial gates (or other gate types) based on flow conditions at remote locations in the sewer system. James and Young (2001a) demonstrated that RGEXTRAN could be used to optimize a combined sewer system operation by fully utilizing all available storage and conveyance capacity in the existing facilities. The program was applied to the combined sewer system in Vancouver, British Columbia, and verification tests demonstrated that the new program accurately represents the operation and hydraulics of the dynamic radial gates and siphon-weirs found in the system. Due to the complex number of available pathways that RDII may enter a sanitary sewer, rainfall dependent infiltration and inflow (RDII) has been one of the most difficult components of the urban wet-weather water budget to estimate (Wright et al., 2001). Various tools have been applied to estimating this special hydrologic response, including the rational method and several unit-estimation methods. The paper highlighted results from a relatively new physically based conceptual method first introduced by Kadota and Djebbar in 1998, a modification to the SWMM RUNOFF module that includes the response of a conceptual non-linear reservoir to changes in groundwater elevations resulting from permeable-area infiltration.

MOUSE, an Arcview-GIS based dynamic model, was selected to analyze the performance of the combined sewer overflow (CSO) system operated by the City of New Haven (Connecticut) and the New Haven Water Pollution Control Authority for 3-month, 6-month, 1-year and 2-year design storms (Cheung et al., 2001). In addition, an average rainfall year was simulated to determine the performance of the system under typical rainfall conditions. The short-term control plan identified minor adjustments to overflow weirs and orifices, and to pump rates, while a long-term control plan included major capital works such as storage tanks or pump station and trunk sewer replacement. Long term numerical modeling was used to verify design parameters for the new King County 7-million-gallon CSO storage and conveyance tunnel, including gate- and pump-operation rule sets for operating the storage systems (Crawford and Swarner 2001). Additional modeling was performed to determine operation strategies for extreme events such as combinations of large

storms, high tides, or unusual flow diversions. The long term numerical modeling verified the suitability of rule sets for conditions which often cannot be anticipated.

Harwood and Saul (2001) reviewed some of the physical model studies which have been carried out in the UK to determine the performance of combined-sewer overflow chambers. The limitations of both physical modeling and computational fluid dynamics approaches were discussed, and it was concluded that the future of chamber modeling combine both approaches. The impacts on DO in the Rouge River from CSO-treatment basins were evaluated using basin effluent monitoring, river monitoring and dynamic water quality modeling (Kluitenberg et al., 2001). Using a consensus-based approach, work groups including State personnel, CSO community representatives and consultants concluded that the demonstration basins could eliminate raw sewage, protect public health and achieve water quality standards, including the DO standard.

Reeves and Lewy (2001) discussed the representation of long term, highly attenuated runoff in collection systems, focusing on rainfall dependent groundwater infiltration. Contributions to urban drainage systems by stream ingress or from large permeable areas do not fall easily into either the runoff or baseflow categories. In addition, the increasing prevalence of Sustainable Urban Development (SUD) structures is promoting a need to represent highly attenuated groundwater contribution. The paper by Miralles et al. (2001) described the methodology that was used to evaluate wet weather flows within the sanitary sewer system in Luquillo, Puerto Rico. The methodology, based on a unit hydrograph model to predict (RDI/I), was calibrated by comparing predicted wet weather flows to those observed in the five flowmeter locations.

For municipalities to cost-effectively plan, organize, and implement infrastructure improvements, they require improved information on structural conditions, decision-making tools, operation and maintenance practices, and techniques for repair and rehabilitation (Tafari et al., 2001). The paper reviewed European approaches for diagnosing and analyzing water and wastewater systems, and in particular the use of performance indicators and non-hydraulic models for predicting failures in these systems.

An abatement strategy was developed for three CSO outfalls in the Bronx, New York (Brilhante, et al. 2000). EPA SWMM was used along with cost and receiving water quality modeling to define the optimal level of in-line storage required to meet regulatory requirements. To achieve desired CSO control for the City of Edmonton's Gold Bar Wastewater Treatment Plant (GBWWTP), the hydraulic relationship between the upstream collection system and the GBWWTP was evaluated by including a detailed hydraulic model of the treatment plant as part of the collection system hydraulic model (Gray et al. 2000). This study provided details on the approach used to simulate these two system components in an integrated model. Hydraulic/hydrologic modeling was conducted using the EPA SWMM model in support of the design of a CSO consolidation/ relocation project in South Boston (Walker et al. 2000b). Findings indicated that an original facilities planning model was reasonably accurate in predicting peak flows in extreme storm events, despite only being calibrated to a 3-month storm.

The U.S. EPA is in the final stage of issuing an SSO Rule that will add control of SSOs to the NPDES permit requirements (Lai et al. 2000). This paper provided a preview of the rule and described the advantages of employing a modeling approach for capacity assurance of various components of a collection system and development of an SSO mitigation plan.

The City of Columbus Inflow and Infiltration Program utilized a comprehensive sewer system evaluation and hydraulic modeling approach to mitigate sanitary sewer overflow and water-in-basement occurrences (Chase et al. 2000). By identifying problems in the collection system and incorporating them into a hydraulic model prior to SSO mitigation alternatives analysis, the City of Columbus will be able to target capital improvement and maintenance dollars to correct the problems in the collection system and reduce SSOs. The Miami-Dade Water and Sewer Department used wet weather data from a supervisory Control and Data Acquisition telemetry system to quantify rainfall dependent infiltration and inflow (RDII) (Christ et al. 2000). The MS Access application developed to quantify the individual pump station's RDII response is discussed in this paper. A detailed computer model of the Metropolitan Sewerage District of Buncombe County, North Carolina collection system was used to identify collection system improvement alternatives (Harris 2000). Alternatives included strategic application of sewer rehabilitation and upgrades, off-line storage and additional treatment capacity. The Encina Wastewater Authority developed a Peak Flow Management Plan, in which effluent equalization storage as an alternative to a new ocean outfall was evaluated using a risk-based approach (Hogan et al. 2000). A continuous simulation model of wet weather flows and storage/outfall facilities was used to generate estimates of peak

flows, storage volume requirements, and project costs over a range of return periods.

A global mathematical model for simultaneously obtaining the optimal layout and design of urban drainage systems for foul sewage and stormwater was presented (Diogo et al. 2000). The global strategy adopted combined dynamic programming and metaheuristics to develop a sequence of optimal design and plan layout subproblems. A computational method for the optimal design of highway drainage inlets was formulated as a discrete-time optimal control problem (Nicklow and Hellman 2000). The example revealed that genetic algorithms and the discrete-time optimal control methodology comprised a comprehensive decision-making mechanism that could be used for cost-effective design of storm water inlets.

The FORTRAN source code in EXTRAN block of SWMM has been modified to take advantage of parallel processing for faster program execution (Burgess et al. 2000). Reductions in run times exceeding 30% were achieved. SWEHYDRO and MOUSE were combined to model both the collection and treatment system for Edmonton, Alberta (Ward et al. 2000). A detailed simulation of the treatment plant hydraulics was performed to optimize its operation during wet weather periods.

The pros and cons of design storm and continuous simulation techniques were compared for treatment plant and collection system design purposes (Dent et al. 2000). Examples were included from several municipal master-planning studies that illustrated how results can vary from one approach to another. The shear stress distribution over the sediment bed in a pipe with deposited sediments was quite uniform but larger than the mean shear stress in the cross section (Berlamont et al. 2000). Comparisons between numerical calculations and (unsteady) sediment transport measurements confirmed these results qualitatively.

Modeling and analysis of combined sewer systems received considerable attention. Milina et al. (1999) described the development of an integrated model and its application to the Hovringen wastewater system in Trondheim, Norway. The model integrates sewage production, transport and treatment simulation, the interface with existing databases and the simulation of processes that were controlled in real time, and has been used to design the treatment process as well as static and dynamic measures in both the catchment and the sewer system. Krebs et al., (1999) use measurements and numerical simulations to show that the first flush effect may cause a significant impact on the receiving water when CSO occurs, or on a wastewater treatment plant when the sewer network was flat and catchment area was large. Alvarez et al. (1999) analyzed, from an environmental point of view, the structural and functional scheme considered for the sewage management of a small coastal community in the Bay of Biscay in Spain, where the presence of overflows in the system during storms leads to the release of a great deal of pollutants.

Furumai et al. (1999) applied a distributed model to study the reduction of CSO pollution for a combined sewer system in Japan, which contains a storage pipe with 3 weirs for inundation control. Results indicate that the model can be applied for evaluating effectiveness of modified operation or new installation in the sewer system for suspended sediment load reductions, once initial conditions on surface deposits and sediments were properly determined. Grum and Aalderink (1999) performed a return period analysis of CSO effects using embedded Monte-Carlo simulations, putting all quantities described by probability distribution in either an inner layer consisting of quantities varying from event to event or an outer layer consisting of uncertain but constant quantities. This resulted in a band of return period curves representing the return period distribution for which confidence limits may be calculated. Jack et al. (1999) described a study which utilized detailed simulation models of the sewerage and treatment plant performance for the City of Perth in Scotland in order to investigate the potential problems caused by introducing system storage to control both flooding and polluting spills. The Jefferson County, Alabama Environmental Services Department was currently implementing a program to address the need for collection system rehabilitation and capacity improvements in its wastewater collection systems, and Keckley (1999) discussed the use of an extensive network of flow monitors and rain gauges in each collection system to assess the extent of needed capacity improvements as well as the impact of rehabilitation. Milina et al. (1999) described some results of an integrated model development and its application to the Hovringen wastewater system in Trondheim, Norway. The developed integrated model has been used to design, in both the catchment and the sewer system, the treatment process as well as static and dynamic measures including extended pumping, adjustment of overflows, separation of stormwater runoff from "non-effective separate systems", retention and real-time control of the sewer tunnel volume.

The local Water Authorities of the Basque Country (Spain) have adopted an integrated model for the design of the sewer system of this community. The model was developed specifically for the study of coastal sewerage under dominant wet



weather conditions. It includes: (1) Establishment of the site specific statutory requirements and environmental objectives, (2) Design of sewer system components with specific reference to influences on marine water quality, and (3) Development of monitoring programs (Alvarez et al., 1999).

Aronica (1999) presented a simple numerical model based on the method of continuity for flood routing in urban networks. The network was represented as a cascade of cells and the flood routing was schematized as a flux transfer between adjacent cells. Preliminary tests were carried out by means of the reproduction of flood wave propagation for some examples of urban drainage systems, both hypothetical and real. The results showed satisfactory numerical stability and an excellent computational efficiency. Barnett and MacMurray (1999) stressed the importance of correctly modeling overland secondary flow paths. At drainage network nodes such as street intersections, the distribution of outflow depends on nodal compatibility conditions, particularly when one or more of the outflow paths was steep, and large errors accumulated from the application of incorrect conditions at a succession of nodes.

Welker et al. (1999) investigated possible changes to quantity and composition of sewage in the combined sewer system and the WWTP caused by new stormwater management strategies (mainly by disconnecting areas from the sewer system). Various scenarios were developed and the consequences on the water systems were calculated by using the simulation model KOSMO, in a fictional catchment.

The Monte-Carlo simulation approach was demonstrated in an integrated setting involving models for rainfall characteristics, CSO loads and impacts on the surface water DO. CSO loads were modeled using event lumped non-linear regression models with rainfall as input and with overflow volume, duration and relevant event mean concentrations as output; oxygen depletion in the surface water was described using a dynamic model including oxidation of dissolved COD and nitrification. The parameters of all the models were estimated from observed data on rainfall, CSO load and surface water impacts (Grum and Aalderink, 1999).

Ideta and Kariya (1999) used hydraulic simulation to maximize inline storage and reduce flooding. Kleckley (1999) described estimating sanitary sewer system surcharging during wet weather using measured rainfall and flow. A rainfall-peak flow relationship was developed and used to analyze capacity improvements and the impact of rehabilitation on peak rates. This method should not be used exclusively as it does not assess the impact of rehabilitation on high groundwater infiltration. Lorenz and Weikopf (1999) presented a form of combined sewerage network storage management called the cascade technique. This technique utilized fully adjustable weirs to dynamically control the flow in the sewerage system. The cascade technique can be seen as an approach to decrease both the water pollution and the investment and operation costs caused by combined sewerage systems. Maitland et al. (1999) presented new features of XP-SWMM32, a model for complex open and closed conduit drainage systems. The application of these new and existing features of the XP-SWMM32 package to real-world drainage problems was outlined through the presentation of several case studies of representative drainage systems in the United States, Japan, and Australia.

Merlein and Valentin (1999) investigated design features of sewer systems to increase the capacity of sewerage systems under pressurized flow. A mathematical model was used to compare the results of the hydraulic model under steady conditions with unsteady conditions as they were during a cloudburst.

Morrow (1999) outlined the hydraulic modeling requirements of a program to meet a new, demanding discharge consent standard (average of 3 spills per bathing season per outfall) at specific coastal discharge points. A program costing over \$105M had to be designed, approved by the regulator, procured, built, and commissioned in a period of 15 months. Continuous simulation was the only valid way of confidently establishing the additional storage volumes required to meet the new consents. Vazquez et al. (1999) proposed a new set of parameters for the Muskingum model for routing in a circular main in a sewer network for a wide range of lengths, slopes and diameters. A neural network was used to design the parameters of this model. This new application of Muskingum equations enables mean relative errors of less than 6% to be obtained for the value and the point in time of the flood in the case of mains up to 6500 m long, with slopes varying from 0.5% to 1% and with diameters ranging from 150 to 2000 mm.

Watanabe et al. (1999b) proposed a practical lumping method for manholes under surcharged flow, in which all the water surface areas of ignored manholes were preserved in the water surface areas of the adjacent manholes. The lumping method was applied to a combined sewer pipe system in Matsuyama City drainage basin in Japan and the adaptability of the method was investigated through stormwater runoff simulations. Wong et al. (1999) discussed the City of San Diego's (California) program for monitoring and modeling of its wastewater facilities. This sustainability concept had

implications in terms of the databases, modeling tools, and applications of the model. Two key elements that were highlighted were the value of developing a custom GIS application to integrate and process data that was developed and updated by other City and County agencies, and applications of the model for both planning and operational studies that resulted in reduced capital and operating costs. During urban storms, the overloading of a sewer system or river bank overflow produced flows which were essentially routed by the road infrastructure and cause flooding of adjacent built-up areas (Hingray et al., 1999).

The evaluation of the damage suffered by these built-up areas required the determination of important hydraulic parameters of the inundation, such as the maximum water depth or the inundation duration. This paper described the hydraulic behavior of flooded built-up areas at different scales: individual plot, block of plots. Online sewer flow forecasting was simulated in this study using an autoregressive transfer function rainfall-runoff model and a recursive procedure for parameter estimation (Gelfan et al., 1999). Three recursive estimation algorithms were used: the time-invariant and time-varying versions of the recursive least-squares algorithm, and the Kalman filter interpretation of this algorithm. The sensitivity of the forecasting accuracy to the model order and to the initial conditions of the algorithm was studied using sewer flow data from the Milwaukee (Wisconsin) Metropolitan Sewerage District. In the UK, current river quality monitoring programs provide little information for management of CSO discharges, or objective assessment of their pollution impact. Balmforth et al. (1999) described a methodology that uses existing river flow data, which was available at sub-catchment level in the UK, to identify intermittent discharges by a development of the unit hydrograph method, based on the hypothesis that intermittent discharges produce unit hydrographs that lie outside the 'normal' correlation between effective rainfall and surface runoff for a catchment.

The EPA and the Miami-Dade (Miami, Florida) Water and Sewer Department negotiated a Consent Decree settlement, which required them to undertake the installation and maintenance of a computerized collection and transmission system model. The "Virtual Dynamic Computer Model" has the ability to predict potential SSO resulting from peak flow conditions (Walch et al., 1999). The Metropolitan St. Louis Sewer District has responsibility for the management of stormwater drainage as well as conveyance and treatment of sanitary sewage within its boundaries. The Watershed Master Plan's hydrologic and hydraulic analyses were conducted using the SWMM (Miller and Loucks, 1999). The local Water Authorities of the Basque Country (Spain) have adopted an integrated model for the design of the sewer system of this community. The model was developed specifically for the study of coastal sewerage under dominant wet-weather conditions and includes: 1) establishment of the site specific statutory requirements and environmental objectives; 2) design of sewer system components with specific reference to influences on marine water quality; and 3) development of monitoring programs (Alvarez et al., 1999). Hsieh and Wang (1999) introduced a semi-distributed parallel surface rainfall-runoff conceptual model. To evaluate the adaptability of this model, three watersheds around the city of Taipei in Taiwan were chosen to test the effectiveness of the model.

Hvitved-Jacobsen et al. (1999) presented a conceptual model for wastewater quality changes during transport in sewer systems. Emphasis was on microbial transformations of heterotrophic biomass and soluble and particulate fractions of organic substrate; the inclusion of sulfate respiration in the model concept was outlined. The model was exemplified as a tool for evaluation of wastewater quality changes in an intercepting gravity sewer. The model concept was tested in gravity sewers as well as in pressure mains.

Schlutter (1999) presented a numerical model capable of simulating sediment transport in combined sewer systems. The main objectives were to model mass transport rates at the outlet from a catchment and at the same time obtaining qualitative information on erosion and deposition going on at different locations in the sewer system. An example was given of a calibration event from a case study. Vollertsen et al. (1999) reported on the biotransformation of wastewater particles with different settling velocities. This was based on analysis of long term oxygen uptake rate measurements and a conceptual model describing aerobic transformations of organic matter. No significant change in the biodegradability of wastewater particles with different settling velocities were found.

Yagi and Shiba (1999) used fuzzy logic control and genetic algorithms to achieve improved pump operations in a combined sewer pumping station. Current pump operations could be improved by adding sewer water quality to the input variables and to the fitness function; the improved operations can reduce not only floods in the drainage area but also pollutant loads discharged to the receiving waters. Zug et al. (1999a) presented a conceptual model for solid production and transfer in combined or separate sewerage systems called HORUS. The objective of this model was to reproduce the hydrographs, taking into account the characteristics of the catchment and the structure of the sewerage system. Simultaneous measurements of rainfall, hydraulic, TSS and COD concentrations on nine very different catchments and

about one hundred rainfall events allowed a large range of validation which can be considered of good quality. Zug et al. (1999b) presented the results of a study whose objectives were the definition of the exceptional rain event compared to the capacity of the sewerage system and the development of recommendations for the design and operation of the sewerage system to efficiently manage most rainfall events. The measurements allowed the calibration and validation of a model (HYDROWORKS), which included hydraulics and masses of total suspended solids. Artina et al. (1999) showed the results obtained from the ongoing investigation in an experimental catchment in Bologna (Italy), monitored in order to acquire data on the pollutant loads entering the sewer network and then spilled to the receiving stream by some CSO. These data were being used to calibrate a detailed model for both the sewer system and the river reach. Skipworth et al. (1999) described an experimental model investigating erosion and subsequent sediment transport of an in-pipe, fine-grained, organic, cohesive-like sediment deposit analogous to those found in sewers.

The Metropolitan St. Louis Sewer District developed a computer model to improve the control of SSO which incorporated the system's physical features, dry-weather flow and WWF, and the impact of bypass flow on receiving waters (Moore et al., 1997). Gall *et al.* (1997) outlined a process-modeling and simulation program which is part of a pilot-scale study of satellite-treatment options for the control of CSO.

Three case studies (force main shut-down analysis, rehabilitation of gravity interceptors, and WWF diversion) demonstrated the benefits of using dynamic hydraulic modeling to improve the operation and maintenance of collection systems (Hwang *et al.*, 1997). A physical model and the HydroWorks model were used to balance hydraulic criteria for an inline-storage tunnel intended for multiple uses (e.g., the control of CSO and SSO; and the reduction of urban flooding) (Switalski *et al.*, 1997).

Arthur and Ashley (1997) proposed to estimate the extent to which sediment in transport near the bed of sewers contributes to the first foul-flush phenomena by describing the movement of a storm wave along a conceptual sewer length. Sweden and the Slovenian Republic have applied the computer model MIKE 11 HD to solve CSO pollution problems. The model provided solutions which would protect the countries' receiving waters (Water Qual. Int., 1997b).

Detroit, Mich. tested and modeled the primary and secondary capacities at their WWTP as part of their Long Term Control Plan (Lieberman *et al.*, 1997). They found that the maximum solids processing and storage capabilities are sufficient to handle additional CSO loads, thereby reducing the need for additional CSO facilities. Results using the Direct Random Search optimization technique, with the planning level model HIRATE as the simulator, are presented for one of the facilities investigated in the Greater Cincinnati, Ohio CSO program (Pisano and Hui, 1997). Houston, Tex. devised a proactive approach by providing adequate planning and design time and realistic construction schedules to correct future potential SSO problems (Kidder *et al.*, 1997). Flanders, Belg. conducted an experimental program to identify the important parameters for evaluating the impact of overflow events on receiving waters, improving the design of storage-sedimentation tanks and overflow structures, and improving the capability of numerical models to predict emissions from CSS (Berlamont *et al.*, 1997).

Ruan and Wiggers (1997a) investigated the application potentials of the methodology of time-series models for predicting some values related to CSO characteristics, e.g., CSO discharge and water level versus rainfall intensity, pollutant load versus CSO discharge, etc. *Sewsim*, a conceptual CSO-emission model was developed from *Matlab* and *Simulink* and can model rainfall-runoff, surface solids buildup and washoff, and sewer-sediment erosion and deposition. Some *Sewsim* simulation results predict pollution load of CSO more effectively than deterministic models (Ruan and Wiggers, 1997b). Physical theory was incorporated in a stochastic model of water level and particulate COD of a Dutch CSO. Results suggested that most of the deviation between model prediction and observation were due to sewer-system behavior, which is not explained by the model (Grum, 1997). The particle-tracking routine in the FLUENT computational-fluid-dynamics (CFD) software has been employed in the prediction of storage-chamber sedimentation efficiencies, which are influential in the management of CSO events. FLUENT was shown to be highly sensitive to the particle injection location but less sensitive to either the particle size or density (Stovin and Saul, 1997).

Worm and Carstensen (1997) applied a stochastic-modeling technique to analyze a subcatchment sewer system in Sydney, Aust.

### **Modeling solids transport in sewers.**

Many computational models are available to simulate the flow and transport of suspended solids and other water quality pollutants through urban drainage systems to wastewater treatment facilities and CSO. However, models capable of

predicting the quantity and temporal distribution of gross solids entering treatment works and CSO are less available. Digman et al. (2002) developed a model to predict the modeling of gross solids in a combined sewerage system. The Gross Solids Simulator (GSS) links directly with Hydroworks to obtain network data and flow depth and velocity. The model also uses a series of diurnal solids profiles based on work performed at the Imperial College in London. The GSS has been calibrated using an extensive set of data sampled from combined sewerage systems. In a separate study, results from a thorough analysis of the water quality modeling components of MOUSE and HydroWorks/InfoWorks CS suggests that results obtained for pollutant transport in the sewers is not as accurate as the hydrodynamics (Bouteligier et al., 2002). Consequently, caution should be exercised when using the water quality modules of the two software packages.

Integrated drainage network, treatment plant, and receiving water modeling. Zug et al. (2002) are creating an integrated model (sewer networks, storage tank, and wastewater treatment plant (WWTP)) for the Grand Couronne sewer system and parts of the Berlin sewer system. The integrated model has been built, calibrated, and validated for hydraulic and pollution load prediction during dry and wet weather. Mark et al. (2002) used integrated modeling of the drainage system, WWTP, and receiving water to evaluate real time control and alternative WWTP operations to protect beachfront water quality. The integrated modeling used MOUSE TRAP to simulate the drainage system, historical data to represent the WWTP operation, and MIKE21 to represent the beach water quality in two dimensions. An assessment of the benefits of an integrated urban drainage modeling approach linking the operation of the sewer system, WWTP, and receiving water was evaluated by Erbe et al. (2002). Mailhot et al. (2002) evaluated the impacts of watershed management and wastewater treatment activities on water quality of the Chaudiere River using an integrated modeling system. Wolff et al. (2002) assessed the use of hydraulic models of the collection system coupled with steady state models of the WWTP hydraulics. Willems and Berlamont (2002b) used deterministic and probabilistic modeling to simulate the impact of combined urban drainage and WWTP system discharges on receiving water quality.

#### **Pollutant sources and transport.**

Mitchell and Diaper (2006) simulated the urban water and pollutant cycle. The model can be applied to alternative control practices.

Fecal coliforms in the Tidal Basin in Washington D.C. were modeling using a three-dimensional model, as part of the development of a Total Maximum Daily Load (TMDL) for that water source. The results showed that the fecal coliform levels in the basin were mainly controlled by the levels in the river, and that sediment storage of fecal coliforms was a concern (Bai and Lung, 2006). Haydon and Deletic (2006) developed a coupled pathogen-hydrologic catchment model for discharges from large catchments. The prediction of pathogen loads was best with the model that considered washoff and loss processes of the pathogens in the surface and subsurface flows. Yeghiazarian et al. (2006) combined a microscopic and macroscopic approach to modeling the transport of pathogenic microorganisms in nonpoint source pollution. A stochastic Markov model was used to predict microorganism transport, including partitioning between water and soil and between soils of different sizes. Model results showed that clayey soils are more likely to contribute to contamination.

Borah et al. (2006) provided a critical review of the existing models for simulating nutrient and sediment loads from watersheds and in receiving waters. The models evaluated for use in TMDL included: GWLF PLOAD, AQUATOX, BATHTUB, CE-QUAL-W2, QUAL2E, QUAL2K, AGNPS, AnnAGNPS, CASC2D/GSSHA, DWSM, HSPF, KINEROS2, LSPC, MIKE SHE, and SWAT. Deng et al. (2006) proposed a fractional dispersion model for overland solute transport. Both hydrographs and the pollutographs predicted by the fractional dispersion model were in good agreement with the data measured experimentally using a soil flume and a moving rainfall simulator.

Park and Stenstrom (2006b) used satellite imagery in combination with Bayesian networks to determine landuse in the Santa Monica Bay watershed. The results provided spatial estimates of each pollutant load as a thematic map. The areas of greatest pollutant loading were identified. Park and Stenstrom (2006a) performed spatial estimation of pollutant loadings in the Santa Monica Bay watershed using Bayesian networks and GIS. This study estimated land use from satellite-image classification. The results showed that the major sources of pollution are multi-family residential, commercial, industrial and transportation sources adjacent to Marina del Rey and the Ballona wetlands.

Koorman et al. (2006) modeled the fate of chemicals typically disposed of in drains using the Geography-Referenced Regional Exposure Assessment Tool for European Rivers (GREAT-ER) in sewers, treatment plants and natural water bodies. Lindblom et al. (2006) performed integrated modeling of two xenobiotic compounds in an integrated urban

wastewater system. The model was able to elucidate phenomena that related to the source and fate of these compounds. Dougherty et al. (2006a) modeled empirically the hydrologic and NPS pollutant flux in an urbanizing basin. Total soluble phosphorus flux was associated with mean impervious surface and urban and agricultural soil disturbance. Inamdar and Naumov (2006) reviewed the lessons learned from a project to assess sediment yields from a mixed-land use in the Great Lakes. They also addressed the accuracy of the SWAT modeling. Thomas and Tellam (2006) modeled the recharge and pollutant fluxes to urban groundwaters. This model, UGIf, predicted a similar average recharge rate for the aquifer as previous groundwater flow modeling studies, but with significantly more spatial detail.

A study procedure used to quantify urban pollutant loadings and provide accurate estimates of street and catchbasin cleaning practices was tested by Sutherland and Jelen (2002) for two case studies in Michigan. The procedure involves intensive monitoring of accumulation and both the physical and chemical characteristics of the contaminated sediment found on streets or parking lots and within catchbasins of a given land use. The accumulation data along with monitored rainfall is then used to calibrate SIMPTM, a continuous stormwater quality model. The procedure was applied to the two case studies and classical economic production theory and marginal cost analyses were used to identify the optimal mix of street and catchbasin cleaning practices. An enhanced version of SWMM was developed by Chen et al. (2002) and applied to the Castro Valley Creek watershed to simulate the process of diazinon application, decay, washoff, and transport. The model was calibrated and validated before simulating the diazinon dynamics in the watershed. Simulated diazinon concentrations in the creek matched observed data when monthly application rates were assumed proportional to the population within each subdivision of the watershed.

The level of uncertainty associated of stormwater quality model predictions generally limits the usefulness of the results for precise decision-making. Substantial calibration data is necessary to obtain reliable predictions. Calabrò and Maglionico (2002) compared the calibration and performance of SWMM, UPSIM (Urban Pollution Simulator), and COSMOSS (Conceptual Simplified Model for Sewer System Simulation). Each model was calibrated and validated for two drainage catchments, one in Bologna and the other in Belgrade. The results of the study indicated that all calibrated models predicted the hydrographs and pollutographs well for both catchments. The simpler models (UPSIM and COSMOSS) required less effort because of their simplicity relative to SWMM. The authors identified several key parameters used for calibration of water quality routines in the three models.

Grum and Aalerink (2002) evaluated the potential of applying random coefficient modeling to describe pollutant concentrations in combined sewers during rainfall. The concept was tested by developing a random coefficient model for suspended chemical oxygen demand (COD) in a combined sewer and compares the model results to those predicted by an equivalent constant coefficient model. Ahlman and Svensson (2002a) applied the SEWSYS model to analyze the flow of substances within an urban catchment. The model keeps track of where each substance originates and where it finally ends up. SEWSYS was also applied by Ahlman and Svensson (2002b) to model substance flows in urban sewer systems. A simple conceptual-modeling approach was used by David (2002) to find a useful relationship between precipitation and total suspended solids loads at several monitored locations in a small urban watershed located in Lisbon. The paper by Pandit et al. (2002) demonstrated how the fully calibrated Continuous Annual Load Simulation model, CALSIM, was used to predict the annual total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP) loads, under wet-weather conditions, for the Briar Creek drainage basin, located in the town of Malabar on the east-central coast of Florida, during an average water year. CALSIM was used to predict the annual loads under historical (1943), current, and future conditions.

### **Models of controls.**

Wu et al. (2006b) described a water-quality based approach for stormwater management strategies. This approach combined CE-QUAL-W2 and HSPF to link watershed and receiving waters.

Schneider and McCuen (2006) presented a methodology to assess the hydrologic performance of stormwater controls. Analyses showed that proper stormwater control validation depends on the type of control used, the hydrologic performance criterion, the number of criteria, and storm characteristics. Chen and Adams (2006e) presented methodologies for developing stormwater quality control measures based on derived probability distributions. The case study showed that the analytical models performed comparably to continuous simulation models for the performance of storage facilities.

Wallis et al. (2006) used mathematical modeling to evaluate the performance of stormwater ponds. Design suggestions for improving water quality were included in the conclusions. Kerh et al. (2006) modeled the control by a detention pond

of flooding and tidal variations in the drainage system using a case study in Taiwan. The detention basin simulation showed that the basin was able to provide effective control for floodwater drainage. Calabro and Viviani (2006) simulated the operation of detention tanks using COSMOSS. The model showed good removals of suspended solids in these tanks.

Hipp et al. (2006) optimized the implementation strategy for placing stormwater filters in an urban area to ensure that the area met TMDL requirements. The model used was a GIS-enabled model for estimating and mitigating pollutant emissions in watersheds.

Huber et al. (2006) performed continuous simulations using SWMM to evaluate regional differences around the United States in hydrologic and water-quality performance on stormwater controls. The stormwater controls were characterized as being limited by peak inflow rate or by storage capacity. Rohrer and Roesner (2006) used SWMM to examine the effectiveness of typical stormwater management practices in reducing the potential for stream erosion. An excess shear stress erosion potential index was used to evaluate changes in erosion between undeveloped conditions of a 10 hectare watershed and four variations of post-development stormwater control.

Wayllace and Likos (2006) numerically modeled artificial soil as an evapotranspirative cover using finite-difference based seepage modeling. Results indicated that the artificial soil acts as an effective ET cover system by restricting wetting front propagation and causing water to either evaporate or flow laterally.

Mike21 was used to model the effect of retrofitting an existing stormwater pond to improve pollutant removal efficiency and hydraulic performance (German et al. 2005). Baffles, culverts and island removal were studied as possible improvements; the results showed that baffle installation was the best alternative. A probabilistic model of a stormwater retention tank was presented by Kwietniewski and Lesniewski (2005). The model accounted for high rainfall and the stormwater balance in the tank.

Dussaillant et al. (2005a) developed a numerical model to describe the water flow through a rain garden. The water flow was broken into three layers – a root zone, a middle storage layer of high conductivity and a subsoil lower layer. Zhang and Mitsch (2005) modeled the hydrology of three created freshwater wetlands. Water budget predictions for a stormwater wetland provided useful data prior to its construction.

In order to perform a life-cycle analysis on the pollutant reduction effects of stormwater treatment practices in a watershed, Haselbach et al. (2005) determined that it was important to know the frequency of installation over the period in which BMP installation was required. Studying a county in South Carolina, it was found that compliance rates of facility installation were very high, even when the area of disturbance was less than 0.4 ha. Ahlman et al. (2005) provided a modeling approach for evaluating the efficiency of several non-structural best management practices for stormwater management. The model predicts pollutant control for a management program that includes prevention, education, and regulations.

Teng and Sansalone (2004) developed a two-dimensional model of a field-scale partial exfiltration trench to simulate the effluent hydrograph and water content profiles under unsteady hydraulic loadings. The model incorporated Richard's equation with parameters estimated from field measurements. Simulations confirmed the importance of the surrounding soil hydraulic conductivity in the design capacity of the trench.

Designing low-impact development (LID) controls is a relatively new task for engineers. Most approaches to design and analyze the hydrologic effects of the controls are based on traditional flood control design procedures. New, more appropriate, approaches are needed. Medina et al. (2004) presented the Low Impact Feasibility Evaluation (LIFE™) model developed to simulate LID hydrology. Applications of LIFE™ in four locations were described and demonstrated the usefulness of the model to analyze a variety of stormwater management objectives. Koch and Micolini (2004) discussed a simplified approach to simulate the effects of LID controls on the runoff hydrograph and detention requirements. Targeting developers, the tool was implemented in a spreadsheet providing user friendly access. The modeling approach was based on an adaptation of the TR-20 unit hydrograph approach. The retention capacity of all proposed LID controls were summed and used to represent the depth of retention across the site, which was subtracted from the rainfall excess and used in to generate the runoff hydrograph.

Faram and Harwood (2003) reviewed a method for the numerical assessment of sediment interceptors for sewer and

stormwater drainage systems. The study concluded that primitive chambers, for example, gully pots, were likely to be far more prone to flushing out during high flow inputs than advanced systems such as vortex separators. MacKenzie (2003) summarized the technical approach to date in assessing the degree of TSS removal provided by a stormwater storage facility. The author also modeled the TSS removal that could be expected from street sweeping sampling and modeled the effect of short-circuiting on TSS removal in a stormwater storage facility.

Traver (2002) investigated the appropriateness of using traditional storage-indication routing to model stormwater wetlands. The contributing area and stormwater wetland were simulated using HEC-HMS and HEC-RAS. The wetland configuration was modeled as a single pond and multiple ponds representing the sediment forebay and primary storage area. The results indicated that traditional routing techniques may not be appropriate for modeling stormwater wetlands, especially for smaller water quality storms. Gómez et al. (2002) performed numerical simulations using a simple detention basin and downstream sewer configuration in order to derive the peak flow attenuation and maximum water depths with a wide variation of detention basin parameters and discharge hydrograph characteristics. The simulation results were programmed into an expert model in an Excel spreadsheet for estimating the size of detention basins.

Jensen and Thomsen (2002) used a 1D linear convection-dispersion-deposition model to compute the variation over distance and time of the vertical mean concentration of suspended solids in rectangular storage tanks. The model simulates steady flow and keeps a record of mass of solids suspended, retained on tank bottom, and contained in outflow. Comparison of the model to laboratory experiments shows the particle deposition velocity increases with free fall settling velocity, but decreases when discharge increases. A CFD simulation study was performed by Faram and Harwood (2002) to compare the pollutant capture efficiency of four generic “flow-through” technology stormwater treatment chambers. The authors concluded that chambers in which the storage region is isolated from the main treatment region are likely to be far more effective than those chambers in which this is not the case.

Calabrò (2002) presented a procedure based on a design storm to configure detention tanks for different levels of suspended solids removal. The accuracy of the technique was evaluated using continuous simulation. Comparison of tank performance predictions by the new technique and continuous simulations were close indicating that the new approach can provide fairly accurate performance estimates when rainfall data is not available for continuous simulation. Using SWMM continuous simulations and classical economic production theory, Burian et al. (2002) analyzed the long-term performance of stormwater storage/release systems. The results of the long-term performance evaluation were coupled with a simple economic analysis to select the most cost-effective combination of storage capacity and release rate that met the receiving water protection goal. Rathnam et al. (2002) presented a case study design of a detention facility using a design storm approach coupled with dynamic programming to optimally configure the facility taking into account the specified quantity of runoff and quality standards of the receiving water system. The optimization approach is tested and validated using data from experimental facilities. Morris and Asunskis (2002) used SWMM to evaluate different outlet structure configurations for detention basin designs for catchments located in Missouri. Conclusions from the study suggest there is no simple universal procedure that can be applied for modification of outlet structures of other problematic detention basins; instead a case-by-case evaluation is necessary. Venkata et al. (2002) used a design storm approach coupled with dynamic programming to predict runoff from a watershed and design a detention facility.

Nehrke and Roesner (2002b) examined the effect of detention basin controls on the peak flow frequency curve, and how well the post-development flows are controlled to pre-development levels. They used SWMM to simulate 50 years of rainfall runoff from a 24-acre portion of a hypothetical subdivision with a detention basin used for flow control. The study compared peak flow frequency curves for a detention basin with its outlet sized to control a series of design storms, plus an extended detention BMP option. The results demonstrated that increasing levels of imperviousness affect high frequency events much more than low frequency events. Moreover, the detention basin configuration with an outlet designed for the 100-yr & 10-yr design storms used in conjunction with the extended detention BMP option was found to provide the peak flow frequency curve closest to pre-development levels for storms smaller than the 6-month storm, as well as lowering the post-development peak discharges of low frequency events towards pre-development levels. Heaney (2002a) described a general optimization methodology for evaluating micro-scale urban wet-weather flow controls. The method allows one to optimize over several controls for each user, aggregate into a single performance curve for each user, and if necessary to find the optimal solution for groups of users. Li and Kyriopoulous (2002) presented a derived probabilistic rainfall-runoff model and a treatment train efficiency model to predict the cumulative reduction of runoff volume and solids loading for a series of retrofit stormwater management practices. Braasch et al. (2002) developed a Site Assessment Tool to help evaluate the hydrologic and pollutant loading impacts of new development projects and evaluate alternative BMP plans.

Stormwater infiltration and vegetative practices have been highlighted as key components of alternative development practices to reduce runoff volume and peak discharges. Several researchers have been developing models of infiltration devices for design and analysis purposes. de Souza et al. (2002) applied the Bouwer Model to simulate the hydraulic function of two infiltration trenches in Porte Alegre, Brazil. Results indicated that the model was able to represent infiltration well for one trench, but not the other. The authors attribute the poor model fit for the one trench to three possible reasons: preferential flow out of the trench, lack of a sufficiently clogged restriction layer, and oversimplification of the model. The authors proposed a modification of the model to account for variations of hydraulic conductivity and capillary tension associated with the soils where the trenches are located. Schaffner and Ostrowski (2002) presented a modeling approach to aid in the design and analysis of a flume-gravel trench stormwater infiltration system. Gharabaghi et al. (2002) developed a vegetative filter strip (VFS) model based on results from comprehensive field experiments that quantified the performance of VFS under different flow conditions, pollutant loads, and vegetation covers. The VFS model is being validated and coupled with a nonpoint source pollution model to evaluate watershed management plans.

Watershed Management and TMDLs. Byun et al. (2002a) used SWMM continuous simulations to estimate runoff contaminant loads for the Schuylkill River watershed Source Water Assessment Program. Wagner and Schmidt (2002) compared the annual load predictions from calibrated SWMM and BASINS models of the Big Creek watershed north of Atlanta, Georgia to predictions from the simpler Watershed Management Model (WMM) to discern the advantages of using continuous simulation models for annual and seasonal load predictions. Richards and Stein (2002) introduced the U.S. EPA Smart Growth Water Assessment Tool for Estimating Runoff (SG WATER). The tool can estimate levels of stormwater runoff and associated pollutants (nitrogen, phosphorus, and total suspended solids) from specific development sites or regions.

Bhimani et al. (2002a) performed an integrated modeling approach on the Truckee River to evaluate water quality impacts of various watershed management alternatives in order to implement a trading program for TMDL modifications. Rousseau et al. (2002) used the GIBSI integrated modeling system to assess the probability of exceeding load allocations from point and nonpoint sources associated with TMDLs. Fitzpatrick (2002) described the use of water quality models to develop pathogen, nutrient, and toxics TMDLs for the New York/New Jersey Harbor.

Quantifying and overcoming uncertainty during TMDL development is a difficult challenge. Zhang and Yu (2002) applied first-order error analysis to quantify the margin of safety for the nitrate during TMDL development for the Muddy Creek/Dry River in Virginia. Precipitation was found to be the most dominant uncertainty source. Benaman and Shoemaker (2002) described a methodology to quantify the effect of multiple model parameter uncertainty on the calibration of the Soil and Water Assessment Tool (SWAT). The sensitivity and uncertainty analysis steps of the methodology were applied to a calibrated and validated model for the Cannonsville Reservoir watershed. Sokulsky et al. (2002) overcame model uncertainty in their efforts to develop a copper TMDL for the Haiwee Reservoir in California by developing a model based on extensive rainfall, flow, copper application, and in-system copper concentration data.

Managing the urban sewershed is a data intensive task, which requires sophisticated data management tools. Mihocko et al. (2002) described the development of a Decision Support System (DSS) to complement the Philadelphia Water Department's Real-Time Control system in the City's Southwest Drainage District. The DSS is being developed as part of the department's Long Term Control Plan and will contain a variety of data views and analysis tools for use by agencies for various kinds of decision-making. Heltzel and Dunn (2002) described efforts to address data management needs through the development of an information management platform called Environmental Management and Analysis System (EMAS). EMAS provides a means to store and organize environmental data, analyze data, and link to modeling software.

Stormwater management systems for new urban development were traditionally analyzed using computer models employing design storm events, rather than continuous modeling using long term historical rainfall data and associated frequency analyses (Farrell et al., 2001). The differences in the results (i.e., designs) generated by the two methods have not typically been understood during the planning and design process. The different flow and storage regimes in the Town of Milton (Sixteen Mile Creek Watershed) generated by the alternate methods have been highlighted, along with a number of modeling and physical factors which are considered to contribute to the differing results. The Clinton River Watershed Council selected the Source Loading and Management Model (SLAMM) as the main instrument in its watershed plan development (Myllyoja et al., 2001). SLAMM accurately computed runoff pollutant loads and flows associated with small storm events, which was critical because most of the pollutant load was associated with the smaller,



frequent runoff events. SLAMM evaluated several control practices including detention ponds, infiltration devices, porous pavements, grass swales, catchbasin cleaning, and street cleaning. A numerical model (sediment trap efficiency for small ponds-STEP) was developed to simulate sediment deposition in small ponds (less than or equal 1 ha) and to calculate the sediment trap efficiency (STE) (Verstraeten and Poesen 2001). Eight runs with an experimental pond in Belgium were used to test the model. The STEP model produced reasonable predictions of STE as well as the shape and magnitude of the effluent sediment concentration graph.

Huber (2001) summarized the ability of SWMM to simulate wet-weather controls favored in current practice, including those related to LID. The model simulated some practices well, such as storage, and other options not as well, such as wetlands and filtration. In designing a permeable pavement installation, surface infiltration capacity that allows an adequate volume of stormwater to be captured and treated by the facility must be provided and maintained (James et al., 2001). The paper detailed the underlying method and function of a free-ware program that uses SWMM for the design of permeable pavement installations.

The water balance model (Aquacycle) developed in this study represents water flows through the urban water supply, stormwater, and wastewater systems (Mitchell et al., 2001b). The daily time step provides temporal flow distribution and enables comparison of the different components of urban water demand. Aquacycle was tested using data from the Woden Valley urban catchment in Canberra, Australia and could satisfactorily replicate its water supply, stormwater and wastewater flows.

The micro- and macro-management of stormwater design was examined from a design engineer's viewpoint based upon the traditional establishment of design values and not just meeting regulatory edicts (Olenik, 1999). Software was discussed by Smith (1999) that provides a decision support system for drainage engineers involved in the design of stormwater management facilities. The program provides suggested design parameter values that the user can modify, test and accept. A special feature allows the output file from one design session to be used as input to automatically test the design for a different storm, test a change in catchment or design parameters or simply to complete a design in two or more sessions (Smith, 1999).

Hushka *et al.* (1997) applied AGNPS to estimate erosion and nutrient loadings to the Mirror Lake watershed in North Dakota from five different scenarios of land use and management practices. AGNPS was also applied to a 72,000 acre watershed in south-western North Dakota for simulating the water quality of runoff overflowing the dam and to investigate the lake's responses to eutrofication (Yoon and Disrud, 1997).

**CSO and SSO control.** Hrabak et al. (1999) use three-dimensional computational fluid-dynamic (CFD) models to simulate various complex sewer and CSO components including mixing tanks, sedimentation basins, clarifiers and contact tanks. The modeling was used in lieu of physical modeling to support design. Vaes et al. (1999) described a conceptual model of storage sedimentation basins based on uniform flow, but taking into account anomalies due to non-uniform flow and turbulence. These anomalies were based on experiments in a physical model and simulations using CFD. This model can deal with time varying input and can be used for continuous simulations. Ta (1999) simulated the flow characteristics in a storm tank using CFD. The efficiency of the storm tank acting as a sedimentation basin to retain the suspended particle was evaluated using a dispersed phase model. A range of particle sizes was included to evaluate the sediment profile at the end of the storm event and the carry-over of suspended particles during the spill. Tyack and Fenner (1999) described a CFD model of a 1600 mm diameter prototype hydrodynamic separator. The result showed that the high vertical velocities within the device permit only particles with a high settling velocity to be removed, with the fine suspended solids (mostly organic) being passed forward for treatment in the WWTP.

Mathematical modeling efforts of Monroe County, N.Y. initially used in the 1970's for a CSO abatement program are being brought into use for current modeling applications in the 1990's (Matzat et al., 1998). The city of Columbus, Ohio conducted a study to upgrade a WPCP and the collection system which included WWF (Abdel-Latif et al., 1998). The comprehensive modeling approach optimized the capacity of the collection system and its relationship to the WPCP. The U.S. EPA and the Miami-Dade Water and Sewer Department in Fla. negotiated a consent decree settlement which required the installation and maintenance of a computerized collection and transmission system model. This model, the "Virtual Dynamic Computer Model" has the ability to predict potential SSO from peak flow conditions (Walch et al., 1998b). The system demonstrated its value in determining that \$20 million of proposed construction was unnecessary (Walch et al., 1998a).

A dynamic hydraulic model of the Baton Rouge, La. sanitary sewerage system was developed and calibrated against recorded flow and rainfall and a number of operational modifications and system augmentations were proposed to optimize the use of the tanks to reduce the frequency of SSO (Moody and Baldwin, 1998). Model construction included the development of Real Time Control (RTC) code to simulate the operation and performance of two major offline storage facilities during the recorded storm events. Three RTC simulations demonstrated that RTC provided an alternative to traditional approaches for handling WWF in separate sanitary sewers. The three simulations all met the specific constraints of the example sewer system, i.e., reduction in the number and volume of SSO without exceeding the existing pump station capacity at the drainage outlet (Pierce and Dillard, 1998). Costs for developing RTC for stormwater treatment range from \$0.055 to \$0.082 /L<sup>3</sup>yr (\$0.21 to \$0.31 /gal<sup>3</sup>yr) compared to the cost of building storage facilities for the equivalent CSO reduction which would cost between \$0.40 and \$0.53 /L<sup>3</sup>yr (\$1.50 and \$2.00 /gal<sup>3</sup>yr) (Agbodo and Nelson, 1998). Colas et al. (1998) presented the technological advances made in a five year R & D project in which methods, software and technology specifically designed for CSO control made RTC a more feasible and accessible solution.

Dorn and Miles (1997) developed a preliminary sanitary-sewer system improvement cost-estimating method by using the U.S. Army Corps of Engineers's Storage, Treatment, Overflow, Runoff Model (STORM) and U.S. EPA Needs Survey Database.

**Pond treatment.** XP-SWMM was used to evaluate the performance of a retention treatment facility in Oakland County, Michigan (Buchholz et al. 2000). The results showed the amount of storage that is necessary to reduce the number of overflow events by 30%. A two-dimensional, vertically averaged hydrodynamic model was adapted to predict the circulation and sedimentation patterns in stormwater detention ponds (Dewey et al. 2000). The performance of the model for a pond system in Toronto was presented. The Storage-Treatment block of SWMM was used to model the effectiveness of extended detention ponds (Newman et al. 2000b). The results showed much improved designs over using traditional methods. The Corrugated Steel Pipe Institute developed software for designing underground stormwater detention tanks (Finlay, 2000). Designers could use the program to quickly perform the calculations associated with the design of underground storage detention facilities. Analytical probabilistic models were applied to analyze the runoff quantity/quality control performance of various combinations of storage and treatment systems (Li and Adams 2000). These models provided closed-formed solutions of the performance equations that were efficient in both a conceptual and computational sense.

Ponce and Klabunde (1999) tested the feasibility of temporarily holding stormwater in parking lots by using a diffusion wave model of catchment dynamics. Four extreme storm types were applied to four typical parking lot sizes to assess the sensitivity of the resulting storm hydrograph to the choice of design slope. Results show the promise of parking lot storage in urban stormwater management. Ristenpart (1999) presented detailed information about a new stormwater management concept. Dimensioning and proof of performance of the different drainage structures was carried out with the help of an innovative rainfall-runoff model that was also briefly described.

Zheng and Baetz (1999) investigated a range of suburban development alternatives from an urban hydrology perspective. An analysis of design scenarios was conducted for a representative urban fringe development application, with the aid of a stormwater runoff simulation model (QUALHYMO) and geographical information systems software. In developing countries like India, the use of stormwater models for modeling and sizing detention basins has yet to acquire widespread application as a standard practice. Currently, design was carried out using the rational method, which was grossly inadequate, particularly as an abundance of sophisticated software was available. Gupta et al. (1999) described the application of Australian software, ILSAX, for modeling the onsite detention basins for the Central Hospital catchment of Jaipur City, India.

Baird and Rogers (1997) reported on a case study using SWMM to determine detention volumes for a series of wet-detention ponds to mitigate increased stormwater runoff due to new urban development in Williamson, Tex.

**Wetland treatment.** Constructed wetlands used for stormwater treatment accumulate metals primarily in their sediment, which has the potential to produce toxic effects in benthic or aquatic organisms. A system dynamics model was developed to represent these processes and the major influences affecting pore water metal activity in a treatment wetland receiving stormwater influent. Simulation results demonstrate that chemical processes of acid volatile sulfide (AVS) and organic carbon in binding metal in reduced sediments were the greatest influences in controlling metal bioavailability (Wood et al., 1999). The wetland model utilizes a hydrology model coupled to a hydraulic stream-routing model. A depth-averaged

laminar flow model was used to simulate the horizontal movement of stormwater both through and over the wetland sediments, a 400-ha first-order headwater swamp located within the Teeswater River watershed in southern Ontario, Canada. An analysis revealed that the simulated wetland streamflows were sensitive to the antecedent saturation of the wetland sediments, the storage and flow transport characteristics of the wetland sediments, and the conveyance capabilities of the wetland channel system (McKillop et al., 1999).

According to Moustafa (1999), long-term data collected at Boney Marsh, Florida and the EPA wetland database were analyzed to develop a simple tool that can be used to predict and optimize phosphorus retention in wetland treatment systems. Wetland properties such as water loading rate, water depth, P-loading rate, and water retention time were examined for their influence on phosphorus retention. The relationship between wetland properties and phosphorus removal efficiency was reduced to a simple quantitative diagram (The Phosphorus Removal Efficiency Diagram) a simple management tool that predicted expected treatment range using controllable hydrologic conditions.

A new concept, transport detention time, was proposed in this paper to describe solute-transport processes. Using this concept, a new mathematical model was developed to describe BOD<sub>5</sub> removal in constructed wetlands. By treating a constructed wetland as a series of continuous stir tank reactors, an n<sup>th</sup>-order ordinary differential equation was derived based on the principle of mass balance and convective-dispersive equation and by introducing transfer functions and Laplace transform (Chen et al., 1999).

Traver (1999) examined the calibration and performance of a hydrologic model in recreating recorded storm events from both the stormwater wetlands and the wetlands stream, and the nutrient removal effectiveness of the stormwater wetland basin.

Nnadi et al. (1999) compared the ability of various design storm distributions to simulate the actual rainfall pattern to the runoff rates used in the design of stormwater management devices in the State of Florida using continuous simulation. A new concept, transport detention time, was proposed in this paper to describe solute-transport processes. Using this concept, a new mathematical model was developed to describe biochemical oxygen demand removal in constructed wetlands. By treating a constructed wetland as a series of continuous stir tank reactors, an nth-order ordinary differential equation was derived based on the principle of mass balance and convective-dispersive equation and by introducing transfer function "Laplace transform" (Chen et al., 1999).

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**Infiltration/biofiltration control practices.** Munoz-Carpena et al. (1999) developed and field-tested a single event model for simulating the hydrology and sediment filtration in buffer strips. The model was developed by linking three submodels to describe the principal mechanisms found in natural buffers. They found that the performance of vegetative filter strips was governed by complex mechanisms and developed a model by linking three submodels to describe the principal mechanisms found in natural buffers: a Petrov-Galerkin finite element kinematic wave overland flow submodel, a modified Green-Ampt infiltration submodel, and the University of Kentucky sediment filtration model. A set of 27 natural runoff events (having rainfall amounts ranging from 0.003 to 0.03 m) from a North Carolina Piedmont site were used to test the hydrology component, and a subset of nine events were used to test the sediment trapping component. Good predictions were obtained with the model if shallow uniform sheet flow (no channelization) occurred within the grass filter.

Urban stormwater quality can be protected by maximizing the infiltration of frequent micro storms that account for the majority of the precipitation in urban areas. A proposed criterion was that the pre-development initial abstraction of precipitation should not be decreased by development. Heaney et al. (1999) used a linear programming model, which in turn uses information from the GIS as input data, to find the mix of functional land use types that minimizes the cost of retaining the initial abstraction at its pre-development level. To assist local governments in their efforts to develop more effective stormwater management programs, Prince George's County, Maryland Department of Environmental Resources in cooperation with the EPA developed a guidance manual for an innovative alternative comprehensive approach to stormwater management referred to as LID (Coffman et al., 1999).

**Best management practices.** A study of a physical model of the design of litter traps for urban storm sewers was carried out at the hydraulic laboratories at the Universities of Cape Town and Stellenbosch (Armitage and Rooseboom 2000). This study clearly showed why most designs fail and identified the use of declined screens as an approach that holds considerable promise. Low Impact Development (LID) is an innovative micro-scale runoff control strategy for WWF management issues based on the incorporation of distributed micro-scale Best Management Practices (BMP's) throughout the subcatchment (Wright et al. 2000). The potential and limitations of existing models to evaluate the effectiveness of this design approach were explored in this study. Numerical techniques for modeling overland flow from pavements were described (James and Wylie, 2000). The efficiencies of various approaches were reviewed and compared. The feasibility of a permeable pavement option in SWMM for long-term continuous modeling was explored by Kipkie and James (2000). The results indicated that it would be feasible but further testing would be needed

A two-phase decision-making software, DELTANOE, was used for the choice of BMP in urban stormwater drainage (Barraud et al., 1999). Two phases were described: (1) an elimination phase - to exclude solutions which were identified as unworkable according to site considerations and (2) a decision phase - to compare and at least to choose a scenario with feasible solutions.

According to Murphy and Lokey (1999) a model was developed to assess urban BMP efficiency on the total pollutant load using a simple spreadsheet and Monte-Carlo style simulator. The model suggests that many BMP used to comply with the National Pollutant Discharge Elimination System (NPDES) requirements appear to have little impact on the annual load. It might be argued that many BMP need to be evaluated at the source, not the receiving stream.

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A calibrated particulate transport model showed that high efficiency sweeping at weekly intervals combined with annual catchbasin cleaning provided removals approaching those of wet vaults for SS and associated pollutants, and possibly better than wet vaults for dissolved pollutants (Sutherland et al., 1998).

### **Real-time control.**

Kurahashi and Kawahara (2006) used optimal control theory and finite element methods to control water levels in a stormwater conduit system. Several papers examined real-time predictions of stream flows. Chang and Chen (2001) employed neural network and fuzzy arithmetic tools to enhance predictions for the Da-cha River, in central Taiwan. They (Chen et al., 2001b) also used the method to predict floods one hour in the future for the Chingshui River during tropical storms using the new models. Khu et al. (2001) and Soon et al. (2001) employed genetic programming to improve real time forecasting for the Orgeval catchment in France. They successfully improved the forecasting for future periods up to the time of concentration of the watershed. Their comparisons showed that genetic programming was a better updating tool for real-time flow forecasting than previous methods. Xiong et al. (2001) combined the simulation results from

different models to improve real-time forecasts.

Fuzzy logic models were used to do real time flow prediction for an urban catchment near Brussels, Belgium (Debede and Bauwens, 2000). A general method to design fast and stable mathematical models for the computation of sewer system outflow hydrographs were shown to be essential for real-time control of urban storm drainage systems (Hermann and Eberl 2000). The unknown inflow-outflow function was developed into a power series resulting in a nonlinear model. The new model formulation was tested with several urban subcatchments of a larger storm drainage network.

A real-time sensor fault detection method applicable to sewer networks was used to aid in real time control applications during wet weather (Piatyszek et al. 2000). This method consisted of comparing the sensor response with a forecast of this response provided by a model in the form of a state estimator called a Kalman filter. The Philadelphia Water Department investigated the application of real time control (RTC) to maximize the utilization of its existing combined sewer network facilities in its Southwest Drainage District (Vitasovic et al. 2000). A version of the SWMM EXTRAN routing model was compiled as a Microsoft Window Dynamic Link Library and included as part of the SewerCAT modeling environment to meet RTC requirements and exploit existing EXTRAN models of the system.

Despite considerable modeling efforts in recent years, a tool was still lacking which allows the simulation of sewer system, treatment plant and river as well as the analysis of real-time control (RTC) strategies using information from all parts of the urban wastewater system. Real-time-control (RTC) systems will be an integral part of future urban-stormwater-decision-support systems. Schutze et al. (1999) presented a software package for synchronous optimization and simulation of the urban wastewater system (SYNOPSIS) that integrated the simulation of the sewer system, treatment plant and receiving water and can be used for RTC. Marti et al. (1999) described an optimization procedure for RTC of a combined sewer system in the city of Barcelona, Spain. The control system involves measuring the variables at various points, collecting the data at the control center, processing and analyzing the data, and deciding on what actions should be taken by the actuators on the basis of the real time, self-calibrating hydraulic model. Moller et al. (1999) described a predictive urban drainage RTC system, which was based on a standard urban drainage modeling tool. The potential operational benefits associated with predictive RTC were illustrated through a test case. Reda and Beck (1999) studied the impacts of CSO on river water quality using the Multiple Continuously Stirred Tank Reactor (MCSTR) dynamic model. The potential for applying this model in a real-time context was demonstrated as a tool to support decisions regarding treatment plant operation during storm events, when it was often not possible to sustain full treatment of the incoming sewage flow.

The city of Barcelona, Spain has a 1,450 km-long combined sewer system with 10 pumping stations, 16 gates and 3 holding tanks. Marques et al. (1999) presented a remote control system that enables images obtained from a meteorological radar to predict current and future rain levels in the city of Barcelona, Spain. The received images were calibrated with the remote-controlled rain gauges in real time. Vazquez et al. (1999) examined the value of real-time management of a sewer system to reduce the impact of effluents and thus improve the quality of the host environment. The aim was to make better use of the storage capacities in the mains and tanks to reduce discharges into the environment. A multi-criteria optimization algorithm was used to provide control strategies for the components of the sewer system, e.g., sluices and pumps. Graph theory has been chosen as the mathematical tool. The study was applied to the sewer network of Saverne. Worm et al. (1999) used control strategies to equalize the hydraulic loading of a WWTP using a grey-box model of the sewer system that was based on correlation properties of flow, water level and pumping activity. The influent flow pattern showed fast transitions due to two major pumping stations in the sewer system that were operated by means of local control. By applying a stochastic flow model, calibration can be avoided since the parameters were estimated directly from the data. Hernebring et al. (1999) described the three Swedish pilot projects carried out as part of the Technology Validation Project "Integrated Wastewater" (1997-2000), supported by the European Commission.

The three Swedish projects were carried out in the cities of Helsingborg, Halmstad and Sundsvall. All three projects focus on the interaction between the sewer system and the wastewater treatment plant under variable operational conditions, created by the application of RTC in the sewer network. Pfister and Cassar (1999) described a research project that focuses on minimizing total emissions from sewer systems using RTC. The main goals of the study cover the optimum use of storage capacities, the best performance of the treatment plant, or by the dynamic management of the combined sewer system. The benefit of RTC increases if forecasted information of rainfall and runoff was taken into account. Cassar and Verworn (1999) described the upgrading of the existing hydrodynamic-rainfall-runoff model HYSTEM/EXTRAN and the decision finding model INTL for real time performance, their implementation on a network

of UNIX stations and the experiences from running them within an urban drainage real time control project. The main focus was not on what the models do but how they were put into action and made to run smoothly embedded in all the processes necessary in operational real time control.

A near real-time, stream-flow-simulation system utilizing continuous simulation rainfall-runoff generation with dynamic-wave routing is being developed by the U.S. Geological Survey (USGS) in cooperation with the Du Page County Department of Environmental Concerns for a 34-km reach of Salt Creek in Du Page County, Ill. (Ishii et al., 1998). The system is critical for more effective management of the Elmhurst Quarry Flood Control Facility, an offline stormwater diversion reservoir located along Salt Creek. A \$1.5 million Capital Improvement Project in the Lake City drainage basin in the northeast area of Seattle, Wash. was evaluated using XP-SWMM32. With an automatic calibration module the stormwater model showed that the system was reliable and took less time than the typical manual, trial and error approach (Ovbiebo and Kuch, 1998). Data collection and computer modeling identified deficiencies in a group of subbasins tributary to a treatment plant operated by Tulsa (Okla.) Metropolitan Utility Authority (Dillard et al., 1998). A model of Tulsa's major (>250 mm) gravity lines evaluated the system's ability to pass design flow. The Greater Vancouver Sewerage and Drainage District in Can. modified the Stormwater Management Model's (SWMM) RUNOFF block to improve simulation of WWF in sanitary sewers with the addition of an effective infiltration/inflow (I/I) area factor and improvements in tracking head differences between the groundwater stage and pipe tailwater level. Calibrated results were plus or minus 15% of measurements (Kadota and Djebbar, 1998). Tsihrintzis and Hamid (1998) examined the applicability of the SWMM RUNOFF block in small subtropical urban catchments with emphasis on parameters used to calibrate the model. Balascio et al. (1998) used genetic algorithm to calibrate the RUNOFF block of SWMM. The calibrated model was used to simulate two storms with good accuracy. Los Angeles, Calif. has a wastewater collection system that serves 3.5 million people in a 1 680 km<sup>2</sup> area. The existing wastewater collection system was modeled using MOUSE (Model of Urban Sewer Systems) for dry and wet weather conditions (Price and Gonzalez, 1998). SWMM and the Corps of Engineers' unsteady flow channel network model was applied to the Big Cypress Basin Watershed in southern Fla., an area of low relief and high water table conditions, with a complex network of drainage design (Walters et al., 1998).

Petruck *et al.* (1997) developed two real-time control (RTC) strategies. The first is a pollution-based RTC and the second is a water-quality based RTC (WBRTC); these strategies seek to improve the water quality of a stream by reducing CSO volume and pollution load. The Department of Hauts de Seine which covers more than 30 urban districts on the west side of Paris, Fr. has decided to implement RTC in order to confront the problem of CSO from its CSS by using the MOUSE computer model. Preliminary studies show it would allow an 80% annual reduction of the volumes of wastewater discharged into the Seine River (Entem *et al.*, 1997). Pfister (1997) outlined the need and use of an integrated approach to combine existing model components to optimize dynamic management of CSS and WWTP.

Schilling (1996) summarized the state-of-the-practice regarding the use of RTC including applications around the world. Nelen and Broks (1996) summarized RTC use in eight Netherlands' cities. Lavallée *et al.* (1996) reported 30-60% reduction in the volume and frequency of CSOs in Quebec City, PQ, Canada using RTC. Rauch and Harremoes (1996a, 1996b) described an RTC system that includes optimization using Genetic Algorithms. Schmitt (1996a) evaluated improvements in two German combined-sewer systems from using RTC. Volume reductions were 30% in one case and 9% in the other. Sirkin (1996) cautioned that RTC should only be used after determining some necessary, preliminary information for the stormwater system. Kjaer *et al.* (1996) described using MOUSE ONLINE, an extension of the Danish Hydraulic Institutes' MOUSE model, for RTC. MacArthur *et al.* (1996) described a computer-based system for conjunctive operation of the WWTP and stormwater controls in Monroe County in upstate New York that includes the City of Rochester. Cantrell *et al.* (1996) summarized an application of HydroWorks developed specifically to use with an existing RTC system in Lima, OH, an early RTC application in the United States. Miles *et al.* (1996) described methods and models for evaluating I/I problems associated with SSO.

### **Optimization models.**

Genetic algorithms for optimizing storm sewer networks were developed by Afshar (2006a). Nodal elevations of the sewer network were decision variables and the conventional roulette wheel selection scheme was used to used in the steady-state simulation.

Scholz (2005) reviewed the development of a BMP Decision Support Model to help optimize treatment and minimize flooding. Vogel et al. (2005) presented a distributed decision support system for watershed quality management. The model was then combined with a genetic algorithm and an economic model of stormwater treatment practices to

determine the optimal location of these stormwater treatment practices. The results indicated that the optimal location and number of stormwater treatment practices is a complex function of nutrient source locations, watershed network connectivity, land use, distance to channel and contributing area. Riverson et al. (2005) evaluated the functionality of a decision support system to optimize the placement of stormwater treatment practices in an urban watershed. The system evaluation addressed four aspects: robust platform for BMP selection/sizing/placement, applicability to urban and mixed-use watershed, computational strengths and weaknesses, ability to evaluate alternative solutions.

Martin and Legret (2005) presented the multi-criteria method ELECTRE III as it would apply to urban stormwater management. The method relies on an alternative ranking scheme, based on a partial performance aggregation approach. The results of an application showed that the evaluation of various strategies can help achieve consensus among stakeholders. Perez-Pedini et al. (2005) used a distributed hydrologic model to determine the optimal location of infiltration-based stormwater treatment practices in an urban watershed in the northeast United States. The infiltration-based BMP was conceptualized as an element that alters the infiltration/runoff partitioning coefficient of the area where it was applied.

Kanso et al. (2005c) outlined a methodology for comparing urban runoff quality models. The methodology is based on Bayesian theory. The methodology allowed for a quantitative assessment of the model parameters' uncertainties and their interaction. Mourad et al. (2005c) determined that the use of more complex models did not necessarily improve the modeling results since more problems and error sources were introduced.

Behera et al. (1999) present an optimization methodology for determining the design parameters (storage volume, release rate, and pond depth) of a single stormwater management pond. The methodology was extended, using a dynamic-programming procedure, to parallel catchments (each with a single detention pond). The least-cost values of pond design variables were subjected to system performance constraints, in the form of specified levels of runoff and pollution control at the outfall to a receiving water. Ndiritu and Daniell (1999) assessed the application of varying levels of optimization on model simulation performance and parameter identification using a genetic algorithm (GA) and a 10-parameter version of the MODHYDROLOG rainfall-runoff model. Four levels of optimization were obtained through the use of two GA formulations, the traditional and an improved GA, and by varying the optimization parameters with each formulation. It was proposed that the systematic verification of the adequacy of optimization should be an integral part of model calibration exercises.

Thomas et al. (1999) described the hydraulic verification of optimal control models that have been developed for large interceptor sewer systems. Both linear- and dynamic-programming models were tested using idealized interceptor sewers. The models include a simple hydraulic verification routine in which a quasi-steady approach was used to estimate interceptor sewer water profiles at each time step in the solution. Veltri and Pecora (1999) applied genetic techniques using data measured from an urban catchment to calibrate parameters from two well-known commercial modeling tools. These genetic techniques can be successfully applied to emulate a modelling environment and subsequently to calibrate indirectly the same model. Blanpain et al. (1999) described how stochastic search algorithms to be used to more fully explain the flows in a sewer network with incomplete information on its physical characteristics. The comparison, based on hydraulic simulations, showed that their method allows reduced flow and water depth deviations by at least 50%. Choi and Ball (1999) presented a decision support system for estimating optimum values of model control parameters. SWMM was used to simulate the runoff response of an urban catchment, while ARC/INFO and an optimization algorithm were employed to enhance spatial data handling and to optimise model control parameters.

Heaney et al. (1999) described a new method for optimizing the design of urban storm-sewer systems. The vertical alignment design problem was defined by a set of discrete pipe diameters and costs, excavation costs as a function of soil type, and a pre-defined horizontal arrangement of pipes and manholes for a gravity sewer. Genetic algorithms were used in place of classical techniques to arrive at the least-cost solution for a specified design storm. An example was presented to illustrate the technique. Use of mathematical models requires the estimation of model parameters. Parameter optimization was preferred to the trial and error visual comparison of observed and modelled output response, due to subjectivity and time-consuming nature of the latter approach. Dayaratne and Perera (1999) described an optimization procedure to estimate the model parameters of the urban stormwater drainage model called ILSAX. The problem of optimal water distribution to a range of retention reservoirs in an urban sewer network during rainfall events was overflows and its impact on receiving waters. A multilayer control structure consisting of an adaptation, an optimization, and a direct control layer, was proposed for the solution of this complex problem (Marinaki et al., 1999).

Pleau et al. (1998) proposed a tool to optimize long-term CSO plans which is linked to an hydraulic/hydrologic model in order to find the CSO plan that best suits the situation and reduces up to 30% of the cost of traditional approaches. A stochastic model based on physical mechanisms and formulated in continuous time to simulate water level and particulate COD at the overflow point of a Dutch combined sewer system was investigated (Grum, 1998). Preliminary results suggested that further work is needed in order to fully appreciate the method's potential and limitations in the field of urban runoff pollution modeling.

#### **Stochastic models.**

A stochastic state space approach to runoff modeling using radar data and flow measurements was described by Kramer et al. (2005). The model was demonstrated on the Emscher river basin, Germany, and highlighted the need to address the uncertainties in radar and flow measurements.

Lei et al. (1999) presented a new Stepwise Hypothesis Test Model Calibration (SHYTMC) procedure that includes explicit recognition of modeling uncertainty and system identifiability. Central in the SHYTMC procedure was the estimate of upper and lower bounds of the modeled output time series. A comparison with the result from 1,000 Monte-Carlo simulations suggests that the worst scenario approach was sufficient in the context of the SHYTMC procedure. Rauch et al. (1999) outlined the background of engineering analysis and applied the methodology to a probabilistic design problem concerning CSO reduction. The geometrical data used in stormwater models were hardly ever 100 percent correct and the process data like hydraulic roughness, overflow coefficients etc. were based upon accepted average values.

Clemens and von der Heide (1999) used Monte-Carlo simulation to evaluate the stochastic nature of this uncertain input data. The uncertainty or reliability of results produced by rainfall-runoff models was a function of uncertainties in model parameters, input data, and model structure. Hoybye and Rosbjerg (1999) presented a stochastic instantaneous unit hydrograph model describing the catchment as a single linear reservoir with input and transfer functions treated as random processes. Errors in runoff predictions caused by errors in input data and model parameters were analyzed by solving the governing stochastic differential equation (SDE) analytically, thus quantifying - in a general way - the error propagation structure and the relative importance of input errors and parameter errors. Data from 34 rainstorms were selected to verify the analytical SDE approach. Monte-Carlo simulation, an approach developed for incorporating the uncertainty of parameters for estimating runoff in the design of polder systems in ungaged watersheds, was used to derive a set of realizations of streamflow hydrographs for a given design rainstorm using the U.S. Soil Conservation Service (SCS) unit hydrograph model (Yulianti and Lence, 1999).

The Monte-Carlo simulation approach was demonstrated in an integrated setting involving models for rainfall characteristics, CSO (CSO) loads and impacts on the surface water DO. CSO loads were modeled using event lumped non-linear regression models with rainfall as input and with overflow volume, duration and relevant event mean concentrations as output; oxygen depletion in the surface water was described using a dynamic model including oxidation of dissolved COD and nitrification. The parameters of all the models were estimated from observed data on rainfall, CSO load and surface water impacts (Grum and Aalderink, 1999). A procedure was introduced for applying the statistical approach to water table management models such as DRAINMOD, a H/WQ model used to simulate lateral and deep seepage through the soil profile. In the evaluation procedure, probability distribution functions were developed for the most sensitive input parameters, output probability distribution functions were developed using Monte-Carlo simulation, and the output probability distribution functions were used to assess the model. DRAINMOD performed successfully in the evaluative procedure in predicting the runoff, subsurface drainage volume, and the water table depth fluctuations, which were expected to be most susceptible to input uncertainty (Sabbagh and Fox, 1999).

#### **Receiving water models.**

Croke (2006) proposed a technique for deriving an average-event unit hydrograph from streamflow data in an ephemeral catchment. The response curves in the stream showed a decay in flow after peak that can be described using a three-parameter function.

Salveti et al. (2006) investigated the Lombardy contribution to the Po River nutrient load using an integrated application of the QUAL-2E and the SWAT models. The source apportionment was investigated considering both dry and wet weather scenarios. Durieu et al. (2006) mapped discharges of stormwater and treated wastewater using remotely sensed data. Stormwater runoff was demonstrated to have a negligible impact on the decline of seagrass communities. Willems (2006) evaluated the current status of the integrated modeling of a combined sewer-treatment plant-river system and



found that the model was no more accurate than discharge concentrations from a frequency distribution for that outfall site.

The application of the HSP-F to an arid, urbanized watershed (in Southern California) was evaluated by Ackerman et al. (2005). HSPF was found to do well predicting flows following rain events, but was much poorer at predicting flows during extended dry-weather periods when the flows were dominated by human-induced activities.

Robinson et al. (2005a) outlined the steps required to model nutrient export in coastal California streams affected by a variety of land uses. The goal of the research was to create relationships between watershed parameters such as rainfall-runoff relationship and nitrate and soluble reactive phosphorus. Stretch and Mardon (2005) discussed a simplified model of pathogenic pollution for managing beaches. The model captures the key physical processes of mixing and dispersion. Daebel and Gujer (2005) described the uncertainty in modeling riverbed erosion caused by urban stormwater discharge. In this case, the greatest uncertainties occurred to the description of the natural system components. Daniil and Lazaridis (2005) presented an overview of the considerations required in new drainage design as a result of the initiatives to maintain natural stream flow and cross-sections. These considerations include the methods for calculating the peak discharge and the need to incorporate a greater factor of safety in drainage design calculations for hydraulics structures that cross the watercourse.

Assessing receiving water impacts from wet weather discharges can take discrete design storm or continuous simulation approaches, although long-term continuous analyses have been shown to be more informative and provide more appropriate designs. One problem with continuous simulation approaches is the lack of guidance for setting the duration of analysis. Naperala et al. (2004) presented a technique to select a typical period for modeling response of the Toledo waterways system to inputs from various control alternatives.

Arrington et al. (2004) reviewed the implementation of a thermal urban runoff model (TURM) to support a thermal control section of a recently enacted ordinance in Dane County, Wisconsin. Further development of the tool was identified as important to make it more general for application outside of the Dane County jurisdiction.

Baratti et al. (2003) investigated the use of neural networks to forecast river flows for reservoir management. The model used five parameters: two geomorphologic parameters for the drainage network identification; two kinematic parameters for the time scale of flood formation on hillslopes and in the channel network; and the last parameter accounting for the soil antecedent moisture conditions. Kokkonen et al. (2003) investigated regionalization approaches, or 'top-down,' to daily streamflow predictions. The factors controlling parameter variability were identified first within the entire region under study. Regionalization results revealed that considering the interrelations between dependent variables can improve performance of regression as a regionalization method. McCuen and Beighley (2003) performed a seasonal flow frequency analysis for the Eastern Coastal Plain since significant differences existed between the annual maximum and seasonal maximum discharges for various storm return periods. The ratio of measured instantaneous discharges above a threshold and the corresponding mean daily discharges was used to predict missing instantaneous discharges in seasonal records.

Patwardhan et al. (2003) reviewed several currently available stream sediment loading models where the input parameters were based on land use. The authors noted that few of the models could provide an estimate of sediment that is generated from the stream banks of the river channels and they presented a simple linked model that could be used to estimate both stream bank and watershed sediment loading.

Shen et al. (2003) presented an integrated watershed-tidal prism model system for fecal coliform transport in the Cockrell Creek watershed and its embayment. The results showed that the use of the linked watershed-tidal prism model approach was a cost-effective management tool for calculating capacity of fecal coliform loading in small coastal basins. Tsay et al. (2003) modeled the wet-weather impacts of fecal coliforms from both stormwater and CSO discharges to the Charles River in Boston, MA. CSO reductions and elimination of illicit connections to the sewer system have resulted in significant improvements both during the dry and wet weather conditions. Booker (2003) hydraulically modeled fish habitat in urban rivers during high flows. The model was a three-dimensional computational fluid dynamics (3D-CFD) model, SSIIM, that simulated hydraulic patterns in two urban river channels. The study concluded that integrating water quality issues and physical channel characteristics must be included in river rehabilitation schemes, as improvements to water quality alone may not be sufficient.

Byun et al. (2003) addressed methods for overcoming the obstacles to applying SWMM to large watersheds using the Schuylkill River as a demonstration. The suggested resolution included reducing simulation periods and external processing using SAS, which would overcome the decreased efficiency of modeling with SWMM at these scales.

Chavan et al. (2003) compared the Hydrologic Simulation Program – Fortran (HSPF) and the Watershed Analysis Risk Management Framework (WARMF) for Steamboat Creek (CO) to assess WARMF's applicability to TMDL studies. Calibration results for WARMF followed the year-to-year and seasonal trends reasonably well for all constituents but underestimated TN, TP, TDS and TSS during storm events. Donigan and Love (2003) reviewed sediment calibration procedures and guidelines for watershed modeling as part of an overall watershed model calibration, using both graphical and statistical measures, and was based on recent experience with HSPF. Model parameterization and calibration procedures were demonstrated using the recommended graphical and statistical procedures to assess model performance for sediment loadings, concentrations, and budgets within a watershed modeling framework.

Conrads et al. (2003) developed an empirical ANN model of a complex, tidally affected river (Beaufort River, SC) as part of its TMDL development. The empirical model used data mining techniques to quantify the relations between the time series of three wastewater point-source discharges and the dissolved-oxygen concentrations recorded at seven real-time gages distributed throughout the system.

Kellershohn and Tsanis (1999) used WASP to create a three-dimensional eutrophication model for Hamilton Harbor, Ontario, Canada. Four remedial options, namely improvements to the WWTP, the CSO, industrial discharges, and removal of WWTP, CSO, and industrial discharges were examined. Improvements in the harbor's water quality were found to range from minor in the case of CSO improvements to significant in the case of WWTP improvements. Lung and Sobock (1999) demonstrated that modeling continues to be the most cost-effective method of water quality planning and that water resource managers should apply water quality modeling on a regular basis to support the present and future needs of the watershed. They indicated that there was a need for increased use of water quality models to review the assimilative capacity of the receiving water for regulatory control and water quality management. Petruck et al. (1999) described the water quality simulation model FGSM, developed by the German Association for Water Pollution Control (ATV) to simulate major water quality parameters of a small urban stream. The FGSM appeared to be a valuable tool for assessing not only the chronic, but also the acute effects of combined sewage overflow events.

Walker and Stedinger (1999) described the movement and fate of pathogens from wastewater and dairy sources and the resulting raw water quality for New York City, New York. Manure and *Cryptosporidium* oocysts were modeled as surface pollutants and assumed to move in response to runoff events in the six watershed-reservoir systems within the Catskill-Delaware watershed. This research highlights the importance of wastewater-derived oocysts, the need for expanded research into oocyst fate in streams and reservoirs, and the concentration of oocysts in sewage effluent. Fitzpatrick et al. (1999) presented an overview of the development and application of a time-variable nutrient based emergent macrophyte model to a southern Florida Everglades wetlands system. The model formulation included the effects of nutrient concentrations on sawgrass and cattail plant growth, nutrient uptake, and nutrient composition.

Three-dimensional simulations of estuarine circulation in the New York Harbor complex, Long Island Sound, and the New York Bight were conducted using the Estuarine, Coastal, and Ocean Model (ECOM) within the framework of a single grid system (Blumberg et al. 1999). The model forcing functions consist of (1) meteorological data; (2) water level elevation and temperature and salinity fields along the open boundary; and (3) freshwater inflows from 30 rivers, 110 wastewater treatment plants, and 268 point sources from CSO and surface runoff.

Hsu et al. (1999) described a flood and inundation forecasting model to be used for flood damage mitigation. The simulated results from the river flood model and the cell inundation model were used to calculate the flow exchanges between the river and inundation area. The results were accurate enough to be used to simulate the water stage in the river and map out the inundation area for the various design rainfalls. Huberlant et al. (1999) described the Urban Pollution Management Procedure that was developed to address the problem of protecting rivers from urban stress in a holistic and cost effective way. The procedure allowed river systems to be modeled, with input from sewer overflows and sewage treatment works discharges, to enable assessment of minimum cost solutions. With the support of the European Commission, five pilot studies were carried out in different countries to test and demonstrate the effectiveness of this approach.

The responses of ADAPT, a daily water table management simulation model, to variations in the principal input

parameters which define hydrologic response units on a watershed were evaluated (Gowda et al., 1999).

Shanahan et al. (1998) found that QUAL2E was best suited for point-source discharges and was limited when examining the contribution of NPS pollutants to river-quality degradation. The combination of models that describe the dynamic behavior of the sewer system, the WPCP and receiving water for the assessment of water pollution gives rise to a complexity far beyond what is needed (Rauch et al., 1998). Simplifications are possible because only a few types of wastewater discharge impacts typically affect the ecological state of the receiving water. Pitt (1998) described the Source Loading and Management Model (SLAMM), and gave an brief overview of its history, as well as its unique attributes and its value in determining the relationships between sources of urban runoff pollutants and runoff quality.

### **Watershed evaluations**

Zhang et al. (2006) studied urban water reuse management modeling. A case study approach was used to demonstrate the modeling process and analyze the impact of uncertainties.

Digital elevation modeling (DEM) was used by Su et al. (2005) to perform a hydrological analysis of an urban area. Moore et al. (2005) provided an overview of the review of hydrologic, water quality and stream models, as well as GIS interface programs, which could be used to develop a watershed management plan. HEC-RAS, SWMM-RUNOFF and SWMM-TRANSPORT were selected as the watershed modeling techniques and procedures were added to model the benefits of detention ponds and other, on-site stormwater treatment practices.

Beighley (2005) presented the methodology being used in Southern California to improve flood frequency prediction in urban watersheds. HEC-HMS was used to model the watersheds and the parameters most sensitive to the modeling in this region are determined. Perrelli et al. (2005) reviewed the calibration of BASINS HSP-F to support a watershed approach to long-term CSO control in Buffalo, New York. The model predicted well sediment erosion and transport in the upper watershed but could not effectively represent the sediment deposition processes in the hydraulically complex, dredged lower channel. Stefanov and Netzband (2005) assessed the ASTER land cover and MODIS NDVI data at multiple scale to characterize the ecology of an arid urban center. The combined measurements were useful in modeling changes to urban climate, hydrologic and biogeochemical cycling caused by landscape modification. Stein and Teifenthaler (2005) examined the dry-season metals and bacteria loading in Ballona Creek (California) – an arid, urban watershed. The results showed that a relatively small number of drains delivered the majority of the pollutant loads.

Moll (2005) introduced the use of CITYgreen software as a means of calculating the value of nature. The software was developed by American Forests and incorporates TR-55 as its hydrologic model.

Being able to predict the impacts of land use change is critical for water resources planning at the watershed and regional scale. Ott and Uhlenbrook (2004) used a process-based catchment model (TAC<sup>D</sup> (tracer aided catchment model, distributed)) to analyze two land use scenarios for a watershed. The simulations predicted little effect of the land use change scenarios on modeled single rainfall-runoff events or the annual water balance. Significant local effects of land use change on flood flow and water quality were demonstrated. Simulating the effects of land use change depends on the accurate prediction of the land use change. Wiley et al. (2004) demonstrated an approach with neural network based landscape change prediction coupled with river valley segment classification. In addition to these two components, other models including MODFLOW, HEC-HMS, GWLF, and a number of regional biological assessment models have been linked within the Muskegon River Ecological Modeling System (MREMS). The framework provided a means to integrate modeling and risk assessment across large-scale river ecosystems by predicting future landscapes and then evaluating likely changes in hydrology, chemistry, and biological integrity/productivity in a spatially explicit framework. Expanding watershed modeling studies to include analyses of effects of hydrologic changes caused by urbanization, water use, agriculture, climate change, and more, Galbraith et al. (2004) described the incorporation of HSI models into a framework combining climate, hydrology, and vegetation modeling to predict the effects and risks associated with riparian wildlife habitat exposed to multiple stressors.

Myers et al. (2004) presented a case study evaluation of a comprehensive watershed planning program in southeastern Pennsylvania aimed at regaining resources in and around streams lost during urbanization. The authors discussed the regulatory complexity of the program and reviewed a case study for one watershed highlighting the implementation of the watershed planning program at the local level.

Assigning parameters representing watershed characteristics in hydrologic models is a time consuming task, especially if

there are many modeling units (e.g., subcatchments, grid cells, etc.). Hundedeha and Bardossy (2004) described a regionalization approach to calibrate a watershed model by associating the model parameters with the physical catchment characteristics. The model parameter dataset determined through optimization was used to simulate the hydrologic effects of different land use scenarios. Altered land use was found to increase lower peak runoffs during summer months, but did not have much of an effect on higher peak runoffs during winter months. Koren et al. (2004) introduced the National Weather Service Hydrology Laboratory Research Modeling System (HL-RMS), a model combining physically-based modeling with conceptual model features. The approach makes the model parameterization more practical and facilitates a transition from current lumped based approaches to distributed systems. The HL-RMS was tested and compared with results from lumped simulations and found to improve the accuracy and resolution.

Lamb and Kay (2004) presented an analysis of the uncertainty of a generalized conceptual rainfall-runoff model. The continuous rainfall-runoff model was generalized by relating model input parameters to spatial catchment properties (e.g., soils, topography, and geology) permitting application to ungauged sites if basic site information is available. Comparison of results from this modeling approach to observations lends confidence to the technique. Montanari and Brath (2004) described an approach to quantify the uncertainty of rainfall-runoff predictions. A meta-Gaussian approach was implemented in a distributed model to estimate the probability distribution of the model error conditioned by the simulated river flow. The derivation of confidence limits of simulated river flows was demonstrated.

Males et al. (2004) compiled regional hydrologic information and created a regional hydrologic model for the City of Tshwane in South Africa. The data and modeling system were used to develop integrated catchment management plans for present and future land use scenarios. An analysis of census, climate, land use, and runoff data by Morgan et al. (2004) suggested the runoff ratio increased significantly over time. But other derived hydrological indices and climate variables did not. The authors suggested the lack of evidence of hydrologic impacts may be due to threshold-dominated dynamics of watershed behavior. Pfister et al. (2004) reviewed the interaction of climate change, land use change, and runoff in the Rhine-Meuse basins. The authors highlighted the importance of land use change at the local level in small headwater watersheds, but did not find evidence of large scale impacts on the Rhine and Meuse due to urbanization. Changes in extreme precipitation were found to be more important for mesoscale basins.

Lopes and Canfield (2004) investigated the effects of watershed geometric representation on runoff and sediment yield. A small watershed was represented using four levels of complexity (e.g., number of channel segments) and simulations were performed using the spatially distributed runoff erosion model KINEROS2. Oversimplified representations were found to significantly influence runoff and sediment predictions, but less complex representations were noted to have less of an impact on runoff and sediment yield predictions for small storm events.

Representing the temporal and spatial distribution of rainfall in runoff is critical for applications to watersheds greater than a few square kilometers. Moon et al. (2004b) evaluated the use of radar rainfall estimates in the distributed parameter watershed model SWAT. NEXRAD rainfall inputs were first compared to rain gauge values and then input to the model of a case study watershed. The results suggested the use of NEXRAD data can be an improvement over using rain gauge data for several types of watershed modeling applications. Moon et al. (2004a) presented a model composed of rectangular pulse Poisson process model for rainfall, the SCS curve number method for infiltration, and the geomorphoclimatic instantaneous unit hydrograph for runoff estimation. The ability to quantify the storm coverage was incorporated into the modeling framework and shown to be an important aspect to simulate rainfall-runoff.

Lin et al. (2004) linked SWMM and the Two-Dimensional Inundation Model (2DIM) to simulate inundation in urban environments. In the model linkage interactions between surcharge and discharge of the manholes were considered dynamically. The modeling framework was applied to a small area in Taipei City and suggested the dynamic interaction between surcharge and discharge from manholes was critical to accurately represent flood stage. The limitations of one dimensional urban flood modeling were reviewed by Mark et al. (2004). Similar to the conclusions from Lin et al. (2004) the hydrodynamic modeling of the interactions between the buried pipe system and the streets via the manholes was noted to be critical to predict accurate water stage depths. Schmitt et al. (2004) also stressed the need for dual drainage modeling frameworks to simulate surface flow and pipe flow and the interaction between the two. They describe a dual drainage modeling framework in the context of integrated planning and management of urban drainage systems incorporating industrial mathematicians, water engineers, municipal drainage engineers, and an insurance company.

As the spatial and temporal resolution improves, remote sensing data continue to be integrated into urban hydrologic studies and have proven useful for water resources decision making. Sokol et al. (2004) discussed the use of C-band

multipolarized radar and polarimetric SAR for soil moisture, snow, wetlands, and flooding hydrological applications.

One of the more common uses of remote sensing data in urban hydrologic modeling is to estimate land cover and impervious surfaces. Impervious surfaces are even being used as a surrogate for water quality. Reilly et al. (2004) presented a statistical planning model to estimate future impervious surface given minimal information about future growth. Correa et al. (2004) reviewed aerial photos and satellite imagery as options to estimate impervious surface cover for use in urban hydrologic models. The results suggested model results can be made more accurate using remote sensing data to classify impervious surfaces for different development patterns, building densities, and varying amounts of vegetation.

Beduhn et al. (2003) reviewed a physically-based urban stormwater model for a Minnesota watershed with land-locked basins. Fitzpatrick et al. (2003) used mathematical models to evaluate strategies to meet water quality standards in a heavily urbanized tidal bay (Jamaica Bay, NY). The authors presented an overview of the anthropogenic changes in the bay, the field-monitoring efforts, the model's calibration and development, and the model's results from various management alternatives.

Christensen et al. (2003) modeled (using statistical and dynamic water quality models) fecal coliforms in Papillion Creek (NE) to determine the extent of fecal coliform pollution and the potential control stormwater treatment practices. Results indicated that fecal coliforms were dependent on sediment transport, urbanized areas contribute significantly to fecal coliform loads, and comprehensive stormwater treatment practices to control sediment, nutrients and bacteria would be needed. Garvey et al. (2003) discussed the parameters for evaluating and selecting models for TMDL development as applied to Steamboat Creek (NV). An approach to selecting appropriate watershed modeling tools, identifying important considerations and potential pitfalls of model selection, were presented.

Medina et al. (2003) presented the Low Impact Feasibility Model (LIFE™). This model was designed based on hydrologic principles in order to evaluate a wide range of LID-related applications, including site design, analysis and review, watershed planning and public education.

Donigian (2002) discussed watershed model calibration and validation drawing from more than 20 years experience with HSPF. Ackerman and Schiff (2002) developed and calibrated an HSPF model for the Santa Monica Bay watershed. Model development was based on detailed land use and stream geometry and calibration was based on rainfall and runoff data from 1988 to 1998 and stormwater quality data from 1993 to 1998. Model validation indicated that predicted bacteria levels were reasonably comparable to observed data. Love and Donigian (2002) presented a statewide watershed model for Connecticut to help identify all key sources of nutrients to the Long Island Sound using the U.S. EPA Hydrological Simulation Program – FORTRAN (HSPF) and the U.S. Geological Survey's (USGS) graphical user interface GenScn. Effectiveness of three nonpoint source BMP implementation scenarios were evaluated and simulated for buildout conditions by year 2020. HSPF was also applied to simulate the Chesapeake Bay watershed by Shenk et al. (2002). They developed an intermediate processor between the land and water simulations to represent the changes in management practices and land use that may affect the pollutant export from the land surface and the pollutant transport in streams. Wang et al. (2002) are developing an watershed model using HSPF for the Sinclair Inlet and Dyes Inlet drainage basins. To better understand the relationship between rainfall and freshwater inflows to the Inlets an Artificial Neural Network (ANN) was developed. The feedforward ANN was trained using concurrent rainfall and creekflow data. Comparisons between the ANN and the HSPF model showed the two models had similar accuracy levels for predicting rainfall-runoff entering the Inlets.

Luzio et al. (2002) modified the BASINS modeling system by incorporating a tool that optimizes the automatic definition and segmentation of the watershed and stream network based on topography and the National Hydrography Dataset or other stream data, a tool that defines the Hydrologic Response Units (HRUs) over the watershed and subwatersheds, and the SWAT model. The enhanced BASINS system was demonstrated with an application to the Upper North Bosque River watershed in Texas. The Watershed Characterization System (WCS) was originally developed for the EPA Region 4 to facilitate physical characterization of watersheds, evaluate water quality conditions, and to assess potential sources of impairment using spatial databases and GIS technology. Greenfield et al. (2002) described the updating of the WCS to include erosion and sediment delivery models, a mercury loading model, and SWMM and NPSM GIS interfaces.

Samuels et al. (2002) developed a GIS-based tool to calculate the time of travel, decay, and dispersion of a pollutant introduced into surface waters. Ponnambalam et al. (2002) demonstrated a GIS-based multi-criteria evaluation decision-

making tool for use in wetlands management. Mohamed and Plante (2002) stressed the need for geospatial information technologies in developing countries to support sustainable development. Donigan and Love (2002) reviewed the Connecticut Watershed Model (CTWM). The interface and framework of the CTWM was specifically designed to promote continuing use by CT DEP staff to assess multiple stormwater treatment practices, implementation levels, and relative impacts of point source controls for nutrient reductions to Long Island Sound. The paper presented procedures and results of using the CTWM to evaluate the loading impacts of alternative future growth conditions, and mitigative impact of stormwater treatment practices for reducing nutrient loads to LIS.

Jia et al. (2001) developed a distributed hydrological model, the Water and Energy Transfer Processes Model (WEP), to simulate spatially variable water and energy processes in watersheds having complex land covers. Variables include depression storage on land surfaces and canopies, soil moisture content, land surface temperature, groundwater tables, and water stages in rivers. Infiltration excess during heavy rains is simulated using a generalized Green-Ampt model, while flow routing is simulated using a one-dimensional kinematic wave method. The model was applied to the Ebi River watershed (27 km<sup>2</sup>) with a grid size of 50 m and a time step of 1 h. The model was verified through comparisons of simulated river discharges, groundwater levels, and land surface temperatures with the observed values. A comparison between the water balances at the present time and in the future was also conducted. It was found that the hydrological cycle in the future can be improved through the use of stormwater infiltration. Santini et al. (2001) modeled the Detroit Water & Sewerage Department collection system to identify flow sources. They also modeled the time needed to return to base flow conditions after wet weather events.

A methodology was developed by the Greater Vancouver Sewerage & Drainage District to estimate future percent total impervious area using population density (Hicks et al. 2000). Percent total impervious area has been found to be an indicator of watershed health, therefore, it would be beneficial if future imperviousness could be forecast based on population growth and land use estimates. The value of benefit-cost evaluation for stormwater quality management decisions at a local level was explored using a benefit-cost analysis (BCA) screening method (Kalman et al. 2000). Ballona Creek, a major urban storm drain in Los Angeles, was used to illustrate the practicality of the benefit-cost evaluation.

The Object Watershed Link Simulation (OWLS) model was developed and used to simulate the hydrological processes within the BBWM. The OWLS model was a 3-dimensional, vector-based, visualized, physically-based, distributed watershed hydrologic model. Simulation results provided a close examination of hydrologic processes of flow separations and Variable Source Areas (Chen and Beschta, 1999). Watershed areas that generate NPS polluted runoff need to be identified prior to the design of basinwide water projects. The model TOPLATS simulates variable source area (VSA) hydrology and therefore provides an improvement to the current generation of NPS models for locating potential NPS-loading areas (Endreny and Wood, 1999). The HSPF has been calibrated for a sub-watershed of the Upper Roanoke River system. The model will provide inputs needed by other components of the study in describing environmental impacts of urbanization (Lohani et al., 1999).

Kornecki et al. (1999) evaluated the Spatially Integrated Models for Phosphorus Loading and Erosion (SIMPLE) for predicting runoff volume, sediment loss, and phosphorus loading from two watersheds. SIMPLE tended to underestimate runoff volumes during the dormant period, from November to March. Results of model evaluation indicated that SIMPLE's predictive ability was acceptable for screening applications but not for site-specific quantitative predictions. Schwartz and Naiman (1999) derived the mean and variance of planning level load estimators under mild parametric assumptions and using a distribution free approximation. Common use of the mean, median, or geometric mean of event concentrations was shown to result, in general, in biased estimates of the mean annual load. Substantive implications for regional assessments, planning, and watershed management were illustrated with a simple example drawn from Chesapeake Bay, Maryland. Alex et al. (1999) described a system of numerical models (PLASKI, SIMBA sewer and SIMBA) for simulation of wastewater production, transport and treatment, respectively. The three modules were all running under MATLAB/SIMULINK and allow integrated simulation of processes in all three-system components.

The Hydrologic Simulation Program Fortran (HSPF) has been calibrated for a sub-watershed of the Upper Roanoke River system. The model would provide inputs needed by other components of the study in describing environmental impacts of urbanization (Lohani et al., 1999). SWMM was applied to study stream-water quality due to diffuse sources on a 14.25 km<sup>2</sup> watershed in Castro Valley, Calif. The simulation was performed over a two-year period for flowrate, Cu, Pb, and SS (Khan *et al.*, 1997).

The responses of ADAPT, a daily water-table management simulation model, to variations in the principal input parameters which define hydrologic response units on a watershed was evaluated (Gowda et al., 1999). Simulated agricultural runoff amended with sediment, nitrogen, and phosphorus, was passed through an experimental sedimentation basin. A series of six sequential runoff events was run through the basin for each of two treatments. The treatments consisted of one-day and three-day detention times, created using a perforated riser outlet structure (Edwards et al., 1999). Most hydrologic/water quality (H/WQ) models that use rainfall as input assume spatial homogeneity of rainfall. Under this assumption this study assesses the variability induced in calibrated model parameters solely due to rainfall spatial variability. A large uncertainty in estimated model parameters can be expected if detailed variations in the input rainfall were not taken into account (Chaubey et al., 1999).

The UP (Upscaled Physically-based) hydrological modeling system to the Arkansas-Red River basin, United States was designed for macroscale simulations of land surface processes, and aims for a physical basis and, avoids the use of discharge records in the direct calibration of parameters. This was achieved in a two stage process: in the first stage parameterizations were derived from detailed modeling of selected representative small catchments and then used in a second stage in which a simple distributed model was used to simulate the dynamic behavior of the whole basin. Outputs from the model were discussed, and include river discharge at gauging stations and space-time fields of evaporation and soil moisture (Kilsby et al., 1999). The UP modeling system has been applied to the 570,000 km<sup>2</sup> Arkansas-Red River Basin (ARRB) as part of the UK NERC Terrestrial Initiative in Global Environmental Research (TIGER). The parameters of the ARRB model were physically-based, being derived either from fine-scale, sub-grid, data on the topography and physical properties of the soils, aquifers and vegetation of the basin, or from the results of fine-scale physically-based simulations. The ARRB model, as described here was a first attempt at large-scale physically-based hydrological modeling of the type outlined in the 'blueprint' for the UP system, and gives a clear, positive, indication of the nature and quality of what was currently practical with the approach (Ewen et al., 1999).

A physically-based model was used to simulate runoff in agricultural watersheds with tile drainage systems. The TOPMODEL, which was based on the detailed topographical information provided by a digital elevation model (DEM), was modified for this simulation study. The simulated hydrologic response was designed to produce several components of the outflow hydrograph which were associated with the various possible flow generation scenarios (Kim et al., 1999).

The geomorphic characteristics of an ungauged watershed were analyzed using a digital elevation model and were used to construct a runoff simulation model. A design storm was applied to the geomorphic runoff simulation model to obtain the design hydrograph (Lee, 1998). The time of concentration for a plane with urbanization from downstream to upstream could be more than four times longer than that for a plane with urbanization from upstream to downstream (Wong and Li, 1998). A physically based, distributed model, applied to a small urban watershed in Japan with an area of 66.18 ha provided a reasonable interpretation of the overall runoff and pollutant generation process in urban areas (Haiping and Yamada, 1998). Motivated by planning and rehabilitation of stormwater overflow tanks in municipal drainage systems, Haberlandt (1998) presented a simple stochastic model with spatially interpolated parameters for the synthesis of short-time increment precipitation at ungauged points. A hydrological model, based on a semi-distributed parameter, was coupled to a simple pollution transport model to analyze the alternative solutions for reduction of CSO from an urban catchment to the river Nidelva in Trondheim, Nor. (Milina, 1998). A watershed management model predicted monthly and annual water yields in two watersheds based on hydrological, geological and land use data. A subwatershed exhibited the same hydrologic behavior as the main watershed (Fuentes and Ribiero-Matos, 1998). Snowmelt Runoff Model (SRM) streamflow predictions for 1990, 1993, and 1994 seasons for the Towanda Creek basin, Pa., using a combination of elevation and land-use zones yielded more precise streamflow estimates than the use of standard elevation zones alone (Mitchell and DeWalle, 1998). The use of multiple-parameter zones was best in non rain-on-snow conditions where snowmelt was primarily driven by differences in solar radiation.

A modeling effort conducted in the Duwamish Estuary and Elliott Bay in King County, Wash. which used the 3-dimensional Environmental Fluid Dynamics Computer Code for a human and aquatic risk assessment compared potential exposure to humans, plants and animals from CSO pollutants and other sources (Schock et al., 1998). A model that described the spatial structure of hydraulic conductivity was developed using stochastic techniques and was then incorporated in the Green-Ampt and Mein-Larson infiltration models. Results showed the combined model was capable of representing the instantaneous infiltration process for spatially-variable soils under field conditions (Gupta et al., 1998). The Watershed Nutrient Transport and Transformation (NTT-Watershed) model was used to investigate the fate and transport of N in the Muddy Brook watershed in Conn. (Heng and Nikolaidis, 1998). The model captured the hydrologic and part of the N dynamics in the watershed.

### ***Watershed Management and TMDLs***

A Decision Support System for urban water management was developed and presented by Barros et al. (2005b). The system combines simulation models for hydrology, hydraulics and water quality. Baptista et al. (2005) proposed a design aid methodology (and associated software) for the evaluation and comparison of drainage scenarios using stormwater treatment practices. A review of the models currently in use in Australia for water balance calculations was reviewed by Boughton (2005). The delineation of the karst groundwater basin in Bowling Green, Kentucky was presented by Crawford (2005). This mapping was prepared to assist the City with meeting its NPDES Phase II Stormwater Management requirements.

During the TMDL development process for Charleston Harbor (South Carolina), limitations were established for nutrients and oxygen-demand (Lu et al. 2005). Investigations into the sources of these pollutants found a positive correlation between nitrates and DO to urban and forested land use.

Modeling plays an integral role in developing and implementing TMDLs. Bierman et al. (2004) introduced a simplified fate and transport modeling approach for PCBs that avoids the complexities of explicit representation of sediment transport, primary production, or sediment digenesis. The modeling approach was implemented using a modified version of WASP5/TOXI5 and demonstrated the utility of a simplified mass balance modeling approach. Kehrberger et al. (2004) provided an overview of the Passaic River Basin nutrient TMDL. Issues discussed included program structure, sampling, data analysis, and modeling. Collins (2004) reviewed the incorporation of TMDL load reductions into the Anchorage, Alaska MS4 permit.

Russell et al. (2003) presented an economical methodology for conducting TMDLs with a limited budget and short time frame. The first step quantified loads at complex sites, including methods for estimating loads attributable to sources that are less straightforward to quantify. Second, a mass balance for the system was performed. Finally, the conceptual model of the system would be 'sketched'.

Rivard et al. (2003) reviewed the historical development of floodplain and stormwater management techniques and then focused on an integration of the two activities for a case study for the City of Saint-Constant (near Montreal, Canada). Ruiter and Schwer (2003) discussed the problems faced by States, Tribes, EPA and Interstate Agencies as they develop TMDLs for waterbodies where extremely stringent water quality standards, complex hydrodynamic and pollutant loading situations, data limitations, and very uncertain implementation approaches exist. An example of this type of difficult TMDL development effort is the TMDL for PCBs that the Delaware River Basin Commission is currently developing for the States of New Jersey, Pennsylvania and Delaware in the Delaware Estuary.

Jagals and Griesel (2003) investigated the impact of urban discharges on the microbiological quality of untreated surface water with the goal of addressing the impact that watershed management has on the control of microbiological water quality. Kieser et al. (2003) reviewed the role of urban stormwater treatment practices in temperature TMDLs. Temperatures were not reduced in the more traditional two-stage treatment process (i.e., forebay and wet detention). The enhanced natural wetland accounted for most of the thermal load and temperature reductions with its dense canopy coverage and higher infiltration rate.

Wagner and Corbin (2003) presented several approaches for determining appropriate nutrient targets in TMDL development for lakes. Comparison of levels achievable by stormwater treatment practices with loads derived from either conversion of narrative standards or relationships between nutrients and targeted conditions (e.g., chlorophyll, Secchi transparency) was useful.

Halliwell et al. (2003) reviewed the evolution of Maine's TMDLs and phosphorus-control action plans for state lakes. Recommendations included using simplified quantified phosphorus load modeling results (direct and indirect external watershed, internal lake bottom sediment, lake assimilative capacity, and loads allocated for future development) for public comprehension. Actions included enhancing the use of specified lake/watershed NPS/stormwater treatment practices to control soil erosion. Rangarajan et al. (2003) presented the technical study used to assist NY State Department of Environmental Conservation in developing and implementing a pathogen TMDL to support shellfish harvesting. SWMM was used to characterize MNC's urban watershed and to assess the hydrologic/hydraulic model parameters using the United States Geological Survey (USGS) flow data in MNC. Calamita and Pomeroy (2003) presented the process for meaningfully refining designated uses in advance of TMDL development, especially as focused on the ongoing work on the Chesapeake Bay Use Attainability Analysis, an initiative beginning on the Ohio River, as



well as several other local case studies.

Baughman et al. (2003) reviewed the activities of the Metropolitan North Georgia Water Planning District in their development and implementation of their watershed management plan, which was designed to support TMDL implementation. A process for inter-jurisdictional cooperation was recommended in the Watershed Management Plan. Osidele et al. (2003) presented an uncertainty evaluation of sediment loading and transport in the Chattahoochee River in Atlanta, GA. Preliminary studies indicated that three uncertain factors influenced sediment behavior in the Chattahoochee River as it passes through Atlanta: (1) reservoir operations at the upstream Buford Dam; (2) watershed loading; and (3) in-stream scour and deposition. Turner et al. (2003) demonstrated the community approach used in the Middle Chattahoochee River watershed to develop and manage TMDLs. The area was used to demonstrate innovative stormwater technologies to restore urban waterways. The four demonstration projects were implemented to represent “further reasonable progress” which is the basis of an adaptive management to the TMDL regulatory process. Costs and benefits will be used to determine the future iterations of the adaptive management TMDL process.

Akridge et al. (2003) summarized Jefferson County/Louisville’s (KY) comprehensive watershed/CSO management program and demonstrated how it is becoming one of the nation’s leading model programs. The management program has steadily implemented an integrated water-quality-based program for prioritizing wet weather activities. Jarrett et al. (2003) reviewed the development of pathogen and dissolved oxygen TMDLs for the sewer district and the modeling efforts required to support the development of pathogen and dissolved oxygen TMDLs. The modeling approach included the development of the Beargrass Creek Water Quality Model (BCWQM). The paper described the development and calibration of the HSPF portion of the BCWQM and the expected refinements to support the TMDLs.

Rifai et al. (2003) reviewed the development of an urban indicator bacteria TMDL for Whiteoak and Buffalo Bayous in Houston, TX. Preliminary modeling results indicated that non-point sources contribute a large portion of the in-stream loading observed in Buffalo and Whiteoak Bayous. The mechanisms maintaining elevated low flow *E. coli* concentrations were shown to be different than the mechanisms acting under high flow conditions. Vargas et al. (2003) reviewed the use of bacterial source tracking (BST) to support TMDL implementation in the Middle Rio Grande watershed. BST was able to provide stakeholders with long-term planning tool and an implementation plan guide for collaboration among local, tribal, regional, state, and federal organizations and agencies. Parker et al. (2003) presented the watershed assessment and modeling study used to support the TMDLs for Lake Elsinore and Canyon Lake, as well as the development of the nutrient management plan for the San Jacinto watershed. In order to simulate nutrient loading impacts on Canyon Lake (from the watershed) and transport to the downstream lake, Lake Elsinore, a simplified one-dimensional Environmental Fluid Dynamics Code (EFDC) model was developed.

Gould et al. (2003) reviewed the Klamath Fall, OR integrated management strategy that was development to address TMDL, NPDES, SSO, GASB 34, ESA and CMOM requirements. Katz and Alberta (2003) presented a stakeholder-driven approach to water quality management planning in the Las Vegas Wash. This paper summarized efforts to develop a comprehensive adaptive management plan for the Wash that can and is already being implemented, highlighted the stakeholder positions and actions in addressing the problem and developing solutions, and described the necessary efforts to foster public awareness, build trust, work with stakeholders and the media.

Kleis and Hammer (2003) reviewed the process used by San Diego to implement the permanent BMP program in San Diego. This experience, in combination with a retrospective analysis of lessons learned by two organizations integral to the process, provided valuable insight into successfully developing an effective storm water program addressing urban runoff from new development. McGowen and Toy-Chen (2003) reviewed the challenges faced by Los Angeles in the development and implementation of a bacterial TMDL for the Los Angeles River, a highly modified and effluent dependent river. TMDLs were especially challenging because compliance must address the extreme flows during rain events, yielding in some cases separate wet- and dry-weather compliance strategies. Orton (2003) reviewed the final nutrient TMDL for the Malibu Creek watershed (Los Angeles County, CA). To achieve these objectives, it identified permissible nutrient loads from various nutrient sources, including recycled water irrigation, which was allocated a zero permissible load. This interpretation of runoff prohibitions, which were ubiquitous in recycled water permits throughout southern California, raised numerous questions about the sustainability of existing recycling efforts and the advisability of new efforts in an era of forthcoming nutrient TMDLs.

EPA’s Technical Support Document for Toxics (1991) provided recommendations on evaluating frequency, magnitude, and duration issues, including the use of statistical permit limit derivations and techniques for dynamic wasteload analysis

(Butcher and Diamond 2001). A survey of state permitting agencies found that few of these recommendations have been put into practice. Instead, most jurisdictions continued to rely on steady-state wasteload analyses. The WERF research project (98-HHE-3) is developing an Implementation Guidance document (with software) to aid permittees in deciding whether to undertake these dynamic analyses and to aid in implementing the analyses under the existing guidance. Information technologies and watershed management approaches have enabled decision-makers to establish predictive relationships between different land-use activities and the sediment and nutrient loads discharged from the watershed (Khairy et al., 2001). These approaches then have been extended to assess the impacts of these wasteloads on the receiving aquatic systems. A case study on the simulation of Tangipahoa Watershed and Lake Ponchartrain Ecosystems was used. The Integrated Plan for the Wastewater Program (IPWP) was a public-driven effort designed to develop policies for the planning and implementation for future wastewater collection, treatment, reuse and disposal projects (Lopez-Calva 2001). The integrated systems model was developed to measure the performance of policy alternatives in relation to a set of objectives and performance measures established by stakeholders. The conceptual character of the model proved to be appropriate for this policy-planning project. Monte Carlo simulations, which account for uncertainty in model parameters, were performed for a model of a 10-km stretch of the River Cam in Cambridge in Eastern England (Duchesne et al., 2001). The simulation results were used to rank wastewater treatment plant control strategies according to their impacts on river water quality. It was found that ranking was robust even with the uncertainty in the parameter values for the control strategies.

The BASINS system was developed to provide technical tools to support EPA's regulatory water quality programs, in particular the TMDL program (Cocca 2001). BASINS 3.0 provides a range of detail in watershed models and provides databases, data management tools, documentation, and other resources to make modeling waterbodies and watersheds easier. The three watershed models in BASINS 3.0 include the complex Hydrological Simulation Program Fortran (HSPF) model, the complex Soil and Water Assessment Tool (SWAT) model; and the simple PLOAD model. Each model has an automated GIS data extraction script. The paper by Dorn et al. (2001) reviewed BASINS-STAR (BASINS Strategy, Analysis, and Reporting system), a set of tools to assist decisions-makers identify alternative management strategies. The main engine of BASINS-STAR is a genetic algorithm-based optimization technique. BASINS-STAR forms a decision support framework for watershed management (Murray et al., 2001b). The capabilities of this framework were demonstrated through several scenarios for the Suwanee Creek watershed in Georgia. The paper illustrated a means by which a decision-maker can determine maximum allowable level of land development in a given watershed while maintaining a target level of water quality. The effect of stormwater treatment practices on land use planning was also explored.

The main concern of using continuous simulation approach is that the use of data during specific representative hydrologic period does not necessarily cover the most "critical" condition and it is very data intensive (Zhang et al., 2001). A practical, event-based Critical-Flow Storm (CFS) was developed with application in the Nitrate TMDL Development for Muddy Creek/Dry River in Virginia using BASINS/HSPF. As an alternative method for TMDL development, the CFS approach gives reasonable results and explicitly addresses the critical condition as a combination of stream flow, magnitude of storm event, and initial watershed condition. The Northeast Georgia Regional Development Center has taken a proactive stance in protecting the Alcovy River watershed (Jha et al., 2001). This project discusses the modeling portion of these larger studies. The purpose of this study was to develop a calibrated watershed water quality model in order to simulate the impact of different future scenarios. The BASINS interface to HSPF was selected as the watershed water quality model for the Alcovy River watershed. Water, sediment, phosphorus and fecal coliform were the constituents modeled. Eight future scenarios incorporating various management practices were modeled. These scenarios include the simulation of conservation subdivisions, riparian buffer ordinances, impervious surface restrictions, storm water quality controls and improved enforcement of erosion and sedimentation controls. Modeled results indicate that a combination of stormwater treatment practices must be implemented in order to reduce pollutant loading to the Alcovy River.

Rockdale County, Georgia assessed its watershed in order to develop a management plan that combines water quality protection with other objectives, including expansion of water supply and wastewater treatment capacity (Clements et al., 2001). An innovative planning process linked management objectives, assessment information, predictive modeling tools, and stakeholder participation to risks. The results were effective for evaluating management options. The paper by Dymond et al. (2001) described the web-enabled integrated modeling system, including data sources, collection, analysis methods, system software and design, and issues of integrating the various component models. The integrated system contained three modeling components, namely hydrology, economics, and fish health. Earles and Jones (2001b) presented a water quality model developed for evaluating pollutant loading from development projects in the Aurora Reservoir

watershed in the Denver metropolitan area, Colorado. Laing/Village Homes developed the model to evaluate pollutant loadings from the development; Aurora determined the allowable pollutant loadings to the reservoir. A linked watershed and water quality model was applied to the Little River watershed, Georgia (Moskus et al., 2001). The model was a modified version of the Generalized Watershed Loading Function (GWLF) model that had been linked to a simplified transport model based on Water Quality Analysis Simulation Program (WASP). This model was to forecast water quality under future development conditions for flow, sediment, phosphorus, bacteria, and metals. Future scenario runs showed that water quality standards likely will be violated in the future. The WERF project 97-IRM-5E modeled the trading market in Maryland under various assumptions with the results used to design and implement a statewide trading program (Bacon et al., 2001). Credits could be created and sold by POTWs, as well as nonpoint sources such as urban, agricultural, and undeveloped land. This paper presents preliminary results from the first round of several trading scenarios. Water quality modeling was conducted to examine the effects of growth in the McDowell Creek Basin on the water quality in Mountain Island Lake (Quinlan et al., 2001). The water quality modeling included both a watershed and a lake model. This study investigated the effects of effluent discharges ranging from the existing 6 mgd up to 24 mgd due to basin development. Nonpoint source loadings were estimated at each level of development and were included. Results of the modeling showed that as the treatment plant is expanded, a reduction in effluent nutrient concentrations will eventually be required to maintain acceptable water quality.

The watershed approach can be used as an integrated method for implementing Total Maximum Daily Loads (TMDLs) (Haas et al. 2000). A discussion of how this approach could be used in Massachusetts was presented. A watershed-based assessment program identified urban stormwater discharges to small streams to be one of the most significant environmental issues in the region's long-term management plan (McCallum et al. 2000). A bacteria TMDL for the Shawsheen River in Massachusetts was described (Mockus et al. 2000). Urban stormwater was found to be the largest source of pathogens. Copper and nickel TMDLs for San Francisco Bay were integrated into the ongoing Santa Clara Basin Watershed Management Initiative with a major emphasis placed on establishing and maintaining public and industry involvement through a specially established TMDL stakeholder group (Olivieri et al. 2000). The TMDL process provided a systematic framework for dealing with long-standing water quality issues in the South Bay. The work by Jones-Lee and Lee (2000) investigated the toxicity to *Ceriodaphnia dubia* due to the contamination of runoff from residential use of organophosphate pesticides in several California cities. This paper provided guidance for the development of a TMDL for the pesticides and for controlling their impacts on the affected streams.

Controversy surrounds proposed revisions in access and recreation policy at central Massachusetts' Wachusett Reservoir, a crucial source of drinking water for metropolitan Boston (Steinberg and Clark 1999). Although tensions persist between Boston and the Wachusett region, area residents' complex valuation of the reservoir as a space of utility and a place of everyday life suggests opportunities for consensual resource coalitions and initiatives. Duram and Brown (1999) present the results of a mail survey of 64 federally funded watershed initiatives in the United States. The perceived effects of participatory watershed planning include increasing awareness of watershed conditions, heightening interagency coordination, reaching consensus on resource management plans, and lending legitimacy to final plans.

Fifty-one municipalities and county and regional agencies in the Rouge River Watershed in metropolitan Detroit, Michigan were using the "watershed approach" to solve water-quality problems from CSO, stormwater, NPS and illicit discharges (Johnson et al. 1999). Latchaw and Jarrett (1999) described a watershed restoration strategy for an urban stream in Louisville, Kentucky that was damaged by a flood. The local flood management agency, the Louisville and Jefferson County Metropolitan Sewer District, chose to change its flood and environmental management practices to reduce similar problems in the future. Letey (1999) presented the results of a case study that illustrates the interaction between the political system and science on a water management issue. Irrigation projects in the western San Joaquin Valley, California led to a situation requiring subsurface drainage and disposal of the drainage water. The original plan was to discharge the drainage water in the Suisun Bay east of the San Francisco Bay, California. Severe damage to birds associated with selenium in the water led to a reevaluation of irrigation and drainage management options.

Norton (1999) outlines the Gulf of Mexico Program (GMP) that was envisioned as a multi-stakeholder endeavor to improve coordination among Federal and Gulf State agencies and to directly involve non-government organizations in the development and implementation of actions to address key environmental problems confronting the Gulf. The GMP works to identify and implement innovative and incentive-based approaches that support Gulf State and coastal community efforts to improve the quality of life for their citizens and their environment. Sneve et al. (1999) summarize a study by the Louisville and Jefferson County Metropolitan Sewer District (Kentucky) to develop and evaluate pretreatment program performance measures that were intended to lead toward a further reduction of pollution from

industrial (indirect discharge) sources. The objective of this project was to develop, implement, and assess specific performance measures designed to measure the environmental impact of the pretreatment program in a selected watershed or watershed. The State of Washington has pioneered the use of watershed analysis as a regulatory tool since 1992 (Sturhan 1999). The rules and methods for conducting watershed analysis were developed by Timber/Fish/Wildlife, a cooperative of the timber industry, Indian tribes, environmental groups, and government agencies. Forested basins of about 10,000 to 50,000 acres were delineated across the state, and about 60 analyses have been completed, with another 35 in process.

A successful public outreach and stakeholder involvement campaign, together with a thorough engineering investigation and planning program, was helping the City of Edmonton, Alberta, Canada develop and obtain support for a cost-effective CSO control strategy (Barth et al. 1999). The Towards A Cleaner River (TACR) campaign was developed based on a need to inform and involve the public and interested stakeholders in the development of Edmonton's CSO control strategy. Schroedel et al. (1999) described efforts to finance Wisconsin's Rock River Watershed Partnership, a broad-based stakeholder group committed to addressing nutrient and other water quality management issues. Williams (1999) described the South Dade Watershed Project that analyzes the relationship between water and land use. It tries to establish consensus with stakeholders, and develops regional planning criteria that would assure a sustainable water supply and protection of species in the Everglades National park and the Biscayne Bay, while improving urban, agricultural and natural systems for south Dade County, Florida.

Australia's 'Landcare' program was a community-based participatory program established by government to tackle the problem of land degradation. Landcare involves thousands of Australians working together in locally based groups, tackling problems of common concern. Ewing (1999) reviews how the State of Victoria has responded to these challenges and suggests what challenges remain. Concerns about stormwater pollution were relatively new in Australia, and the physical and administrative systems necessary to cope with these have not fully evolved. O'Loughlin and Robinson (1999) described the growth of these concerns and how they came to be important, dealing particularly with the Australian State of New South Wales (NSW). Stormwater management practice in NSW has developed in a somewhat haphazard manner (Robinson and O'Loughlin, 1999). The evolution of current practice was critiqued. The impact of recent government initiatives including the NSW requirement to prepare catchment based stormwater plans was reviewed and suggestions made. A more rational policy framework was proposed which may have additional advantages to the current arrangements.

Eckert et al. (1999) summarize a management plan for an urbanizing river in Australia. A management system, including gross pollutant traps, automatic flocculant dosing and 16 ha of lakes was designed to address many of the failings observed in similar systems. McAlister et al. (1999) summarize major scientific studies conducted in south-east Queensland that highlight the importance of stormwater runoff as a significant contributor to the degradation of the local environment that has occurred since European settlement. These studies have identified the fine sediment component of urban stormwater as a key cause to these environmental impacts. As a consequence of these studies, a 'total catchment' approach has been developed and applied to urban stormwater quality management in Brisbane. A 1996 amendment to New Zealand's Local Government Act 1974 requires local authorities to complete asset management plans (Watts and Greenaway 1999). This required the identification and locating of all assets owned and operated by local authorities, condition and performance assessments, and the definition of accurately cost estimates of levels of service for all service delivery activities. It became clear in Christchurch that commonly accepted infrastructural asset management approaches threatened to undervalue or ignore assets with natural or social values. Currently over one hundred and sixty local government agencies in NSW, Australia have a legal requirement to prepare catchment-based stormwater management plans. Brown and Ball (1999) report on their efforts to gauge and evaluate responses by stormwater managers in the process of preparing these plans.

Clifforde et al. (1999) described developments that were currently taking place towards the creation of a comprehensive integrated management capability for urban wastewater systems. The principal vehicle by which these developments were taking place was a European Union (EU) funded collaborative project led by WRc and DHI together with numerous other partners. The project comprised both technological developments in terms of procedural issues, hardware and software and extensive practical testing via a series of pilot studies. Konig et al. (1999) described some results of an integrated model application in the Hovringen wastewater system in Trondheim, Norway. The model includes wastewater production, surface run-off, infiltration, transport and treatment under a joint Matlab/Simulink platform. The model also allows the effects of real time control to be simulated. The objective was to minimize pollution discharges to receiving waters and to define design loads for the extension of the treatment plant. Bazzurro et al. (1999) described a pilot project

carried out in the framework of the EU Technology Validation Project. This pilot project was related to the combined urban drainage system of Genoa's historic center that consists of eight natural streams flowing in culverts under the urbanized area. The Venice, Italy study was one of the pilots of the "Integrated Wastewater Project under the EU sponsored Innovation Program (Pretner et al. 1999). The project aims to demonstrate that an integrated approach to the planning and management of wastewater facilities was feasible and cost-effective. The project focuses on the integrated modelling of the sewer network, wastewater treatment plant and the Venice lagoon. The model will aid in optimizing the planning and management of the wastewater structures by adopting innovative monitoring and control technologies.

Musiak et al. (1999) discussed the basic concept of improving the water cycle to better support sustainable urban systems in Japan. An investigative procedure was presented that explains how to set up the project goals and how to evaluate the water cycle. Tsunoyama et al. (1999) described efforts to restore the hydrologic cycle in the Ebi River, which flows through Funabashi City in Japan. Using a physically-based distribution model, the authors studied quantitative changes in the water circulation system over time, and deduced future changes.

Sustainability. From definitions of sustainability, Rijsberman and van de Ven (1999) derived five key elements, by which sustainable development can be described. The most important differences in the approaches can be reduced to the basic attitude towards (a) people in their environment and (b) norms and values. Combining these two components led to four basic approaches to sustainability. The suitable definition of spatial scales of investigated systems was one of the most important questions within the water management (Stransky et al. 1999). The approach of transfer of global principles to local scale allowed determining major problems in areas investigated and establishing linkages to their causes. The urban water management objectives of ecological sustainability, economic efficiency and urban amenity required the adaptation of an integrated approach to water management. Lawrence et al. (1999) reviewed developments in the application of total water cycle based management approaches across Australia, Canada, United Kingdom and United States. The authors concluded that the need for a more integrated approach to urban water management was now being widely recognized, with a growing adoption of total-water cycle-based management, and substantial investment in ongoing studies and research related to its further application.

Loke et al. (1999) presented a framework that attempts to give an overview of the scientific tools used in urban storm drainage to water-quality problems. It tried to clarify the structure and terminology of current engineering methods by using diagrams, namely the problem identification and management scheme, the decision-making process scheme and the actual methodology overview. Recent emphasis on citizen group or stakeholder involvement in a variety of urban stormwater related policy making situations has led to the need for the technical professional to become proficient in facilitating such groups. Reese (1999) described a series of related techniques, principles and a process that have been used successfully in a variety of stormwater-related policy making settings including stormwater financing credit approaches, rate making studies, master planning and program development. Langeveld and Wiggers (1999) look at urban storm drainage and urban sanitation, not as technical problems but as conceptual ones. This paper introduces a three-stage approach, first focusing on concepts of urban water systems by combining unit-flows (water and material flows). Then the concepts were classified, and an assessment of both the possibility and desirability of the selected concepts was made. The advocated approach offers opportunities for more appropriate urban water systems by proposing new concepts for urban water systems and by guiding existing urban water systems towards sustainability.

Three municipal treatment plants and stormwater runoff were designated as sources contributing to the impairment of South San Francisco Bay, California (Tucker et al. 1999). The City of San Jose, California believed that the TMDL process served as an important way to engage stakeholders in the development of regional- environmental-management strategies. Mooney et al. (1999) presented a new TMDL-modeling framework for the Delaware River to accurately represent the current condition of the river. Novotny (1999) provided direction for TMDL research. TMDL methodologies and concepts have several problems, including determination of loading capacity only for low-flow critical periods that preclude consideration of wet-weather sources in water-quality management. Research was needed to develop watershed pollutant loading and receiving-water loading-capacity models that link wet- and dry-weather-pollution loads to the probability of exceeding water-quality standards. Chen et al. (1999) presented a decision-support system (DSS) to calculate the TMDL of various pollutants for water-quality limited sections within a river basin. The DSS includes a watershed-simulation model, a database, a consensus building module, and a TMDL module that provides a worksheet for the calculations. The methodology was demonstrated with an example application in the Catawba River, Alabama.

Borst (1998) provided an outline of the U.S. EPA research direction for modeling efforts supporting the urban watershed

over the next few years. The U.S. EPA released an updated version of its BASINS modeling system (Whittemore 1998). This software integrates database queries with environmental modeling and mapping and greatly reduces the time required to manually assemble and statistically summarize monitoring data from an array of spatial databases.

Wise and Palukiewicz (1997) presented a framework for implementing watershed approaches to protect water quality. Many communities were seeking to understand how future urban development could be used as a basis for developing long-term watershed management plans (Bhaduri *et al.*, 1997). According to Pelley (1997) nearly half of the United States have adopted watershed approaches to tackle recalcitrant water-quality problems. Leland *et al.* (1997) reported that the future health of the Willamette River would depend on actions taken today. Bae *et al.* (1997) showed local environmental authorities can extend the watershed monitoring capacity through the development of a stream monitoring and stewardship program involving a partnership between community organizations. Ten watershed management projects were reviewed by the U. S. EPA (1997b) and in a separate report, successful watershed projects from State and Tribal NPS programs were also highlighted (U.S. EPA 1997c).

Kaufman and Marsh (1997) identified three classes of edge cities and assessed the impacts on stormwater runoff, groundwater contamination, and habitat fragmentation. The results indicate edge-cities may pose a significant threat of contamination to the groundwater and runoff volumes increase dramatically and water quality declines, as development displaces wetlands and creates impervious land cover. Black (1997) identified and discussed watershed functions that dominate the hydrologic environment in order to suggest a framework for understanding and managing the growing move to “restore watersheds”. Such hydrological and ecological functions are considered in relation to the storm and annual hydrographs and to water quality. Sustainable urban drainage should maintain a good public health barrier, avoid local or distant pollution of the environment, minimize the utilization of natural resources (e.g., water, energy, materials), and be operable in the long term and adaptable to future requirements (Butler and Parkinson, 1997). An integrated approach was outlined containing both high- and low-technology solutions to appropriate problems but each case must be decided on its merits.

A public-private partnership approach to water-resources management was adopted in the San Pasqual Valley, San Diego, Calif. and included groundwater management, river-corridor management, and watershed management (Gagliardo, 1997) and control of fertilizers, pesticides, and livestock (Hon, 1997).

The strategies adopted by Singapore were to keep the flood situation under control despite the vast extent of new land developments that were continuously taking place (Check, 1997). A drainage-master plan and drainage-development programs were implemented over the years to maximize land use and the creation of aesthetic waterways to enhance the urban environment. The stormwater- and floodplan-management programs were outlined for Tulsa, Okla. and Maricopa County, Ariz. (Richman, 1997a).

Based on recent developments in urban-storm drainage, further advancement in drainage planning would require consideration of the catchment, drainage system, groundwater, treatment plant, and receiving waters as one entity and ensuring sustainable integrated development and ecological enhancement of urban streams and corridors (Ellis and Marsalek 1997). Taylor (1997) reported a case study on a stormwater-management program for the Eastern Transportation Corridor in Orange County, Calif. to mitigate freeway and highway stormwater runoff. The management program included a new concept in water-quality assessment termed evaluation monitoring that incorporated a watershed approach to determine if real water quality beneficial-use impairment in the receiving waters was occurring. Watershed planners in Wisconsin Department of Natural Resources and in county governments applied a method to estimate chemical constituents loads in non-monitored areas based on the data from a monitored stream within the watershed (Corsi *et al.*, 1997).

The community of Bellevue, Wash. resisted burdening itself with the exorbitant costs of stormwater-drainage systems. In 1974, Bellevue adopted a surface-drainage system originally out of a financial imperative and working cooperatively, stormwater engineers and parks planners wove a complex web of public open space and innovative stormwater management (Girling and Helphand, 1997). A multiobjective-mixed-integer-chance-constrained-optimization model was developed to determine design- and rehabilitation- management strategies for stormwater-drainage systems conditioned on the likelihood of exceeding the system’s conveyance capacity (Jacobs *et al.*, 1997). Model objectives included the minimization of cost and probability of system failure.

Krebs and Larsen (1997) evaluated CSO problems and a series of possible measures to enhance the system performance

for the development of urban drainage towards sustainability based on case studies of mature urban-drainage systems. CSO, receiving-water quality, and decreasing groundwater levels were considered. Sewerage system and centralized aerobic WWTP should not be considered as the only possible solution for wastewater disposal. Systems with source control could avoid many problems of end-of-pipe technology by respecting different qualities of wastewater and by treating them appropriately for reuse (Otterpohl *et al.*, 1997).

The Richmond Transport Project of California, which addresses complex geologic conditions, control of surface settlement to avoid damaging adjacent residences, and an unconventional outfall design, will reduce future discharges at Baker Beach and reduce CSO into San Francisco Bay by 80% (Maiolini *et al.*, 1997).

Interest in wet-weather impacts within watersheds is at an all-time high as evidenced by the more than 300 papers presented at Watershed '96 (Water Environ. Fed., 1996a). St. John *et al.* (1996) described using hydrodynamic and water-quality models to evaluate the overall impact of dry- and wet-weather loads on dissolved oxygen in receiving waters near New York City, NY. Brosseau (1996) explained how the Bay Area Stormwater Management Agencies Association in the San Francisco, CA area operates. This Association has membership from seven stormwater agencies in the area. A major motivation for watershed-based approaches is improved economic efficiency. Brewer and Clements (1996) described how organizations formed a consortium to share the cost of monitoring at the watershed scale. Another source of savings from watershed management is to remove pollutants within the watershed in the most cost-effective manner. Market-based pollutant upstream-downstream trading has emerged as a potentially valuable mechanism. Methods for discharge trading and case studies were presented by Podar *et al.* (1996); and Stephenson and Shabman (1996). Frederick *et al.* (1996) estimated the benefits of stormwater-detention systems as increased property values due to the waterfront amenity value. The results of property valuations in many areas were included. Marx *et al.* (1996) described how a watershed-based approach has resulted in more cost-effective CSO control in Boston, MA. Weiss and Lester (1996) outline how watershed ideas can be used to address SSO problems within The EPA's regulatory program. Brady (1996) summarized the accomplishments of the first five years of the EPA's watershed-protection approach. Stumpe and Hamid (1996) described how applying a watershed approach can develop more cost-effective SSO control programs. Urban stormwater is but one of many impacts in urban watersheds. Studies in Boulder, CO (Heaney *et al.*, 1996) and in Quebec City, PQ, Canada watersheds (Vescovi and Villeneuve, 1996) illustrated the complexity of urban watersheds. This complexity may be typical for urban areas because man invariably makes significant modifications to the watershed system. Roesner *et al.* (1996) described an integrated master-planning approach for management in a new development near Orlando, FL.

Stephenson (1996) compared the water budgets of an undeveloped catchment with an urbanized catchment in Johannesburg, South Africa. The results show the expected increase in direct storm runoff and the need to import water for water supply. Nelen and Broks (1996) described the planning of a new development for about 10,000 people in Ede, Netherlands. The three underlying environmental principles are sustainability, quality, and ecology. This area has a high groundwater table so groundwater management is an important part of the project. It is planned to incorporate water conserving hardware and divert the more polluted stormwater into the sanitary sewer and consideration is being given to a dual-water-supply system. Escartin (1996) provided an overview of how Spain has used the watershed approach since 1926 to achieve more efficient water management. Grottker and Otterpohl (1996) described and integrated neighborhood urban water system for a 100 unit development in Germany which operates as a quasi-closed system.

### ***Geographic-Information Systems (GIS)***

As part of stormwater management planning, Fairfax County (Virginia) needed to determine the level of stormwater control already in existence in the urban areas (Kumar *et al.* 2005). They related the level of stormwater control to the land uses reported on real estate taxes and to the implementation date of various levels of stormwater regulations. The results were presented in a GIS format. A GIS-based map was used as the stormwater management plan for the Emscher catchment (Geretschauser and Spengler 2005). The map consisted of two independent layers – the stormwater management method map and the information on the potential to prevent stormwater from entering the sewer system (as a function of buildings and characteristics that can be used to manage stormwater runoff). Underwood and Davis (2005) examined the use of GIS-based planning tools to mitigate channel enlargement and water-quality impacts resulting from impervious surfaces. Geomorphic stress has been demonstrated at total basin imperviousness of 2% or more, and active channel adjustment to imperviousness greater than 9%. The GIS tools can be used to predict geomorphic conditions resulting from increased development. The results can then be used to inform decision-making.

A web-based GIS and spatial decision-support system were used to analyze the impact of urbanization on the quantity of direct runoff and non-point source pollution (Choi *et al.* 2005). The system incorporated map browsing, web-based

watershed delineation and hydrologic spatial data extraction. Abellera and Stenstrom (2005) reviewed the use of satellite imagery and GIS in stormwater modeling to improve the predictions of impervious cover in a watershed. These techniques, when combined with knowledge-based systems, have been evaluated as a method of reducing the need for expensive field surveys. Results showed that these new systems were comparable to the older field surveys. The use of GIS for stormwater management and land planning was reviewed by Johnson and Zelinsky (2005). The GIS mapping allows for various alternatives for stormwater management to be investigated, as well as indicates what the impact of future development is likely to be.

GIS have been used in various water resources and hydrologic modeling applications because of their ability to manage and process spatial data. The use of GIS has also increased as more spatial data has become available. The required resolution of the spatial data for a variety of applications remains uncertain and limited general guidance is available. Ikenberry et al. (2004) assessed the affect of data resolution on the values of SCS curve number, runoff depth, runoff volume, and peak discharge. The summary results provided general guidance on the need for relatively low or high resolution soils and elevation data.

Early applications of GIS in watershed modeling were as pre- and post-processors of watershed data and model results. Recently, models have been developed to function entirely or almost entirely within the GIS environment. Jain et al. (2004) developed a distributed rainfall-runoff model in GIS that uses Philip two-term infiltration model and diffusive wave for runoff and flow. Testing of the model for several catchments indicated the model can realistically simulate the runoff hydrograph at the watershed outlet. Developing the network topology is a major effort in developing a hydraulic model of an urban drainage network. Lhomme et al. (2004) introduced a method using geomorphological routing based on a DEM instead of physically-based routing methods. Tests of the method found the geomorphological model produced flood simulations that were similar to the physically-based routing model, yet avoided the tedious network topology creation.

GIS-based models used to predict stormwater runoff quality and receiving water quality are becoming more common. They have the advantage of spatial relationships being included in the analysis results to suggest sources, impacts, etc. Park and Stenstrom (2004) presented an approach using image processing of satellite imagery to classify land use and empirical relationships between land use and stormwater pollution to predict pollutant loads. The technique was applied to the Santa Monica Bay Watershed and results suggested the major sources of nonpoint source pollution were from residential, commercial, industrial, and transportation land uses adjacent to Marina del Rey and the Ballona Wetlands. Kelsey et al. (2004) integrated regression modeling techniques into a GIS system to determine relationships between land use and fecal pollution in a South Carolina estuary. The regression analysis was used to identify land-use characteristics that may influence fecal coliform densities in the estuary. The location of high fecal pollution indicated that proximity to areas with septic tanks and rainfall-runoff from urban areas may be important indicators, but other research has not confirmed the relationship to septic systems. Recommendations from the analysis were to intercept stormwater runoff, reduce dumping of wastes from boats, and reduce pet waste accumulating on watershed surface. Wise and Armitage (2004) reviewed the use of GIS to estimate the source and quantities of litter generation in urban watershed. The model has been tested and used to identify the most appropriate litter removing devices.

Qin et al. (2004) introduced a comprehensive stormwater quality management planning tool developed within a GIS environment. The tool has two modules, one for construction site erosion and sediment control planning based on the Revised Universal Soil Loss Equation and one for post-construction stormwater management based on SCS curve number hydrology. Both modules enable placement and definition of best management practices and compute pollutant removal capabilities and cost of watershed management plans.

The benefits of GIS have been realized for a variety of water infrastructure planning, management, and maintenance activities. McInnis et al. (2004) developed a system to manage stormwater systems that integrated a maintenance management system, GIS, and CAD mapping. The integration reduced the inefficiencies that had historically occurred. Rappaport et al. (2004) described how water/wastewater utilities were taking advantage of GIS technology to meet demands of recent regulations by U.S. EPA. Primary applications include visual representation, fast retrieval of information, and managing utility data and utility activities. Shamsi (2004) reviewed the use of GIS for water distribution system modeling, specifically development of hydraulic models, creation of thematic maps of model results, network simplification for hydraulic modeling, estimation of demand and elevation at nodes, water main isolation, and delineation of pressure zones.



GIS is being used for a wide array of other functions in wet-weather flow management. Zhan et al. (2004) presented a GIS extension for the ESRI ArcGIS software that produces spatially distributed curve number and runoff maps. Xu et al. (2004) demonstrated the use of GIS to aid in the simulation of snowmelt dynamics.

Al-Sabhan et al. (2003) reviewed the use of GIS and web-based systems for flood forecasting and hazard mitigation. The Web-based hydrological modeling system permitted integrated handling of real-time rainfall data from a wireless monitoring network. He (2003) reviewed the integration of a GIS and a simulation model for watershed management. The simulation results show that expansion of urban land would likely lead to an increase in surface runoff, peak flow, and soil erosion. The magnitude of the effect was related to the extent and proximity of proposed land use change to water bodies in the watershed. Choi et al. (2003) presented a GIS-based long-term hydrologic impact evaluation of urbanization in a watershed. Analysis of the ratio between direct runoff and total runoff from 30 years of simulation results and the change in these ratios with urbanization shows that estimated annual direct runoff increased from 49.2 percent (1973) to 63.1 percent (1984) and 65.0 percent (1991), indicating the effects of urbanization are greater on direct runoff than on total runoff.

Brown and Toomer (2003) reviewed Atlanta's use of GIS to support sewer evaluation under MOMs and focused on how web-based mapping tools improved the method in which cities conduct day-to-day sewer operations and hopefully, aid in compliance to the Consent Decree. The GIS also serves as an extremely helpful planning tool for Maintenance Operations Management System (MOMS). Heltzel and Horvath (2003) reviewed the implementation of a GIS and a computerized maintenance management system (CMMS) from scratch by Allen County. This study follows the processes that Allen County went through to gather data, select an appropriate CMMS and implement that system.

Evans (2003) proposed the use of GIS in the public works maintenance department in order to improve efficiency and effectiveness. The process was demonstrated with a case study in San Diego. The application includes maintenance dispatch spatial optimization, automated map-based service request printing, and maintenance frequency optimization. Bunce and Brown (2003) reviewed the development by the Orange County Sanitation District of a comprehensive and reliable system map and asset inventory. Cobb (2003) reviewed the quality assurance aspects required in Loudoun County, VA, as they developed a GIS-based storm sewer inventory. The numerous redundant checks and balances between Loudoun County and the outside contractor are ensuring that a highly accurate stormwater GIS is being created according to the county's specifications. Proakis and Cathcart (2003) demonstrated the use of GIS for municipal I/I studies in the Town of Concord. Taber et al. (2003) reviewed the integration of GIS and CMMS in Onondaga County, NY. Benefits of the GIS/CMMS interface for collection system maintenance include easily finding maintenance information, ease of planning and scheduling maintenance work, and ease of summarizing and analyzing maintenance data.

Hummel et al. (2003) discussed the calibration of the watershed model for Metropolitan Atlanta. Factors such as availability of observed streamflow data, diversity of subwatershed size and land use, and representation of the major river basins in the area were considered. Liu et al. (2003) proposed a GIS-based diffusive transport approach to determine the rainfall-runoff response and flood routing through a catchment. The model was tested on the Attert catchment in Luxembourg, and the results were in excellent agreement with the measured hydrograph at the basin outlet. A sensitivity analysis shows that the parameter of flood frequency and the channel roughness coefficient influenced the outflow hydrograph and the calculated watershed unit hydrograph, while the threshold of minimum slope and the threshold of drainage area in delineating channel networks had marginal effects.

Lohani et al. (2003) discussed the optimization of Clark's unit hydrograph using HEC-1 support by GIS. The calibrated model parameters were tested for flood events of the years 1983, 1985, 1987 and 1988. Results showed that Nash-Sutcliffe's coefficient was close to unity, indicating that the calibrated model performed satisfactorily. Nyabeze (2003) reviewed the modification of a rainfall-runoff model that can be interfaced with a GIS and its validation. The use of a GIS made the relationship between parameter estimates and land cover characteristics more evident. Sanghavi and Mattejat (2003) reviewed the use of GIS by the Maryland State Highway Administration to manage state-wide stormwater stormwater treatment practices. Shamsi (2003) presented a case for the use of an Internet-based GIS by the water industry to present and review water quality data for water, wastewater and stormwater systems.

Nie et al. (2002a) connected a GIS to urban runoff and pipe flow models to make the modeling task more efficient. Connecting the GIS to the MOUSE runoff model indicated that the GIS connection made the subcatchment delineation and characteristics calculations much simpler and more accurate compared to conventional methods. The GIS urban

runoff predictions were reasonably close to measured flow rates for the low flow part and the front peak discharge, but not for other flow rates later in the hydrograph. Nie et al. (2002b) applied a GIS-based hydrologic approach to incorporate buildings into urban watershed analyses and to evaluate the influence of grid cell size in distributed urban drainage modeling.

Hiramoto and Kariya (2002) presented a method to predict areas of inundation in cities even when rivers are not overflowing. The technique involves computing runoff flow paths using topography and other data in a GIS to derive the areas and depths of inundation. The technique was applied to a case study and found to provide fair predictions when compared to observed data. The model is concluded to be sufficient for production of forecast charts of inundation if human judgment and other model factors are incorporated into the analysis. Morita and Fukuda (2002) introduced a DSS for flood-control facility planning. The DSS is composed of a flood inundation prediction model and a flood damage estimation model. Analysis using the DSS yields damage reductions created by a flood-control facility. The DSS was demonstrated for a highly urbanized catchment located in the Tokyo Metropolis. Al-Sabhan et al. (2002) described a web-based hydrologic modeling system that integrates real-time rainfall data to predict runoff and display the results on-line using GIS-based platforms. Islam and Sado (2002) integrated NOAA Advanced Very High Resolution Radiometer (AVHRR) data with GIS data layers to develop a flood hazard map and land development priority map for Bangladesh to aid in the mitigation of future catastrophic flooding damages. Bedient et al. (2002) created a hydrologic modeling system for the Brays Bayou watershed in Houston, Texas that incorporates radar-rainfall data. The system was created for the Texas Medical Center to provide real-time predictions of flows in Brays Bayou for flood warning.

Reginato and Piechota (2002) used a GIS model based on the Simple Method to simulate the runoff and pollutant loads from the Las Vegas Valley watershed to Lake Mead. Model results indicated that nonpoint source nutrient loads were approximately 10% of the total nutrient loads to Lake Mead. The authors also highlighted several of the uncertainties associated with their modeling approach. Miller et al. (2002b) developed a landscape assessment tool using GIS that automates the parameterization of the Soil and Water Assessment Tool (SWAT) and KINematic Runoff and EROSION (KINEROS) hydrologic models. The tool was tested by simulating runoff and sediment yield for the Cannonsville and San Pedro watersheds. Moglen and Beighley (2002) presented a GIS-based method to derive spatially explicit time series of land use change and then a method based on TR-55 to predict peak discharges. Results from application of the technique can be used to produce graphical displays of the temporal and spatial distribution of peak discharge for a watershed. Pandit et al. (2002) used the Continuous Annual Load Simulation (CALSIM) model to predict the annual total suspended solids, total nitrogen, and total phosphorus loads under wet-weather conditions for the Briar Creek drainage basin in Malabar, Florida. The model predicted pollutant loading for historical, current, and future conditions and will be used to develop a wet-weather flow control plan to reduce annual stormwater pollutant discharges to historical levels. Lenz (2002) described the development of a comprehensive water quality management plan for Central Park in New York City consisting of a series of structural and non-structural stormwater treatment practices. The BMP plan is being evaluated with an integrated modeling system composed of GIS, SWMM, and WASP. Chong et al. (2002) provided an overview of the results of applying a Geographical Information System (GIS) and Global Position System (GPS) application to the management of sanitary sewer infrastructure at the Environmental Management Flight of Nellis Air Force Base (NAFB) north of the City of Las Vegas, Nevada. The desired program implemented for this assessment project would be required to be user-friendly, upgradeable with the changing computer technologies, and be capable of managing massive amounts of information and this study highlighted issues and methods associated with the system.

The collection and management of data is vital to the urban drainage planning process. Shamsi (2002) reviewed the application of GIS for wet weather flow management tasks including thematic mapping of system elements, facilities management, work order management, and management of data from TV inspection of sewers. van Luijelaar and Baars (2002) introduced a wastewater planning system being developed as a planning tool in a GIS. The tool will connect important digital information for use in managing the urban watershed. Garrett (2002) described a GIS application to handle cost-effectively and efficiently SSO reporting and MOM requirements. Heltzel et al. (2002) collected sewer network data and created a GIS data layer of the system for the Allen County Sanitary Engineering Department. The GIS data served as the means to conduct a condition assessment process and to organize the resulting data. Ohlemutz et al. (2002) developed a set of WWW-based GIS tools that provides access for the Vallejo Sanitation and Flood Control District's staff to engineering drawings, GIS data, and maintenance management information for their CMOM compliance efforts. Trypus et al. (2002) described the use of relational database management systems and GIS for managing the assets of the District of Columbia Water and Sewer Authority's Potomac Interceptor. Rappaport and Loper (2002) described the GIS-based hydrologic modeling management system used by the City of Clearwater, Florida for the Stevenson Creek watershed. The system is linked with the AdlCPR hydraulic model through a graphical user interface

that allows the user to access engineering data in the form of GIS layers and to visualize input and output data. Wride et al. (2002) presented the use of GIS by the Metropolitan Sewer District of Greater Cincinnati staff to extract useful information from hydraulic model results of their system's performance.

A proactive approach to sewer system management involves the rehabilitation of the correct sewer at the correct time by using the correct rehabilitation technique at a minimum total cost (Sægrov and Schilling, 2002). To enable the pro-active approach, Sægrov and Schilling (2002) are developing a rational framework for sewer network rehabilitation. Computer Aided Rehabilitation of Sewers and Storm water networks (CARE-S) is aimed to improve the structural and functional reliability of the wastewater networks (risk of in- and exfiltration, collapse and blockage due to pipe deterioration, hydraulic overloading resulting in flooding and/or receiving water pollution). Kathula and McKim (2002) presented the preliminary developments of field-tested sewer-deterioration prediction models. Models based on survey responses of municipal infrastructure management experts have been developed for five common degradation states: cracks, open joints, displaced joints, corrosion, and deformation for both clay and concrete sewers.

The residual inflow to combined sewers must be quantified it affects the CSO activation frequency and thus the degree of roof drainage separation that must be undertaken to eliminate CSOs (Ho et al., 2001a). Hydrologic models have employed coefficients to represent the directly connected impervious area (DCIA), with the coefficients being proportional to the total amount of impervious area in the region. Better estimation of the DCIA requires sufficient geographic information and field data. A GIS application was developed to automate the process of calculating drainage utility apportionment percentages (Hughes et al., 2001). The application used the rational formula to estimate stormwater runoff. The application was applied to the Twelve Towns Drainage District (Oakland County, Michigan) 2000 Apportionment for Improvements to their combined sewer overflow retention treatment facility.

The application of HEC-HMS, HEC-RAS and HEC-GeoRas, coupled with GIS and NEXRAD radar, efficiently analyzed proposed alternatives to previous Army Corps of Engineers' plans including voluntary floodplain property buyouts and various, smaller-scale channelization schemes in Clear Creek (Benavides et al., 2001). Applying the latest HEC tools, NEXRAD and GIS to test the viability and effectiveness of specific flood control alternatives provided acceptable results. An ArcView GIS interface was created to view and facilitate the development of EPA's SWMM RUNOFF and EXTRAN models (Heineman 2001). The interface contained Avenue scripts that allowed the user to visualize a SWMM model in conjunction with existing GIS data. The scripts permitted viewing of model input and output summary data within ArcView, but could not substitute for existing SWMM-commercial software interfaces, since they do not permit viewing of conduit profiles, dynamic display of results, or editing of input data. The EPA SWMM model was a major tool of the stormwater management master plan for Hillsborough County, Florida (Ho et al., 2001b). Hillsborough County coupled the SWMM model with a county-wide GIS model. Hussein (2001) reviewed the MODFLOW Hydrologic Modeling System (MODFLOW-HMS), a physically based model capable of simulating the land phase of the hydrologic cycle including overland and channel flow on the surface, variably saturated flow in the subsurface, as well as transport during flow in both systems. GIS utilities were developed to estimate model parameters. The paper discussed the algorithms used to process these data and estimate the spatial and temporal variation in parameters over the finite-difference mesh, using a Mad River, Ohio study as a case study. Johnson County, Kansas embarked on an aggressive program to complete stormwater master plans and new floodplain delineations county-wide (Koch et al., 2001). The primary goals included (1) developing new hydrologic and hydraulic models for both existing and ultimate development conditions; (2) updating the existing FEMA floodplain boundaries for existing development conditions; (3) providing local communities with a floodplain management tool; (4) defining flood-prone areas; (5) developing sound engineering and bio-engineering solutions to alleviate identified problem areas; and (6) developing GIS-based stormwater data for ongoing asset management purposes. HEC-1 was used for hydrologic analyses, and HEC-RAS for hydraulic analyses. GIS techniques were used to automate the process of model development.

Two of the most data-intensive programs in use include computerized maintenance management systems (CMMS) and GIS (Ratliff and Schmitz 2001). The integration of these systems would result in greater efficiency of resources, improved data collection processes, and reduced data redundancy and data maintenance requirements. The paper discussed the major phases of a project that included asset inventory and a multi-year condition assessment program for sanitary sewers and storm drains. This paper presented lessons learned from the project and highlighted recommendations for the successful integration of inventory and condition data into CMMS and GIS. Xu et al. (2001) reported on the integration of a physically-based distributed model with a GIS in watershed-based water resources management. The integration facilitated the examination of a wider range of alternatives than could be done using conventional methods, and provided a 'living' management tool that could be modified and updated if the watershed condition changed. With the

increasing availability of digital and remotely sensed data such as land use, soil texture, and digital elevation models (DEMs), GIS has become indispensable in preprocessing data sets for watershed hydrologic modeling (Yu et al., 2001c). The transfer of inputs and outputs between the model and GIS can be greatly simplified by incorporating the model itself into the GIS environment. The authors incorporated a simple hydrologic model that used the curve number method of rainfall-runoff partitioning, a groundwater baseflow routine, and the Muskingum flow routing procedure, into the GIS model. Then the model was used to simulate the hydrologic response of the Upper West Branch of the Susquehanna to two different storms. The simulated hydrographs compared well with the observed hydrographs at the basin outlet.

Chester County, Pennsylvania municipalities have been working with Green Valleys Association to develop a “Sustainable Watershed Management Program” (Cahill et al., 2001). The heart of this program is a “Water Balance Model” that is interactively linked to a detailed GIS model. Municipalities can determine if the sustainable watershed goals are attainable or if changes are needed in municipal regulations. The visual component of the GIS allows the planners and municipal officials to quickly “see” the areas of concern, as well as the effects of regulatory changes. A comprehensive watershed approach to sewer separation planning was developed by the City of Atlanta, Georgia (Smith et al., 2001b). The holistic approach considered future land use and urban development within the combined sewer area basins, and determined the additional sewer conveyance capacity needed to accommodate the City’s future growth. The GIS-based tool will provide Atlanta with the ability to store and analyze data related to existing and proposed land uses, transportation improvements, storm water detention and other water quality enhancement projects. Due to the pending SSO Rule and CMOM requirements, the City of Phoenix (COP) needed to manage the large amount of data generated by the required studies (Malone et al., 2001). The COP used the Water Department’s GIS database as the format. Direct electronic collection of data and a “hands-off” data transfer and collection of data into the COP’s GIS was established.

A GIS model was developed for the Bushkill Creek in eastern Pennsylvania watershed to address the needs of various constituencies (Ruggles et al., 2001). This paper described the development of the GIS that supports the needs of each group having an interest in the Bushkill Creek watershed and provided examples of the information currently available. The application of GIS technology to the field of urban storm-water modeling was reviewed by Sample et al. (2001b), and an application in urban stormwater management at a neighborhood scale was presented. Using economic analysis to compare the cost of controls, including the total cost for land intensive controls, the optimal mix of stormwater treatment practices was found. The paper by Shamsi and Cigana (2001) demonstrated the reduction of wet weather overflows by conducting TV inspection of sewers using multimedia computer technology and GIS, and using the information to improve the maintenance of sewer systems. The paper proposed a four-step method for implementing a GIS-based TV inspection program.

Shamsi (2001) showed how digital elevation models (DEM) can be used to develop hydrologic models using the off-the-shelf GIS software. The chapter showed how to automatically delineate watershed subbasins and streams using DEM. A case study was presented that compared the DEM results with the conventional manual delineation approach. The work described by Sibiga et al. (2001) attempted to quantify pollutant loading sources as a function of land use within the Cazenovia Creek sub-basin of the Upper Buffalo River watershed by applying a GIS-based Watershed Loading Model (WLM). The model was also used to evaluate reduction options for meeting water quality criteria in the Cazenovia Creek. A program developed within Arc-Info GIS was used to identify storm characteristics from a set of rainfall gages (Tsanis and Gad 2001). Three different interpolation techniques (spline, inverse distance weighted, and kriging) were used to visualize the spatial distribution of rainfall using an example in the Hamilton-Wentworth Region in Ontario, Canada. Supported by GIS, snowmelt runoff simulation models have been built for the Qushenan basin in the west of China (Wang and Li 2001). Digital Terrain Factors (DTF) were employed to divide the basin. The results showed that this approach was significant and practical.

Models and decision-support systems are incorporating GIS. The EPA recently released a package called BASINS that includes a CD for each of the EPA regions (Lahlou *et al.*, 1996). BASINS provides links to nonpoint models including HSPF and QUAL2E using ArcView. An American Water Resources Association (AWRA) conference proceedings contain several useful articles on evaluating urban-stormwater-management problems with GIS techniques (Hallam *et al.*, 1996). Shamsi and Fletcher (1996) described how ArcView can be used for a variety of GIS-related linkages to urban-stormwater models and data management including AM/FM systems. Haubner and Joeres (1996) described using GIS as a preprocessor for the Source Loading and Management Model (SLAMM) to estimate pollutant loads in urban areas including a case study of Plymouth, MN.

Automated Mapping/Facilities Management, and geographical information system (AM/FM/GIS) applications for

stormwater systems were reviewed by Shamsi and Fletcher (2000). Popular AM/FM/GIS software was reviewed and six case studies were presented of applications for urban stormwater systems. Traditional hydrologic models have focused on peak discharges and NPS pollution from high-magnitude storms, but were usually of limited use in assessing the long-term impacts of land-use change (Bhaduri et al. 2000). A long-term hydrologic impact assessment model was developed using the curve number (CN) method linked to a GIS for convenient generation and management of model input and output. The City of Greensboro, NC has developed a Municipal Stormwater and Watershed Management Program to prioritize infrastructure maintenance, assist with stormwater permitting, track water quality data, enhance floodplain management, and facilitate stormwater management master planning (Bryant et al. 2000). Due to the flexibility of GIS tools and databases, the program could be expanded to include water supply system optimization, sanitary sewer system inventory and modeling, and advanced water quality modeling to support TMDL programs. A successful approach was used by the Sanitary District of Decatur, IL to develop a flexible and expandable information management platform (Kuchy et al. 2000). The platform was used to integrate GIS and database applications, a collection system hydraulic model, and a graphical user interface built specifically to satisfy end-user needs. A macro urban inundation model was created for Yokohama City, Japan to support benefit-cost analyses of flood control projects (Nakata et al. 2000). While the accuracy of the macro model (250 meter grid size) did not produce highly accurate results, the solution speed has made it an effective planning and decision-screening tool. The City of Livonia, Michigan used GIS technology to enhance the implementation of its illicit discharge elimination program (Rohrer and Beckley 2000). As a result of the GIS integration, record keeping was improved, problem areas were identified earlier, and joint efforts with surrounding communities were simplified. A site in Novi-Sad, Yugoslavia was modeled using a GIS system and the results were used to control flows through the drainage system by improving predictions of where various flow reduction techniques would work best (Makropoulos et al. 2000).

A GIS-based system designed to manage both sewer maintenance and I/I reduction programs was developed to integrate a wide range of over-lapping data types for these two activities (Shaffer and Greiner 2000). The system included inventory, complaints, and reporting components of the collection system. Methods for differentiating between agricultural and urban/suburban sources of water quality impairment were of interest in New England, where farms have been generally located in "mixed-use" land-use areas (Sturdevant Rees and Long 2000). This study utilized source-specific indicator monitoring techniques and a grid-based, distributed hydrologic model, incorporating them into a single GIS-based watershed management tool. A spatially variable rainfall model for a small-urbanized catchment based on records stored in a time series database was developed in Australia (Umakhanthan and Ball 2000). From the spatial patterns of rainfall, it was possible to develop individual hyetographs for each of the 42 subcatchments within this catchment. The City of Columbus used an integrated GIS/hydraulic model to address SSOs and flooding (Wolff et al. 2000). Project goals included reduction of inflow and infiltration, reduction of basement and surface flooding and improved system operations and preventative maintenance. The methods and advantages of using a GIS to plan a future sanitary sewer expansion to minimize the likelihood of SSOs was presented by Young (2000). Future flows were projected for this study based on the number of proposed new homes with existing flows being added as a known quantity.

The integration of GIS and watershed modeling was moving hydrologic and hydraulic analysis to a new dimension (Preusch and Rezakhani, 1999). BASINS--Better Assessment Science Integrating Point and Non-point Sources, a GIS-based tool developed and released by the EPA, provided a convenient interactive framework for watershed management (Parandekar and Ranjithan, 1999). Walker et al. (1999) reported the integration of the EPA SWMM runoff model and ESRI's ArcView GIS for utilization by the City of Phoenix, Arizona for decision support concerning land-use changes and pollutant loading.

The GIS Weasel, developed by the US Geological Survey, was a graphical user interface developed to aid hydrologists and other physical process modelers in the delineation, characterization, and parameterization of an area of interest, drainage nets, and modeling response units for distributed and lumped parameter models (Kenner and Love, 1999).

Fankhauser (1999) presented an automatic determination method of imperviousness from aerial photographs. The color infrared aerial photographs and orthophotos used have a ground resolution of 25 to 75 cm. A maximum likelihood classification algorithm was applied to assign each pixel to a surface category. Classification results were then overlaid with the subcatchments to determine the imperviousness of each subcatchment. Classification and overlay were carried out with the raster-based GIS IDRISI. The accuracy of the estimated imperviousness for the entire catchment areas was within 10%. Anderson (1999) described how hydraulic modeling, financial reporting and GIS have been integrated into a drainage management system in the city of Victoria in Australia. Butcher (1999) described a semi-lumped, GIS-based, transition matrix approach to estimate land use that was consistent with the level of complexity achievable in most

watershed models. Several recent reservoir water supply projection studies were used to demonstrate a general framework for simulating changes in land use and resulting impacts on water quality. Butt et al. (1999) described a unified database for 14 Lake Tahoe Basin (Nevada) streams that included an inventory of riparian vegetation and stream morphology, using stream classification and riparian vegetation cover data sets. The authors provided detail on data collection and explain the development of the resultant database.

Calomino et al. (1999) described using GIS for large urban areas based on all the information needed for urban storm-water modeling. The GIS has been used together with a diffused rainfall-runoff model, MOUSE, to simulate a number of experimental events. Herath et al. (1999) presented a framework for rapid estimation of urban flood damage. The economic damage estimate was based on the property distribution within the inundated area, inundation depth and stage-damage functions. The stage-damage functions were derived from past flood data while the property distribution was represented in a detailed GIS. The method was applied to a recent flood in Chiba prefecture, Japan, and estimations and compared well with post damage assessments. Hijioka et al. (1999) described the use in Japan of distributed simulation for sewer systems to reduce inundation and water pollution events caused by CSO. An integrated system was developed to solve the problems of data-conversion from the existing sewer ledger data and the land use data. The values were generated using the detailed land use mesh database (10 x 10-m). The comparison of the simulation results with the existing rainfall data showed very good agreement. Preau and Ahmad (1999) described the components of a collection system model developed by the Sewerage and Water Board of New Orleans, Louisiana as part of a multi-year sewer system evaluation and rehabilitation program. The authors demonstrated how the utilization of a GIS in collecting and storing the data in a single location eased the model building and calibration process. Sieker et al. (1999) used GIS to process data related to the applicability of on-site, decentralized stormwater management.

Zech and Escarmelle (1999) described how distributed hydrologic models were promising but their development depends on the availability of high-resolution data able to represent urban features. Public databases from satellite imaging were not yet adequate. The authors investigated the possibility of using other kinds of databases designed more specifically for cartography. The advantages and inconveniences of such an approach were pointed out, based on two actual examples. According to Nelson et al. (1999), the Watershed Modeling System (WMS) was a comprehensive computer software application for watershed characterization and rainfall-runoff modeling in a graphical user interface environment. Through several GIS operations and tight integration with GIS databases, WMS enabled hydrologists and water resource engineers to perform rainfall-runoff modeling more efficiently than conventional modeling methods.

Difference in impervious cover estimates between land use/population density and digital vector land-based methods were as much as 55% for a single sub-sewershed (Angell et al., 1998). However, the difference in impervious cover estimates produced only minor differences in model estimates of sewershed hydrologic response. Bishop et al. (1998) evaluated maps of runoff with a 5-km and 10-km resolution from Parameter-Elevation Regressions on Independent Slopes Model (PRISM) and found less interpolation errors in the 5-km resolution. Although geographic information system (GIS) allows sophisticated visualizations for modeling NPS pollution, this should never be allowed to disguise the legitimacy or overemphasize the certainty of model results (Loague et al., 1998).

Physical parameters for a digital elevation model (DEM) generated from satellite imagery for the Cumberland Pond Dam, in Cumberland County, N.J. varied less than one percent from measured (Hourani, 1998). Using spline surfaces within a GIS, Ball and Lok (1998) produced robust and accurate estimates of rainfall and enabled real-time estimation of spatially distributed patterns. GIS enabled estimation of alternative hyetographs for different locations within the catchment. Kull and Feldman (1998) discuss the unit hydrograph method, as well as the incorporation of spatially distributed rainfall data and travel times, using radar data and GIS. The Sanitation District of Northern Kentucky developed a sophisticated implementation and response system based on GIS data to deal with wet-weather pollution (Martin et al., 1998).

Fort Worth, Tex. implemented a low budget GIS to evaluate field data and to develop recommendations for I/I and structural rehabilitation for a study area of approximately 130 km (81 mi) of the city's sanitary sewer collection system (Hegwald et al., 1998). Moeller et al. (1998) reviewed the application of a Desktop GIS to the East Baton Rouge City/Parish (La.) Sanitary Sewer Overflow Corrective Action Plan. The key functionality of the GIS was in the areas of overlay analysis and network tracing. The effects of various types of NPS pollution on the degradation of surface and groundwater within the state of Pa. was assessed (Evans and Nizeyimana, 1998). Annual loads for N and P were computed for each watershed by NPS category, including on-lot septic systems, agricultural runoff, non-agricultural fertilization, urban runoff, and atmospheric deposition. Greensboro, N.C. instituted a comprehensive stormwater infrastructure and conveyance system inventory project to be used as a citywide preventive maintenance program in

addition to stormwater and urban watershed modeling applications (Bryant et al., 1998). GIS tools were applied to the estimation and prediction of stormwater flows impacting a steel plant construction site. Data layers included USGS digital and scanned image maps, SCS soils maps and engineering drawings for the site (Lieberman et al., 1998).

In an effort to quantify the many flooding problems of the Norfolk Naval Base in Norfolk, Va., the existing storm drainage network was surveyed and inventoried, hydrologic model parameters were generated using GIS, and the Extran Block of SWMM was used. Fifty projects based on this work are planned over the next 10 to 20 years and should solve 90% of the flooding problem (Small et al., 1998). The HSPF model is being integrated with ArcView to facilitate hydrologic simulation with respect to water quality, urban storm runoff and flood damage modeling for the Dardenne Creek Watershed in Mo. (Barnett and Fulcher, 1998). The Marine Corps Recruit Depot (MCRD) in Parris Island, S.C. implemented an automated mapping and facility maintenance management program designed to create physical inspection and inventory databases of the sewer infrastructure and update the sewer system AutoCAD map (automapping) (Lynn, 1998). The program consisted of a link between ArcView 3.0 which views AutoCAD map and CASS WORKS (facility maintenance management program). The city of L.A., Calif. used GIS to prepare and analyze data for water quality to facilitate the city's NPDES stormwater permit (Tam and Murillo, 1998). The system predicts water quality throughout the city and tracks identified polluters and violations.

According to Denes *et al.* (1997), an Arc/Info GIS package was used to conduct a cost-benefit evaluation study for the environmental restoration of the Passaic River adjacent to Newark, N.J. Yoon and Padmanabhan (1997) evaluated NPS pollution control for the upper Sand Hill River in eastern Minnesota by using a framework of a distributed-parameter-hydrologic model coupled with GIS and a relational-database-management system.

GIS was interfaced with a geomorphic-based-hydrologic and sediment-transport model to simulate six years of runoff and sediment data for a watershed in western Puerto Rico. The GIS/model interface is capable of modeling runoff and sediment yield over large spatial scales and is accomplished on an interactive basis in order to allow the user to have some decision-making ability (Mashriqui *et al.*, 1997). Hromadka and Yen (1997) coupled a stormwater-pollutant estimation analog to a flood-control-master plan linked to a GIS capability. The GIS functions developed land use versus area tabulations that readily input into pollutant-loading equations. A GIS based-NPS-source-simulation model was developed to simulate the hydrologic and NPS processes for the Fall Creek Watershed of New York and produced a daily-time series of estimated NPS-pollutant loadings of N and P into the Cayuga Lake (Dikshit and Loucks, 1996-1997).

An empirical-urban-stormwater runoff model, in conjunction with a GIS, was implemented in Santa Monica Bay of California in order to help identify catchments with the largest pollutant contributions. Single-family land use was responsible for contributing the highest amount of pollution with the highest concentrations in ten out of the 11 water-quality parameters tested (Wong *et al.*, 1997). Based on GIS analysis, increased preventive maintenance and rehabilitation of deteriorated sewers are two of the important elements in a program that San Diego, Calif. implemented in order to reduce SSO (Giguere *et al.*, 1997).

A decision-support and educational-software system, WATERSHEDSS (Water, Soil, and Hydro-Environmental Decision Support System) defined water-quality problems and selected appropriate control measures. The program provided management-/land-treatment decisions, assessed NPS pollution in watersheds, and used a GIS to model land-treatment effects on water quality (Osmond *et al.*, 1997). The use of the AGNPS or other ad-hoc interfaces between a distributed model and a GIS is a non-traditional method of watershed-water-quality modeling. These efficient interactive-modeling-environment systems have significantly reduced the task of watershed analysis through the use of coupled GIS databases and distributed models (Liao and Tim, 1997).

Haubner and Joeres (1997) applied a GIS to provide input parameters to the Source Loading and Management Model (SLAMM), an empirical urban-stormwater-quality model, for a small urban watershed located in Plymouth, Minn. The results demonstrated that the use of GIS in stormwater management could allow even small communities to reap the benefits of stormwater-quality modeling. Emrani (1997) addressed the integration of predictive modeling tools into a GIS which will serve as a decision-support tool to aid the development of improved maintenance plans associated with failure of storm drainage, water, and wastewater systems. Corwin *et al.* (1997) reviewed the modeling of NPS pollutants utilizing GIS as the environmental modeling tool.

## **Regulatory Policies and Financial Aspects**

## ***Policy***

Bradley et al. (2005) reviewed the US EPA's encouragement of having regulatory agencies issue watershed-based NPDES permits, rather than site-specific ones. The US EPA's water-quality trading policy for stormwater management and smart growth was reviewed by Trauth and Shin (2005). The issues that must be ironed out before trading can begin were identified, as well as potential solutions. Broviak (2005b) provided an overview of the US EPA's blending policy, where part of the sewer flow is fully treated and part is partially treated. The purpose of blending is to reduce the overall pollutant load in the effluent, but without sending destructive flows through the treatment plant.

Collaborative education and outreach activities are promoted by Aston (2005) as a means of producing effective nonpoint source pollution control. Pines (2005) outlined using NPDES permit requirements as a way of getting students involved in a service learning project. Gregg (2005) discussed the nonpoint source pollution control program used to protect California's beaches and ocean.

Boller (2004) reviewed the need to move towards sustainable urban stormwater management and the techniques that could be used to achieve that goal. New directives for the management of urban stormwater prioritize infiltration and direct discharge into receiving waters and this paper reviews the proposed technologies and what is needed to successfully implement them.

Almai and Ports (2004) reviewed the development of a vision, principles and priorities for an integrated stormwater management program for Kansas City, Missouri. Blumberg and Ferrando (2004) examined the use of watershed environmental management systems as a tool in municipal planning. This approach allows for integration of regulatory and non-regulatory programs using proven models such as the business franchise model, the business strategic plan model, and the environmental management systems (EMS) model. The master planning effort of the Duluth (Minnesota)/Western Lake Superior Sanitary District was reviewed by Bennett et al. (2004). The concerns of the master planning effort included primarily rainfall-induced I&I, which led to SSO events. A major outcome of the master planning effort was the development of a concept for the level of service the District will provide its satellite communities.

Christian et al. (2004) presented the Michigan Department of Transportation's perspective on an illicit discharge elimination program (IDEP). Instead of receiving more than 350 permits from the Department of Environmental Quality, MDOT received a single permit and approval for their IDEP as a general category.

The NPDES Phase II rules were summarized by Anonymous (2003a). Gardner (2003) reviewed case studies of water recycling in Australian urban environments, including the recycling of stormwater in urban areas. The first initiative was a centralized scheme based on local authorities recycling sewage effluent and/or stormwater in urban areas. The other type of initiative operated at a household scale (Healthy Home). Swamikannu et al. (2003) compared stormwater pollution prevention policies in California and in Victoria, Australia. The authors analyzed the different approaches used in Australia and the USA, commented on their comparative success, and discussed the relevance of the two experiences for developed and developing nations in the context of environmental policy making to control storm water and urban runoff pollution.

Gregory et al. (2003) presented a level of service (LOS) evaluation for stormwater performance assessments. A brief background on general asset management for stormwater systems and the concepts and philosophies of establishing LOS standards/objectives was provided. Christensen (2003) provided an overview of the Papillion Creek Watershed Planning Project in eastern Nebraska which was considered a success because it established the tools and partnerships needed for long-term watershed planning and assessment. The paper by Hawley and Godley (2003) discussed how the San Antonio Water System decided to protect the Edwards aquifer in a watershed that is undergoing urbanization. The authors presented an overview of how the San Antonio Water System is overcoming the challenge of meeting the 213 Edwards Aquifer Rule.

Ward et al. (2003) discussed the implementing of a stormwater utility in Edmonton, Canada. The rate model was area-based, and used property area and development intensity the means of proportionately allotting a stormwater fee to each customer. This approach reflected a realistic impact of each property on stormwater infrastructure and services. Wilber and Cole (2003) evaluated the Chesapeake Bay Programs' use attainability analysis (UAA) for nutrient reduction. Consideration was given to the potential of social impacts on growth and the displacement of growth to non-sewered areas. The evaluation included the potential of negative environmental impacts exceeding the benefits of the proposed



EPA water quality criteria.

Gregory and McLamarrah (2003) reviewed Houston's business plan for Continuous Improvement for Collection Systems. The outcome of this work is anticipated to be a reduction in the number of SSOs. Hawley (2003) asked about the impacts that developers have on sewer design and inspection programs and argued that it is critical that utilities have programs that look at opportunities to reduce O&M costs during the design process. Taube et al. (2003) discussed the strategic "how to" approach used by the City of Atlanta in implementing their Management, Operation and Maintenance (MOM) program. The program was designed as an integrated management system with established goals, objectives and schedules for the entire sanitary sewer utility, and reflective of the reality of available resources and resolution of any conflicting priorities. Tsay et al. (2003) reviewed the planning required for sewer separation in Boston, MA. An approach that linked an extensive field survey with collection system modeling was used to develop a sewer separation plan in the Stony Brook portion of Boston, MA. The goal of this separation was to reduce CSO discharges to the Charles River to two or fewer overflows per year.

Larson and Pearl (2003) reviewed a recommended O&M strategy for older, small-diameter clay sewer pipes that were failing due to joint breaks in the oakum and cement mortar, tar or hot sulfur used to seal the joints. This paper presented an overview of clay pipe service issues, a maintenance data analysis, and a cost model, based on actual maintenance data, for use in evaluating the real cost of continuing to maintain a pipe segment compared to the cost of replacement. The decision to replace now (or soon) was discussed in light of current and future costs and SSO standards.

Flores and Toth (2003) described the proactive programs and partnering used by the City of San Diego in responding to an EPA CWA enforcement action. Dorward et al. (2003) described the components of the consent decree in New Orleans, Louisiana, along with the tools, processes, education and contribution of stakeholders required to successfully fulfill the obligations of the consent decree. Farr (2003) reviewed the challenges presented to the City of Baltimore (MD) by the requirements and stipulations of the Consent Decree. The majority of areas that experience overflow activation are in wooded areas, near waterways, heavy traffic areas, and near major utilities crossings.

Agbodo et al. (2002a) reviewed the upcoming U.S. EPA CMOM regulations on SSOs. The paper highlighted the integrated watershed modeling approach for overall control, as opposed to the isolated capital improvement projects that address site-specific SSOs. Blackwell et al. (2002) presented the required elements for a system evaluation and capacity assurance plan, as required under the draft SSO regulations, if peak flow conditions contribute to an SSO discharge or to noncompliance at a treatment plant. The program elements include methods to determine the current capacity and the impacts of growth and new flows, confirming wet and dry weather flows in the system and a means of tracking existing legal obligations to accept new flows. Sullivan and Dwyer (2002) reported on the major findings of the EPA's CSO report to Congress. The objective of the report was to describe the nature and extent of activities in EPA and in the states to implement and enforce the CSO control policy. The major findings included that progress has been made in implementing CSO controls; communities have made substantial progress and are seeing the benefits in public health and water quality; the CSO policy provides a sound approach to assess and implement cost-effective CSO controls; and the CSO Control Policy fosters and expects significant involvement of the public and authorities in the process.

Jensen et al. (2002) reviewed the need for applying appropriate criteria for contact recreation, especially in streams negatively affected by wet-weather flow. The paper presented two methods for reducing these types of possibly inappropriate listings. One would be to assess physical suitability in the field and only screen data collected when the stream is suitable for the use. The other, that does not require field suitability determination, would be to exclude some high flow data where the use is not likely to be supported, based on watershed size and flow distribution.

After over 20 years of progress, many rivers, lakes and stream still failed to meet water quality standards (Kwan 2001). Studies and monitoring data have shown that stormwater runoff was a major source of water quality impairment. Currently, five regional states have reported stormwater runoff as a major cause of water quality impairment. An effective, integrated and coordinated storm water enforcement strategy will need to be established in full partnership with the eight Region 4 states.

EPA has been completing a series of federal initiatives to address wet weather discharges due to CSOs and SSOs (Hall et al., 2001a). As a result, communities nationwide will need sewer system/treatment plant improvements to address these wet weather discharge issues. Little attention has been paid thus far to a series of subtle changes in EPA's implementation of its existing bypass regulations and secondary treatment requirements for controllable CSO and SSO flows. Reducing

wet weather discharges is a core activity of EPA's Office of Wastewater Management (Cook 2001). The office's programs include combined sewer overflows, sanitary sewer overflows, storm water, and animal feeding operations. Several current regulatory initiatives have been designed to improve water quality by reducing the environmental impacts of wet weather events. Bell and Powell (2001) described the pending SSO regulations, where there are three standard permit conditions for sanitary sewer collection system owners: capacity, management operation and maintenance (CMOM); prohibition on SSOs; and reporting, record keeping and public notification. The paper focused on the CMOM aspect of the permit conditions. Although the SSO Rule is not currently effective, Sowatzka et al. (2001) advocated using the draft Rule to provide system owners and operators guidance on EPA's expectations for systems, including satellite facilities, for their (CMOM) program.

Centilla and Slack (2001) reported on the outreach efforts of the EPA. EPA has been working with stakeholders during the "toolbox" development. The "toolbox" includes fact sheets, case studies, technical guidance documents, training and outreach efforts, sample self-audit reports, sample model ordinances, technical research, and compliance monitoring and assistance tools. The paper by Foess and McNitt (2001) presented the methodology, scope, and key results of collection system management, operation, and maintenance (MOM) program audits for two Florida wastewater utilities. Selected MOM program performance metrics for the two utilities were compared to data from other well-operating utilities and published guidelines in order to assess the effectiveness of the programs. In mid-2000, the City of Thousand Oaks's Public Works Department updated its Wastewater System Master Plan (Giguere et al., 2001). Anticipating the future Sanitary Sewer Overflow (SSO) Rule and the Capacity, Management, Operations, and Maintenance (CMOM) program requirements, the City included in the Master Plan a task to perform a preliminary CMOM program assessment. Integrating the CMOM assessment into the Master Plan provided a convenient mechanism for the City to tap into the expertise of the engineering consultants who were working on the Master Plan.

Gwinnett County, Georgia recently revised their storm water regulations in order to improve the water quality in the county's receiving streams and to meet the designated uses of the waters for fishing and drinking water supply (Chastant 2001). To meet that goal, a Watershed Protection Plan was developed, with the six major components being public education/participation, pollution prevention, development regulation, planning, engineering and construction, and maintenance. The current management strategy has been based on four key storm events: protection from major flooding events, overbank flooding bank protection from moderate events, channel bank protection for the 1-year storm, and water quality treatment for rainfall events of 1.2 inches and smaller. Atlanta's Clean Water Initiative was developed in order to coordinate water resource management for the Atlanta region and to generate the political momentum necessary for implementation (Green 2001). The task force recommended the creation of a "Metro Atlanta Water Planning District," which would be charged with developing watershed protection, wastewater, water supply and conservation plans. These recommendations and the District were enacted into law in 2001. In 1999, the City of Atlanta completed negotiations with the EPA and the Georgia Environmental Protection Division (EPD). The consent decree and an amendment required implementation of management, operation and maintenance (MOM) plans for CSO treatment facilities, Water Reclamation Centers (WRCs) and gravity wastewater collection and transmission systems (Griffin and Sukenik 2001). The MOM plans for the wastewater collection and transmission systems included emergency response plans; long- and short-term operation plans; maintenance plans; pump station evaluations; grease management plans; sewer mapping plans; safety and general training plans; and a short-term capacity certification plan. Hamid et al. (2001) presented an overview of Atlanta's Wastewater Systems Improvement Program. Three specific regulatory requirements drove this program: Senate Bill 500 enforcing phosphorus level compliance at WRCs and CSO control facilities by December 2000; the CSO Consent Decree requiring completion of the long-term plan by 2007; and a second Consent Decree requiring WRCs, pumping stations and sewer improvements by 2014. The City's preferred option for the CSO plan included consolidated storage/conveyance tunnels, two CSO treatment facilities, and sewer separation in selected areas costing about \$1 billion. The total capital cost of the program was estimated between \$2.5 and 3 billion with a 14-year completion schedules. In November 1997, a Federal District judge ruled that the City of Atlanta's CSO discharges violated water quality standards for metals and fecal coliform. In addition, the Georgia EPD required compliance with water quality standards at the point of discharge for CSO facilities with no allowance for dilution (Richards and Kreutzberger 2001). Data is being collected in order to characterize water quality related to metals toxicity.

Clark et al. (2001a) combined hydrologic models of flood control and biotic models of ecologic risk with economic models of willingness-to-pay and psychological models of risk processing and planned behavior in order to evaluate these two alternative policy objectives. The findings reveal that flood risk exposure does influence the willingness-to-pay of local residents for a flood control project. Other important determinants include demographic factors, such as income, and attitudinal measures of the respondent.

The Department of Natural Resources in Queensland, Australia conducted the Queensland Water Recycling Strategy (QWRS) to determine future Government directions in water recycling (Gibson and Apostolidis 2001). This strategy considered the beneficial use of all waste streams such as domestic sewage, industrial and agricultural wastes, as well as urban stormwater. The Urban Development Corporation (UDC) in Japan developed a new system, a “Rainwater Recycle Sewer System” (Matsushita et al., 2001). This system is supported by “Rainwater Storage and Infiltration Technology (RSIT)” for new town creation and urban renewal. The new system consisted of two elements: RSIT components based on Public-Private Partnership (PPP) and a stormwater drainage system. The private sector is responsible for the main part of RSIT, and the public sector is responsible for the stormwater drainage from the development area.

Augustenborg and Duke (2001) evaluated the effectiveness of current regulations for stormwater pollutant control from industrial facilities, and resulting efforts by the regulated community to reduce pollutants. Using the Notice of Intent filed by industries in three municipalities, trends and patterns of compliance were characterized. The research has evaluated the relative effectiveness of municipal programs at achieving the pollutant reduction goals of the storm water NPDES regulations. The wastewater and stormwater infrastructure in the U.S. was a significant financial investment; however, the maintenance of these systems has often been lacking (Kosco et al., 2001). Maintenance problems on private lands, particularly I/I from private sewer laterals, have been shown to represent a significant part of the water quality problems on a system. Many communities have aggressively addressed O&M issues of wastewater and stormwater systems on private property, with these programs backed up by local ordinances with penalties. Recently, Portland, Oregon revised their Erosion Control Program to have almost a zero tolerance for erosion and sediment leaving a site (Lauder 2001). The program also placed additional controls on construction site pollutants. The program required some new technology, but mostly management techniques and management issues were targeted. PDR Engineers, Inc. and the Louisville and Jefferson County Metropolitan Sewer District (MSD) produced the Watershed Approach to Environmentally Responsible Stewardship (WATERS) of Jefferson County report (Potempa et al., 2001). The report reviewed MSD’s activities involving the Municipal Separate Storm Sewer System (MS4), the Combined Sewer Operational Plan (CSOP), and the Sanitary Sewer Overflow Abatement and Elimination Plan (SSOAEP). The unique nature of the WATERS report is that the reader can view information from a programmatic and watershed approach. The Louisville and Jefferson County MSD prepares facility and watershed action plans with 20-year planning horizons (Wilson et al., 2001). This allows consideration of multiple factors, such as population projections, land use, environmental conditions, capital and operation and maintenance requirements, political issues, projections of economic conditions, etc. Using the multi-variable risk model has allowed MSD to assess the performance of a wastewater service area configuration over a range of views of the future.

The Federal Water Pollution Control Act Amendments of 1972 (a.k.a., the Clean Water Act (CWA)) mandated that States lead aquatic resource protection and restoration activities. Congress directed the states to establish water quality standards for waterbodies based on use, identify waters that were not attaining those standards, and develop plans to improve the impaired waterbodies (Savage 2001). As Congress fashioned the statute, the EPA’s role was to oversee the program. Although the Total Maximum Daily Loads (TMDLs) statutes (§303(d)) have not changed, the regulations promulgated by the USEPA regarding TMDLs have grown more complicated. While §303(d) and its regulations are a comprehensive approach to water management, they also have the potential to become a bureaucratic exercise in meeting deadlines and satisfying requirements that do not improve or protect the nation’s water resources. Cited causes of impairment are often from sources that are not managed under Clean Water Act programs (Staveley et al., 2001), and are instead regulated under other statutes. These include sources such as atmospheric emissions, discharges of groundwater contaminated by past waste disposal practices, surface runoff from inadequately controlled landfills, historically contaminated in-place sediments, and the legal application of pesticides and herbicides. Thus, the possibility exists for overlap or conflict between the TMDL regulations and other statutes. Additional complications have arisen when comparing the provisions of the Safe Drinking Water Act (SDWA) and the Endangered Species Act (ESA) with the CWA.

The year 2000 saw several new stormwater regulations issued nationally, and a variety of guidance documents published in support of new and existing regulations. USEPA published the final Storm Water Phase II rules in December, 1999 (Anonymous 2000b), and the members of the Sanitary Sewer Overflow (SSO) Federal Advisory Subcommittee voted unanimously to support the EPA’s draft proposal for developing federal SSO regulations (Anonymous 2000a). EPA also announced plans to release a draft guidance on water quality and designated use reviews for combined sewer overflow (CSO) receiving waters in April, but not everyone was satisfied with the current guidance outline (Anonymous 2000c). Urban and agricultural wet weather sources were named as the most significant causes of impairment to our Nation’s rivers and streams. However, these “impairments” were typically assessed in reference to water quality standards

developed in the context of historical efforts to control dry weather wastewater sources. Therefore, the significance of wet weather impairments and the need for costly controls was debatable. Freedman (2000) explored the issue of wet weather water quality standards for CSO impacted waters, provided an overview of the obstacles to undertaking and completing the water quality standards review and revision (WQSRR) process, and included a summary of the steps that EPA and other organizations are taking to support scientifically sound and regulatory compliant WQSRRs. The amount of hydrocarbons allowed in industrial and stormwater effluents has been found to vary greatly from one locality to another or from one country to another. Some countries have mandated hardware solutions to the effluent problem, while others have stipulated a specific concentration allowable. Mohr (2000) presented the regulations governing effluents in many countries, as well as states and localities within the US and offered discussions of some of the hardware systems required by various jurisdictions. Implementation of the Total Maximum Daily Load (TMDL) provisions of Section 303(d) of the Clean Water Act has been shown to impact both point and nonpoint sources of pollution. Programs related to TMDLs often have reached beyond the purview of the agency responsible for the TMDL and have crossed into programs that operate under different regulations administered by other agencies. TMDLs thus will have significant cross-media and cross-programmatic impacts (Staveley and Christman 2000). The Center for Environmental Research and Service (2000) at Troy State University, Alabama published a guide to developing a storm water control program to comply with Phase II requirements.

Other regulatory issues involved local stormwater managers trying to develop stormwater management efforts that meet both local needs and regulatory requirements. As currently designed, TMDL limits are based on the assumptions that there is a direct correspondence between the total mass of waste loads and ambient water quality, and that an annual cap on total wasteload allocations (WLAs) can sufficiently maintain water quality. Based on a study of the nutrient loads and water quality in the tidal freshwater Potomac River over the period 1985-1995, Sklarew (2000) suggested that hydrology was an important factor to consider in developing adequate WLAs for metropolitan tidal rivers. Furthermore, the hydrograph could be a vital tool in designing flexible and adaptive TMDLs for such areas. The City of Portage, MI has pioneered a comprehensive approach to storm water management in light of the Phase II Storm Water regulations. The city has endeavored to define "Maximum Extent Practicable" (MEP) within the constraints of available space for treatment facilities, city budget, and community support. This approach could be used by other municipalities with existing infrastructure and limited controls that now face similar storm water regulations. The approach illustrated opportunities and benefits of storm water controls implemented beyond the minimum requirement (Breidenbach et al. 2000). In November 1999, the City of High Point, North Carolina adopted a watershed protection ordinance that initiated "Phosphorus Banking" and provided greater water quality protection than the state requirements while also accommodating planned growth. Brewer et al. (2000) documented the watershed assessment and modeling approach, the successful involvement of key stakeholders, and the innovative phosphorus banking strategy.

A major effort, the Use and Standards Attainment (USA) Project, was launched by the New York City Department of Environmental Protection in August 1999 as part of its continuing efforts to maintain and improve water quality in New York Harbor and its environs. With the active participation of major stakeholders, a watershed-based approach was used to conduct an integrated evaluation of the interdependent factors affecting receiving water uses, including storm water, combined sewer overflows (CSOs), wastewater treatment, upland uses, shoreline uses, habitats, sediment and water quality (McMillin et al. 2000). The New York City Department of Environmental Protection enacted final watershed regulations prohibiting surface discharges from wastewater treatment plants, and subsequently stopped the Kent Manor housing project in the Town of Kent, Putnam County, New York. The watershed regulations included provisions for a pilot phosphorus offset program, whereby projects within the watershed with surface discharges would be approved, provided that any increase in phosphorus loading would be offset somewhere else in the watershed. van der Heijden (2000) described the steps taken to offset expected phosphorous loadings from the Kent Manor project by reducing phosphorous discharges elsewhere in the watershed. Vlier and Sandquist (2000) highlight some lessons, guidelines, and patterns emerging from the growing field of watershed-based trading. by identifying the similarities and differences in program design and linking key elements to scientific, economic, and institutional conditions in the watershed community.

The Rouge River National Wet Weather Demonstration Project in Michigan (Rouge Project) has attempted to identify the requirements of a generic comprehensive watershed management plan to meet multiple program objectives, requirements or recommendations in a wide range of individual Federal, State, and local programs to restore and protect water resources. Cave et al. (2000) identified what the Project found to be the crucial elements of a "comprehensive watershed management plan" in order to achieve multiple program objectives, such as the reissuance of NPDES permits on a watershed basis, implementation of the water quality trading programs that are currently under development,

implementation of the Section 319 non-point source program, development and implementation of Watershed Restoration Action Strategies envisioned under the Clean Water Action Plan, implementation of monitoring programs and for addressing the requirements of the TMDL program. McDonald et al. (2000a) presented the preliminary findings, conclusions, and recommendations for the development of a pollutant load trading program and the modification of the existing nutrient (nitrogen and phosphorous) and TDS TMDLs and WLAs on the Truckee River, Nevada. As a result of the TMDL process, the Truckee Meadows Water Reclamation Facility had WLAs incorporated into their NPDES permit, resulting in potential restrictions on planned growth. In order to accommodate for planned growth and to meet water quality objectives, a pollutant load trading program to develop “watershed offsets” was beginning implementation. McDonald et al. (2000b) described a multiyear project to develop revised TMDLs and a pollutant-load trading program for the Truckee River.

Additional papers examined community and political issues related to WWF control programs. Lindsey et al. (2000) explore five programs led by EPA’s Office of Water that address today’s environmental issues in wastewater management. Many of the programs are voluntary but regulatory programs continue to play a role in wastewater management. Through humor, Jones (2000) focused upon constraints that now inhibit a watershed solution to environmental, multi-media problems, and proposed potential remedies. The Tollgate Drainage District (Ingham County, Mich.) had to convince reluctant stakeholders that a sewer separation and stormwater outlet project had to be undertaken (and locally funded). After 2 years of education and outreach, the stakeholders not only accepted that a solution was needed, but approved a nontraditional approach (Lindemann 2000). Topping (2000) reviewed what the business community was hearing about planning and linking the planning directly to a watershed approach. Lessons from management consultants were matched to startlingly similar advice from watershed experts from federal, state and private organizations. Recommendations to focus on action and avoid “paralysis by analysis” provided a refreshing perspective for those burdened with the minutiae of the often interminable planning process (Topping 2000). It was shown that if all social and political needs of the community were not considered and addressed in a watershed protection effort, a proposed project, though technically sound and within budget, likely still would meet with significant community opposition. Halloran et al. (2000) presented one project where a front-end loaded, proactive, community oriented approach turned neighborhood opposition into enthusiasm. A new comprehensive land use plan was recently adopted to guide development of the undeveloped land area in the City of Battle Creek, Michigan. The results of this project would allow the City to gain a Certificate of Coverage under Michigan’s Voluntary General Permit for Municipal Storm Water Discharges, which has been accepted by the EPA as fulfilling the requirements of the Phase II Storm Water Regulations. As a result of performing this project, the City of Battle Creek, Michigan has learned the value of gaining stakeholder input during the watershed planning process, and has formed a Steering Committee to guide the implementation of the proposed Watershed Management Plan (Scholl et al. 2000). The decision to include the public in public works and utility projects has often been made without any ‘real’ consultation with the public or consideration of the issues that the public would be interested in. Kunz et al. (2000) discussed how the right amount and type of public involvement early in the project planning process could mean the difference between a successful project completed on time and within budget or a cancelled project after millions have been spent on design.

WWF control policy in the United States, including the ongoing implementation of EPA’s Phase II stormwater regulations, prompted a number of publications. Despite the world’s most sophisticated regulatory system, and an unprecedented level of public and private investment in wastewater infrastructure, 44% of the United State’s waterways were still unsafe for fishing and swimming, largely due to urban WWFs such as CSO and stormwater discharges. Guta (1999) discussed the challenges of identifying and managing this ubiquitous source of pollution and building sustainable cities for the future. Calamita (1999) reviewed legislation that was considered in Congress, especially the CSO Control and Partnership Act of 1999 - H.R. 828 and S. 914, and the draft Urban Wet Weather Priorities Act, both of which were intended to help create wet weather uses and standards in the United States. The paper also reviewed EPA’s efforts to comply with language added to their budget for this year that requires that they develop a guidance document to facilitate wet weather use reviews nationwide. EPA has made significant efforts to comply with this congressional mandate thereby greatly enhancing the prospects for wet weather use reviews nationwide. While the apparent direction of EPA’s Phase II stormwater regulations due to be promulgated in September 1999 appeared to encourage the use of the watershed approach, the details in the regulation do not reflect that theme.

A comparison of the directions the Phase II regulations appear to be taking and the approach of the Rouge River National Wet Weather Demonstration Project in Southeast Michigan was made and discussed by Cave et al. (1999). Murray et al. (1999) described the lessons learned in building institutional and regulatory frameworks necessary to accommodate a watershed approach to wet weather pollution management by Wayne County's (Michigan) Rouge River National Wet

Weather Demonstration Project. Also described were the consensus building strategies that were used to engage numerous stakeholders, provide them opportunities to influence decisions, and participate in the Rouge River restoration.

Hudson (1999) discussed EPA efforts to encourage the use of decentralized wastewater treatment systems by focusing on encouraging alternative technology where appropriate, promoting management systems, and coordinating its initiatives with other ongoing efforts nationwide. The EPA Long-term CSO Control Policy "Presumptive Approach" provides guidance for specific levels of control, namely, no more than four overflows on average per year or the elimination of no less than 85% of volume of the combined sewage collected in the entire system on an annual basis. The EPA believed that there was a general "equivalence" between the performance criteria that specify "percent capture" and the "number of overflows." However, Morgan et al. (1999) demonstrated a wide variation between the storage controls developed under either of these criteria, and recommended that the municipalities should look at the site-specific nature of the CSO problem, and develop control alternatives accordingly.

A Natural Resources Defense Council report supported EPA's proposed rules to clean up stormwater runoff and storm sewer discharges in small cities and noted that the proposal's cleanup strategies have been successfully employed by more than 150 urban towns. At the same time, however, some states were complaining that the EPA proposal would undermine many state-run programs already in place (*Environmental Science & Technology*, 1999). Until now, no legal principle has been used to ensure that equity and economics were incorporated into the TMDL adoption and allocation processes. However, Clean Water Act section 305(b) may be a viable vehicle for finally including these concepts into the TMDL process (Thorne, 1999).

Stormwater discharges associated with industrial activities must be characterized for effective analysis of pollutant loads in urban watersheds. Regulatory compliance lists and inventories developed for other purposes may be poor estimators of discharging facilities. This research evaluated usefulness, flaws, and limitations of multiple forms of existing databases; then demonstrated methods to assess, combine, and correct databases to refine estimates of potentially discharging facilities in a given region (Duke et al., 1999). This research evaluated compliance with U.S. pollution prevention regulations from stormwater discharges associated with industrial activities, focusing on facilities that had failed to complete first-stage compliance requirements ("filed") approximately 5 years after the regulations took effect (Duke and Shaver, 1999). In the City of Bergen, Norway, extensive measures against point pollution sources were implemented and to be finished before the end of year 2000 for improving the receiving water conditions. Future improvements in the receiving water quality was planned through different measures aimed at reducing stormwater-meltwater runoff which causes surface pollution washoff and CSO (Thorolfsson, 1999).

Field et al. (1998) described the U.S. EPA's WWF management and pollution control research needs and anticipated research directions for the next five years, and covered areas of characterization and problem assessment; watershed management; toxic substance impacts; CSO, SSO, and stormwater runoff pollution control; and infrastructure improvement. A summary of Volume 1 of a two volume manual developed by the U.S. EPA's Office of Wastewater Management and Office of Research and Development provides a process for effective decision making and long-term planning, suggested practical guidance for municipalities to best implement their stormwater management programs, and provides a watershed protection approach (Liao et al., 1998b).

Weatherbe et al. (1998) highlighted the findings and status of implementation for WWF management of the Pollution Prevention and Control Plans funded by Environment Canada's Great Lakes 2000 Cleanup Fund and the Ontario Ministry of the Environment. American cities evolved from dense urban areas to contemporary low-density suburbs with open space. Multi-functional urban stormwater projects can be integrated into the drainage structures of cities' civic, recreational and ecological fabrics and the redevelopment of the Stapleton International Airport in Denver, Colo. is presented as an example (Wenk, 1998).

A proposed method to assess and communicate the relative public-health risk associated with coastal recreational water use in San Diego County, Calif. is based on point-source and NPS information and will be displayed geographically (Gerheart et al., 1998). Elliott (1998) determined expected rate of illness for ocean bathers near an outfall based on temporal frequency distributions of indicator bacteria concentration coupled with a concentration-response relation. Hurt (1998) presented some methodologies used to heighten public awareness for CSO related issues using Detroit (Mich.) Water & Sewerage Department's Long Term CSO Control Program policies as an example. The Surfrider Foundation started the Blue Water Task Force in 1990 and initiated a water testing program designed to evaluate human health risks from swimming and surfing in polluted water. The water testing program taught the activists that the problem with the

beach-water quality was urban runoff and Surfrider activists stenciled signs on street gutters to educate people that all street gutters were connected directly to the beach (Labeledz, 1998).

After 100 years of industrial development, the Emscher area in Ger. has been presented with the need for environmental restoration and social changes (Geiger and Becker, 1998). Special attention has been paid for the choice of the future drainage system linking source control by infiltration of stormwater with collection and treatment of polluted runoff and currently a large number of pilot projects are underway which show the need for public participation to accept new technologies. Geldof (1998) reviewed urban water management in the Neth. over the last few years and provided some suggestions to cope with emissions from sewer systems, peak discharges, high ground water levels and dehydration of soil in agricultural areas and nature reserves. The solution for urban runoff and water quality management in the Birkeland basin Sandsli, Bergen, Nor. is based on urban hydrological planning and the new blue-green concept in the urban stormwater management that uses the capabilities of the basin to store runoff and melt water and to reduce pollution (Thorolfsson, 1998). The goal is to manage runoff and water quality in a way that reduces environmental damage at the lowest possible cost. The Oakland Ravine Stormwater Treatment System project was developed as part of the NYC comprehensive program to reduce CSO discharges into receiving waters (Dinkle, et al., 1998). The project reduced discharges into Alley Creek in Queens, addressed stresses and disturbances identified within Oakland Ravine and Oakland Lake, i.e., erosion and lack of vegetation on the slopes of the ravine and deterioration of water quality, and created a natural park setting in an urbanized area. As the principal permittee of the new Los Angeles (L.A.) County Municipal Stormwater NPDES Permit, the L.A. County Department of Public Works, Calif. is undertaking one of the most comprehensive water quality monitoring programs of any municipal stormwater program in the country. The program features water quality monitoring of storm and dry weather flows from both mass emission and land-use specific drainage areas, an illegal connection elimination program, a critical source monitoring program, and a receiving-waters impact study (DePoto et al., 1998). Swamikannu (1998) reported on the process followed to reach agreement on the municipal stormwater and urban runoff program in L.A. County, Calif., the progress to date and imminent challenges that lie ahead.

Most industrial facilities in the L.A., Calif. area inadequately evaluated activities with the potential for stormwater pollution and most prepared incomplete plans for stormwater sampling and inspection procedures (Duke and Bausersachs, 1998). Only 35 to 40% of the metal plating facilities in the L.A. region recognized the need for first stage compliance to stormwater pollutant regulations. Preliminary results in evaluating compliance with stormwater regulations by industrial facilities in Calif. suggested that many facilities identified in broad-based databases do not need to comply because activities on site do not meet conditions specified in regulations (Duke and Shaver, 1998). Although industrial activities are identified as one source of pollutants in stormwater discharges from urban watersheds, the proportion of specific pollutants from industrial activities relative to other urban activities remains poorly understood. Doll et al. (1998) reviewed the key legal, financial, institutional, and political issues in setting up a stormwater facility.

A comparative study of variations in stormwater management approaches and regulations revealed additional commitment is needed to improve the water quality of the bay for several states in the Chesapeake Bay watershed (Sherman and Dee, 1998). The Mass. Water Resources Authority (MWRA) (Hornbrook et al., 1998b) developed a long-term plan for CSO control based on U.S. EPA's CSO control policy using the demonstration approach. Review of the plan by the U.S. EPA and the Mass. Department of Environmental Protection indicated that the demonstration approach was not a clear-cut process, in part due to different interpretations of the CSO control policy by the parties involved. Heath et al. (1998a) presented the process followed by MWRA to document compliance with the criteria for a successful demonstration under the U.S. EPA CSO control policy. Facilities planning for controlling CSO in the greater Boston, Mass. area in accordance with a federal court schedule were finished in July, 1997. In a study comparing four midwestern stormwater ordinances and their effects on a hypothetical subdivision, Schuller et al. (1998) found that although detention storage is required virtually everywhere in the midwest, the requirements and the resulting storage basin sizes can differ greatly. A reoriented stormwater management approach (Swietlik, 1998) should continue to address undesirable chemical changes, changes in flow rates and volumes, changes in other physical characteristics such as habitat, temperature, and DO, and maintain targeted watershed balances for nutrient cycling.

The new national water policy adopted by the S. Afr. Parliament established an integrated catchment management system for ambient water quality and point and NPS of aquatic pollution (Marjanovic and Miloradov, 1998). The repercussions of this policy and a proposed method for continuous water quality assessment are considered. D'Arcy (1998) presents a review of Scottish policies dealing with stormwater management including the formation of the Scottish and Northern Ireland Forum for Environmental Research (SNIFFER), the Scottish Environmental Protection Agency (SEPA), and some

homegrown Scottish BMP to deal with poor water conditions as a result of urban runoff. Lawrence (1998) outlined the national approach to stormwater management in Aust. including implementation practices by both state and local government powers.

Lee (1997) discussed issues and regulatory requirements related to the privatization of water and wastewater services in Latin America. Lyon (1997) examined privatization law as it applies to water management in Europe and in the United States and classified it into three categories: institutional, management, and product law. In addition, Corssmit and Brunson (1997) discussed the transition of the Fairbanks Municipal Utilities System to private ownership, including water, wastewater, electric, steam heat, and telephone utility in and around greater Fairbanks, Alaska.

The degree of compliance in the industrial sector for General National Pollution Discharge Elimination System (NPDES) permits is not readily determined (Duke and Beswick 1997). Data for California statewide and for the Los Angeles region show about 8% — 15% of motor-vehicle transportation facilities have complied with first-stage requirements and facility-specific evaluation in one Los Angeles County watershed suggests <50% of facilities in the industry conduct industrial activities of the kind covered by regulations; others need not comply. Luppold (1997) found considerable variation in permit cost and requirements of state and federal stormwater-discharge permits for the wood-products industry and sawmills versus chromium-copper-arsenic treating facilities. The variations in monitoring requirements appeared to be the result of different priorities and varying levels of human and financial resources and the continuous evolution of federal regulations. The renewal of the deadline for the NPDES permits was discussed. Phase I and II applications were outlined with listings of facilities covered by phase I and II permits (Christou, 1997). Ford *et al.* (1997) demonstrated and outlined the proper completion of a NPDES application..

Small CSO communities may not be required to complete each of the formal steps outlined in the National CSO Policy. Shamsi and Scally (1997) provided insight into the small community aspects of the CSO Policy as well as identified the opportunities to take advantage of the small system considerations of the Policy. Morgan and Rowe (1997) presented how the Water Works and Sanitary Sewer Board of Montgomery, Ala. reorganized to meet the uniform operational and maintenance requirements and other provisions of the U.S. EPA's draft SSO Policy/guidance document.

The U.S. EPA is working with farmers, state regulators, and environmental groups to craft a program to address NPS runoff from farming operations. These efforts are an attempt to comply with the expanded Clean Water Act's (CWA) discharge permit requirement for large pollution sources (Cooney, 1997). The U.S. EPA (1997f) published a comprehensive report on the monitoring of NPS which defined and categorized NPS, described analytical- and biological-monitoring techniques and provided data-analysis techniques, quality assurance and quality control. The total maximum daily load (TMDL) program is a water quality policy, released by the U.S. EPA, requiring state controls on NPS of water pollution (Environ. Sci. Technol., 1997a). The U.S. EPA and the Environmental Law Association have teamed up on a project which consists of the assessment of relevant state laws and incentives in order to help states combat NPS water pollution (Environ. Sci. Technol., 1997b). The U.S. EPA is funding 20 National Monitoring Program projects implemented to determine the most cost-effective BMP for preventing NPS pollution (Richman, 1997b).

Roesner and Rowney (1997) reviewed the stormwater-quality regulations of six major industrialized nations: the United States, Canada, the United Kingdom, Germany, Australia, and Japan. The differences among these countries reflected the culture of each individual country.

### **Reuse and Water Resources**

He *et al.* (2006b) discussed enhancements to the urban infrastructure investment planning practices to offset the consequences of changing climate. The case study evaluated the resiliency of the existing drainage system to changes in the runoff hydrology of the flows entering the system.

Massoud *et al.* (2006) investigated the factors influencing the development of management strategies for a Lebanese river. The results showed the importance of anthropogenic influences on river water quality. Jain (2006) proposed the concept of bio-drainage for flood prevention and water scarcity avoidance in India. This proposal would combine restoration of natural drainage and storage areas with man-made structures.

Mitchell (2006) reviewed the Australian experience in integrated urban watershed management. Radcliffe (2006) discussed future directions for water recycling in Australia, including strategies to increase the use of recycled water, stormwater and rainwater. Hatt *et al.* (2006a) discussed the integrated treatment and recycling of stormwater in Australia.



The review of existing stormwater recycling systems focused primarily on the recycling of general urban runoff (runoff generated from all urban surfaces) for non-potable purposes. Chanan and Woods (2006) reviewed total water cycle management activities in Sydney, including a complete review of current water management strategies. Marks et al. (2006) described a South Australia development that integrates local water resources. The use of urban stormwater in an apartment development in Melbourne (Australia), including the treatment required prior to use, was outlined by Goddard (2006).

Stedman (2006) reviewed the centralized and decentralized approaches used in the United States and United Kingdom for urban stormwater management. Scholz et al. (2006) reviewed the Glasgow (Scotland) sustainable urban drainage system (SUDS) management project. Their results showed that a combination of infiltration devices and underground storage were the most likely SUDS options for the demonstration site. Zavoda (2006) reported on the New York City high rise that uses a water reclamation system to collect rainwater for reuse in irrigating two green roofs.

McCann (2006a) described the rainwater harvesting planned for Seoul, Korea. Rivard et al. (2006) discussed the application of stormwater management strategies in tropical countries, where rainfall amounts are substantially larger than in other regions. This paper presented specific elements to be considered, and highlighted the particulars which often prevent the approaches used in temperate climate for stormwater management to be applied without adjustments in tropical areas. Wang et al. (2006d) described the integrated water management in an urban area in China. These management techniques included steps to protect the area's ecology.

Hunt et al. (2006b) proposed a water efficiency rating system for land developments using integrated urban water management. Hwang et al. (2006) described public perceptions and attitudes toward stormwater recycling for irrigation in Canada. Concerns were expressed by the public regarding water quality and health risks. Landers (2006b) presented a Massachusetts project which combines smart growth and sustainable design, including the collection and use of roof runoff for landscape irrigation. Larson and Sanchez (2006) reported on the implementation of stormwater management during a recent renovation at a football stadium.

Jorgensen et al. (2006) discussed the role of uncertainty in the relationship between fairness evaluations and the public's willingness to pay, especially as it applied to stormwater management. The study concluded that uncertain individuals generally were not more likely than other participants to draw on either fairness evaluations or pro-environmental attitudes in decision-making for stormwater pollution abatement. Smith et al. (2006) reviewed the public outreach campaign used in a California district to garner support for the construction of a new pump station in a residential neighborhood.

Brown et al. (2006) discussed the impediments to implementing an institutional approach to urban stormwater management. One impediment identified by the authors was the assumption by administrators that there is a technical solution to water management. Miller (2006) discussed integration of concepts in water reuse and the barriers to reuse implementation. Grace (2006) reviewed the considerations faced by municipalities who are planning offshore stormwater outfalls. Hook (2006) reviewed the concerns investigated by federal regulators regarding stormwater runoff management at a housing development in Kansas.

The International Rainwater Catchment Systems Association was formed in 1989 and developed affordable rainwater catchment systems development guidelines to provide a common ground for the public and private sectors to solve water supply problems (Fok, 1998 a and b). Mitchell et al. (1998) described the components of urban water demand in terms of quantity and quality and discussed the opportunity for using stormwater and wastewater in Aust. Göransson (1998) proposed and reviewed stormwater projects that have aesthetic and architectural qualities for future urban environmental developments. The town of Mersing, Johor, Malaysia, identified the importance of beautification and landscaping of drains and waterways as part of the drainage and flood control plan. The landscaping of the drainage reserves and waterways will not only improve the urban drainage system and the aesthetic visual quality of the area, but will also promote the image of Mersing as a tourist destination (Chin et al., 1998a).

Anderson (1996a, 1996b) described new initiatives for reusing stormwater for urban-residential- and industrial-water-supply systems in Australia. Mitchell *et al.* (1996) analyzed urban-catchment drainage by using a water-budget approach to integrate storage and reuse of stormwater and treated wastewaters for two sites in suburban Melbourne, Australia.

Nelen *et al.* (1996) described the planning of a new development for about 10,000 people in Ede, Netherlands considering a dual-water-supply system. Storing the treated wastewater on-site during wet-weather periods can be more attractive than only using black water for reuse (Pruel, 1996). Herrmann and Hase (1996) described rainwater-utilization systems (RWUS) in Bavaria, Germany saving drinking water and reducing the roof runoff to the sewerage system.

### ***Watershed Management***

Polaskova *et al.* (2006) proposed an integrated approach to protect an urban catchment area for indirect water reuse. This theoretical investigation analyzed the dynamic interaction of CSOs, wastewater plant effluent and receiving water, and included using real-time controls in the sewer system to maximize storage and minimize CSO events. Bries and Rook (2006) reviewed the preventive maintenance program adopted by Olathe, Kansas.

Taylor and Fletcher (2006) proposed a methodology to assess urban stormwater projects. The methodology has three levels of evaluation. The paper discussed how assessment methodologies that evaluate the financial, ecological and social dimensions of projects can, under some circumstances, be used to evaluate the relative progress of options for urban water management. Zhen *et al.* (2006) presented a stormwater control analysis system for watershed-based stormwater management. The tools supported watershed analysis, innovative stormwater control selection and optimization. The system incorporates a meta-heuristic optimization technique to find the most cost-effective placement and implementation plan given a control target, or a fixed cost.

A review of the requirements for stormwater pollution prevention plans, including the need to keep the plans updated, was provided by Goodemote (2005). The paper by Brach and Zeytinci (2005) reviewed the thought processes involved in the investigation, analysis and design of alternative solutions for the remediation of an urban flood. The study briefly discussed the many facets involved in an acceptable engineering solution, including the engineering (hydrologic and hydraulic) considerations, the social, economic, political and legal aspects of the problem.

Brooks *et al.* (2005) reviewed the research needs for assessing on arid and semi-arid ecosystems where effluent is the dominant water flow source. Issues addressed included identifying reference streams, understanding the effects of ephemeral flows, etc. Brown (2005) presented potential impediments to integrated water and stormwater management, including, as the author sees it, historically entrained forms of technocratic institutional power and expertise, values and leadership, and structure and jurisdiction. The solution, according to the author, would institutionalize change specifically directed at fostering horizontal integration of the various functions of the existing administrative regime. The effect of TMDLs on municipal stormwater management and NPDES permits was reviewed by Bateman (2005). The former regulator explained how he feels that documenting pollutant reductions will be required, rather than strictly implementing stormwater treatment practices.

The Gwynn Falls Water Quality Management Plan (Baltimore County, Maryland) was reviewed by Brennan and Lien (2005). Field assessments were used to develop cost estimates and ranking for over one hundred projects proposed in the watershed. Factors involved in the project rankings included cost, water quality, habitat benefit, land availability, public acceptance and educational opportunities. The Hellbranch Forum Watershed Action Plan was reviewed by Dixon *et al.* (2005). The action plan united the local officials, the Army Corps of Engineers and local consultants with the watershed group. The group was tasked with creating policies for overall watershed and stream protection.

Arhontes (2002) reviewed the Collection System Outreach Program of OCSD that was developed in response to the SSO program and the CMOM program. The goals of the program have been to improve the knowledge of the assets, leverage expertise in the region, and promote improved networking among cities and collection system owners, operators and managers. Coppes (2002) reviewed the challenges of stormwater management, including the implications of NPDES for this management. The development of economical and effective technologies was discussed with reference to new standards for stormwater products, testing and performance.

Bandy *et al.* (2002) presented an overview of the Hillsborough River watershed management plan. Cave *et al.* (2002) reviewed the Main 3-4 Subwatershed Plan in the Rouge River. The group established several long-term goals: improve water quality and restore impaired uses; remove pollution sources that threaten health; educate the public; increase recreational opportunities; enhance and preserve habitat; and reduce water volumes and velocities in the river during storms to minimize bank erosion and flooding. Turner *et al.* (2002) reviewed the programs implemented by the Columbus Water Works on the Chattahoochee River. Overall program findings include load generation rates and yields for various

pollutants correlated to watershed impervious area and aquatic biology indices. Wieske and Penna (2002) reviewed the stormwater strategy of Laguna Beach, California. The papers reviewed the methodology that engineers have used to manage the urban runoff problems plaguing the city. Zimmerman and Thomas (2002) presented the Clayton County Watershed Management Team's approach to watershed management plan implementation. Plan implementation relies heavily on teamwork and enhancing existing water quality programs versus creating new mechanisms to protect Clayton County waterbodies. Gassman and Lee (2002) discussed the planning needed for Broward's Countywide Integrated Water Resource Plan, which required a regional perspective at the local level in order to meet the Everglades' restoration goals and the county's growing water needs. The plan has four integrated components: Natural Systems, Canal Systems, Utilities and Policies. Rose (2002) reviewed the Lake Allatoona water resource planning and source water protection activities, which required working across jurisdictional boundaries. This paper explored the various trends, policies and planning that the Lake Allatoona Preservation Authority initiated for water resource planning and source water protection within the Lake Allatoona watershed, including the development of public and private partnerships for watershed protection, a Comprehensive Watershed Management Plan that included the development of "unified" planning across jurisdictional boundaries. Hiscock (2002) presented The West Palm Beach Renaissance Project, which is an integrated water resource management plan for diverting runoff from a 375-acre urban watershed and conveying the water through a settling basin and wetlands before it becomes part of the City's potable water supply. The Renaissance Project has been developed with the combined expertise of City staff, local engineering consultants and other governmental agencies, including the United States Environmental Protection Agency (EPA), the Army Corps of Engineers (ACOE), the Florida Department of Environmental Protection (DEP) and the South Florida Water Management District (SFWMD). Morgan and Ricketts (2002) reviewed the Alabama Clean Water Partnership. The new approach was addressing water resources on a watershed basis and addressing watershed concerns at the local level through the development of grassroots efforts and the Partnerships were created to develop inclusive public/private stakeholder committees to support community-based river basin protection and management efforts. Schrameck and Andrews (2002) reviewed the development of subwatershed pollution prevention initiatives in the Rouge River watershed. The Storm Water Pollution Prevention Initiative (SWPPI) was designed to reduce the discharge of pollutants to the maximum extent practicable; be consistent with the watershed management plan and emphasize the mitigation of undesirable impacts; include actions expected to be implemented over the term of the permit; and address specific actions to be taken by each permittee to meet the goals.

Chen (2002) presented the use of Watershed Analysis Risk Management Framework (WARMF), a decision support system that presents scientific information for stakeholders to evaluate alternatives, by the Truckee River, Muddy Creek and Blue River stakeholders. Alternatives included in the model include combinations of controls on atmospheric deposition, point source loads, water diversions, fertilizer application, street sweeping and buffer strips. Philadelphia's Source Water Protection Program's Source Water Assessment Project was reviewed by Byun et al. (2002b). The project has been designed to identify and prioritize potential sources of contamination across the watersheds and to assess the vulnerability and susceptibility of the water supplies to these sources. The use of comprehensive, watershed-wide, long-term continuous simulation models were used and were combined with GIS to show areas of high pollutant loads and of high protection priority. Clark et al. (2002a) studied combining hydrologic models for flood control, biotic models of ecologic risk, economic models of willingness-to-pay, and psychological models of risk processing and planned behavior to evaluate two policy alternatives. The findings reveal that flood risk exposure, especially for those individuals who would remain outside the 100 year flood plain if the project were enacted, does influence the financial support that local residents would be willing to make to a flood control project. McMillan et al. (2002) reviewed waterbody/watershed planning for New York City. A watershed-based approach was used to conduct an integrated evaluation of the interdependent factors affecting receiving water uses, including storm water, CSOs, wastewater treatment, upland uses, shoreline uses, habitats, sediment and water quality with the active participation of major stakeholders from the start of the process. Zimmerman (2002) postulated that a watershed-level approach to planning is well accepted today. However, he noted that there is a continued reliance on planning models that fall far short of understanding the complex interactions between wet weather, groundwater and water infrastructure on a watershed scale.

King et al. (2002) reviewed the implementation of watershed management recommendations through stormwater master planning in Gwinnett County, Georgia. The major components of the stormwater master plan involve 1) a flood study, 2) infrastructure inventory, 3) BMP analysis, and 4) stream restoration. This paper presented a method for prioritizing subwatersheds to focus stream restoration recommendations and develop water quantity and quality stormwater treatment practices to improve watershed biotic integrity. MacGregor and Tichy (2002) presented an implementation tool for a developing watershed: The Regional Alcovy River Watershed Protection Plan. The goals of the plan included protecting water supplies; developing an economical, basin-wide approach for water quality protection; providing local government with tools to make decisions related to water quality easier; defining clearly strategies that meet state requirements for

watershed protection; preserving the unique ecology of the watershed; fostering informed public opinion; involving the public in watershed protection planning and implementation; and working with existing organization to create an ongoing program. Miller et al. (2002a) reviewed alternative wet weather permitting strategies that recognize real-time conditions in the Indiana systems. The City of Indianapolis considered several strategies (mass, seasonal and tiered limit strategies) used in other places, as well as a 'flow-proportional limit' strategy.

Tuomari and Thompson (2002) reviewed the success of Wayne County's IDEP Training Program. The key goals of the training program are sharing our expertise with other local units of government involved in stormwater management and collaborating efforts in reducing improper discharges to surface water. The modules of the training program are: Overview, Basic Investigations, Advanced Investigations, Construction Related Illicit Discharges, Combined Basic/Advanced Investigations, and two (2) specialty training sessions.

British Columbia's Stormwater Management Guidebook was reviewed by Stephens et al. (2002). The Guidebook describes the adverse impacts of past stormwater management practices and walks its audience through stormwater management planning, including: how to develop goals, objectives and priorities; how to undertake public consultation; how to assess watershed health; how to select, implement and monitor best management practices (stormwater treatment practices); and how to finance the long-term implementation of a stormwater management program. The Stormwater 'Source Control' Handbook for Australian practice was presented by Argue (2002). The Handbook attempts to provide 'step-by-step' advice regarding sustainable drainage systems and it is geared toward the student, the novice practitioner and the busy municipal engineer. Crabtree and Morris (2002) reviewed the Urban Pollution Management procedure and associated standards in England and Wales, and how they encourage the use of integrated wastewater planning and therefore, ensure the anticipated environmental improvements are delivered. Calcagno et al. (2002) wrote about the establishment of a non-governmental regional approach to integrated watershed management in the La Plata River Basin. As a concrete response to this need, the efforts of a number of organizations from various countries within the basin, with the support of international and national governmental organizations, resulted in the foundation of La Plata River Basin Environmental Research and Management Network (RIGA). Backstrom et al. (2002) discussed the future of Swedish stormwater management and what activities are not helpful in creating a sustainable system. The Swedish environmental objectives, which try to encapsulate all aspects of sustainability, may be used a foundation for a "sustainability screen," which will then be used to evaluate programs and activities.

Fulton County has begun addressing the surface water issues created by stormwater runoff (Ammons 2001). The resulting Water Resource Management Plans have a 15-year program to improve the surface waters of Fulton County. In order to increase wastewater plant capacity and effluent discharge, the Georgia EPD required development and implementation of a watershed protection plan to address the "secondary" pollution impacts created by stormwater runoff from the development supported by the increased wastewater treatment capacity. The State of Georgia required watershed assessments to control nonpoint source pollution associated with degradation of surface water quality and non-attainment of designated uses (Ahmad 2001). EPD required local governments to conduct watershed assessments as a part of the NPDES permitting process for wastewater treatment plant expansion. The study objectives included identifying the current aquatic health of the watershed; predicting the impacts from the proposed development; and identifying and assessing the performance of stormwater treatment practices. The conclusions were that the creek currently meets all adopted and recommended water quality standards; the aquatic habitat show some degradation of biotic integrity; the planned level of development in the watershed will increase pollutant (and sediment) loads; the structural stormwater treatment practices will mitigate the increased pollutant loads; nonstructural stormwater treatment practices should be implemented as part of a long-term Water Resources Management Plan (WRMP); and a long-term water quality monitoring and sampling program should be implemented.

Batchelor and Rogers (2001), in response to the lack of improvement in some of the nation's waters, advocated finding smarter, more cost-effective ways of water quality and watershed restoration. Work in the Saginaw Bay Region showed that a point-source and non-point source trading program could be effective (Faeth, 1995). Two important points were made. (1) The current regulatory system needs to change to incentive-based systems. (2) Trading systems work for integrated water quality, air quality and natural resource programs. A trading program, on a watershed basis for trading, should provide major watershed restoration in the fastest time and for the least money. Bhimini et al. (2001) presented the findings, conclusions, and recommendations from a trading program for TMDLs on the Truckee River. In addition, the viability of a seasonal TMDL and a discussion on the phased approach towards developing pollutant trading permits were discussed. The development of the trading program included establishing the technical basis for modifying the TMDLs and WLAs and for identifying the optimum mix of structural and nonstructural stormwater treatment practices. Kochoba

and Wilber (2001) reviewed TMDLs in several states. The reviews indicated that TMDLs, and the resulting Load Allocations (LAs) and Wasteload Allocations (WLAs), often were based on limited data, unsound modeling and poor characterization of non-point source loads. Active involvement in the TMDL development process by contributing entities was advocated to help ensure that TMDLs are based on good science and result in reasonable, achievable WLAs and LAs.

As the first phase in its Integrated Resources Planning (IRP) process, the City of Los Angeles embarked on a program to restructure and redefine the future of water resources for the City and its neighbors (Boyle et al., 2001). The City developed the Integrated Plan for the Wastewater Program (IPWP), a set of policies to guide the next phases of wastewater facilities planning. The IPWP process used by the City integrated water supply, water conservation, water recycling, and stormwater management issues with wastewater facilities planning through a regional watershed approach. It also solicited and relied on public input in establishing planning-level policies. Philadelphia Water Department's Office of Watersheds was charged with integrating traditionally separate tasked programs, including the Combined Sewer Overflow (CSO) Program, the Stormwater Management Program, and the Source Water Protection Program (Dahme 2001). The goal was to maximize the resources allocated to these programs and to ensure the comprehensive achievement of each of their goals. The paper focused on the Darby-Cobbs Watershed Partnership.

The watershed storm water regulatory framework from the Rouge River National Wet Weather Demonstration Project (Rouge Project) in southeast Michigan was institutionalized in 1997 as a new statewide watershed-based general storm water National Pollutant Discharge Elimination System (NPDES) permit ("General Permit") (Cave et al., 2001). The General Permit required the immediate initiation of some activities such as illicit discharge elimination and participation in watershed management planning. The paper reported on the effectiveness of the subwatershed management plans developed under the General Permit in (1) contributing to the overall restoration of the Rouge River; (2) meeting the requirements of the state's Storm Water General Permit, and (3) satisfying the federal mandates contained in the Phase II Storm Water Regulations. Two years ago, most of the Rouge River Watershed communities became covered under the state's voluntary general stormwater permit program (Powell and Ball 2001). The permit required that the communities create a public education plan that included programs on the Rouge River, its impairments, stormwater pollution, and individual responsibility and stewardship. This paper discussed the initiatives and tools used by Wayne County's Rouge River National Wet Weather Demonstration Project and the involved communities to obtain public input during the subwatershed management planning process. In most cases, public meeting participation was the most difficult to predict and ultimately the least dependable, and many approaches were required.

Disaster mitigation related to floods and debris flows were discussed in the context of sustainable land and water management in Taiwan (Chen et al., 2001a). Engineering approaches to modify natural systems were contrasted with approaches that require changing human behavior. Mitigation success depended not only on the characteristics and magnitudes of the disasters but also on human responses related to socioeconomic, cultural, and political factors. Herricks (2001) discussed the renewed emphasis on watershed management programs that are based on ecosystem protection and restoration. The integration of ecosystem-based objectives into watershed management programs has demanded a substantial shift from past practices. This new paradigm integrated past management science and practice with ecosystem protection. This has assisted in the development of projects that produce needed ecosystem benefits.

Public involvement in watershed protection and stormwater management was reviewed by Cole (2001). Focused public involvement has encouraged residents to acknowledge individual responsibility for the impact of their actions on area waterways. It has also fostered voluntary participation in Watershed Management Plan recommendations. The paper discussed the objectives of a well-managed public involvement plan. Ames and Neilson (2001) presented an Internet-based, Bayesian Decision Network model to aid watershed stakeholders in collaborative decision-making. Bayesian Decision Networks (BDNs) have been shown to be a useful tool for diagramming the decision process, for describing relationships between variables, and for analyzing the anticipated effects of management decisions while still accounting for the associated uncertainties. An Internet-based BDN was described using the East Canyon watershed in Utah. Public participation was a key factor in the success of watershed management (Lu 2001). China Time's ten-year experience of promoting watershed planning was analyzed for public participation. Piasecki (2001) presented a methodology to compute sensitivities between benefits and costs that can be used to develop an efficient WLA procedure for CBOD/DO load scenarios. Steady state and unsteady flow scenarios were presented along with method sensitivities. The 2-dimensional dynamic modeling approach permitted identification of a large number of temporally distributed sensitivities for sources along an estuary. The project described by Watkins and Paladino (2001) educated and mobilized watershed residents and other stakeholders to participate in the activities of a local watershed council. The underlying strategy was

to engage stakeholders in discourse on watershed issues, as well as in activities that promote the decision-making skills necessary for sustainable watershed planning and management.

A watershed approach to Sanitary Sewer Overflow (SSO) management was applied for the Vallejo Sanitation and Flood Control District in Northern California (Dent et al., 2001). This watershed approach was used to estimate the total pollutant loads from SSOs, urban stormwater, and flows from the Napa River watershed. The results were then used to set permit limits for wet weather events. The watershed approach combined monitoring and modeling techniques to estimate the water quality improvements for a variety of SSO elimination activities. A joint stormwater initiative for the City of Lincoln and the Lower Platte South Natural Resources District was successful in achieving three goals: adoption of comprehensive stormwater ordinances for new development; implementation of revised, comprehensive design criteria; and completion of the City's first stormwater basin plan (Masters et al., 2001). Ordinance and design standard revisions addressed maintenance issues for stormwater storage facilities, erosion and sediment control, localized flooding, water quality, and the specific criteria for meeting objectives in these areas. Holmberg et al. (2001) reviewed the need for municipalities to balance establishing peak flow standards with these other issues: dynamic sewer flows resulting mostly from I/I originating on private property; capital funding; risks of public health and environmental effects from SSOs; and threats of third-party citizen lawsuits. The Water Works and Sanitary Sewer Board of the City of Montgomery (Board) advocated the watershed approach to manage collection systems. The Board used the watershed approach in two of its three sewer basins – the Towassa and the Catoma Basins. The Board also recently used the watershed approach process to set peak flows in the Towassa Basin. Lewis and Hilson (2001) explained how environmental benefits were optimized against cost through integrated catchment modeling in North West England. These solutions were obtained from detailed modeling of the wastewater networks, along with the modeling of the wastewater treatment works and the receiving waters. The stormwater management system in Calgary is a zero discharge system incorporating sedimentation, biological uptake/treatment and irrigation for disposal of stormwater runoff (MacKenzie and Dumont 2001). The system was designed and implemented, and is in successful operation. The zero discharge stormwater system allowed the development area to proceed without off-site treatment facilities. The system controlled/mitigated the effects of stormwater runoff on receiving waters. Continuous simulation, using long-term records of precipitation, temperature, and evaporation combined with estimates of plant moisture requirements formed the basis for the design of the system.

McGrath (2001) discussed the growing need to forecast land use changes and urbanization patterns over longer time frames so that regional environmental and hydrologic consequences can be forecasted and the consequences of different development scenarios compared. Obstacles to achieving such forecasting capability included the integration of spatial environmental/hydrological and spatial economic models. In addition, the econometric problems associated with estimating spatial economic changes were reviewed. The recognized difficulties in combining the relevant disciplines to produce accurate long-range forecasts of land use change were discussed. Ecological impairment and flooding caused by urbanization was expressed numerically by calculating the risks throughout the watershed (floodplain) and along the main stems of the streams (Novotny et al., 2001). The methodologies for ascertaining the risks in the Geographical Information Systems (GIS) environment were described. The objectives of urban flood controls and ecological preservation/restoration of urban waters often have conflicted. A solution to this may be achieved by linking the risks to the concepts of risk communication, risk perception, and public willingness to pay for projects with ecological restoration and ecologically sustainable flood control. Reeves et al. (2001) developed a method that would incorporate the effects of both chemical and physical parameters on aquatic life (Reeves et al., 2001). The resulting method, termed the Integrated Impact Analysis method, used existing analytical methods, including Principle Components Analysis, All Possible Regressions, and Chi-Square Automatic Interaction Detection (CHAID), to identify key variables. Non-linear interactions between the key variables were identified using a three-dimensional modeling program. The method was refined using three datasets (Santa Ana River in California, South Platte River in Colorado, and Cuyahoga River in Ohio). Webster et al. (2001) considered the problems of developing a perceptive and efficient rehabilitation strategy for a large urbanized catchment, specifically the River Tame in the West Midlands. The following were considered: (a) rainfall-runoff relationships, (b) water quality and ecological status, and (c) the impact of various management strategies. Spalding and Sweeney (2001) advocated the use of the Internet by wastewater utilities to achieve closer customer and production integration. A "Digital Utility" approach using the Internet to create new, robust, customer-oriented applications was described.

In Cleveland, Ohio, channel erosion and flooding, water quality, and aquatic life and habitat were evaluated (Yingling 2001). The purpose of both the Mill Creek and Doan Brook Watershed Studies was to develop comprehensive approaches for controlling wet-weather impacts on the respective streams. The cost and effort involved in actually performing the watershed studies, as well as the potential for overall cost savings and creativity in developing final solutions, were

reviewed. Although watershed studies require a significant investment in data collection and in public involvement, the resulting solutions were typically more cost-effective and accepted by the public. Waterific, an interactive science program about water, was created to educate the public about water-related issues (Ziegler et al., 2001). The focus of Waterific was to enhance environmental awareness, education and celebration. In addition, the program is a fun, hands-on activity that meets the core content required by the Kentucky Department of Education for sixth-grade science. By pooling talent from various water quality agencies, the school students saw first-hand how all the agencies work together and independently to maintain the water quality in Northern Kentucky.

According to the U.S. EPA's Index of Watershed Indicators, at least 21% of watersheds have serious problems, 36% have some problems, 16% have good water quality and 28% lack sufficient information to analyze (Hun, 1998). Managers for the Joshua's Creek, a 21 km<sup>2</sup> watershed in southern Ont., Can. used a three stage process to sustain water resources in the face of rapid urban development. The process included a macro-scale watershed plan, detailed subwatershed plans, and specific stormwater management plans (Bishop, 1998). The Tualatin River Basin in northwest Oreg. experienced rapid urbanization bringing changes in land uses, increased pollutant loads to the river and its tributaries from the WPCP and urban runoff (Jackson, 1998). Requirements defined by the Clean Water Act such as NH<sub>3</sub> and P load limitations were implemented in 1988 and temperature allocations were scheduled for 1997.

Municipalities are required to implement multiple regulations with regard to water resource protection including erosion and sediment control laws and stormwater requirements under NPDES. Integration of these regulation requirements under a comprehensive watershed management plan would enhance enforcement and reduce implementation costs (Pasquel et al., 1998). Coherent watershed management must rest on clear political goals regarding environmental use, risk protection and urban development (Cyr et al., 1998). The stormwater master plan must become permanently part of the water resource master plan for the whole watershed, with its objectives of flood control, erosion control and maintenance of acceptable physical-chemical and biochemical water quality, as well as assured resource use.

Sixteen state and federal agencies with management and regulatory responsibilities in the San Francisco Bay and Sacramento-San Joaquin River Estuary (Bay-Delta) in Calif. have come together in a collaborative effort with Bay-Delta stakeholders, urban and agriculture water users, fishing interests, environmental organizations, businesses and other public interests to develop a long-term solution the CALFED Bay-Delta Program (Yaeger and Ott, 1998). Integrating traditional stormwater management techniques and the watershed management approach into the city of San Francisco's existing water quality control programs reduced potential impacts of CSO and facilitated the city's efforts to comply with Phase II stormwater regulations ahead of schedule (Rourke and Brosseau, 1998). The U.S. Army Corps of Engineers, North Central Texas Council of Governments and its member local governments have cooperated in a regional initiative to more comprehensively assess the problems and opportunities of the Trinity River corridor of the Dallas/Fort Worth metroplex (Promise, 1998). The Lake County Stormwater Management Commission (SMC) of Ill. performed a multi-phase project on one residential subdivision that experienced chronic flood damages (Royal, 1998). Alternative management measures included modification of detention basins and wetlands, drainage improvement, stream maintenance, and acquisition and demolition of flood damaged residential structures. The City Center of Johor Bahru, Malaysia has been undergoing intensive urban development and redevelopment since the early 1980's and is planning for the management of urban stormwater. The factors considered in the formulation of the plan include: (1) the level of minimum acceptable flood risk; (2) town planning and other related guidelines; (3) ease of maintenance; (4) future use of the waterways; (5) accessibility to the river reserve zones; (6) flora and fauna to be used for the systems; and (7) aesthetic and safety features for recreational purposes (Chin et al., 1998b).

The Lake Pontchartrain Basin Foundation of La. developed a plan to identify water-quality and habitat problems and make recommendations. The plan addressed the impact of designated use areas by microbial contamination and suggested BMP with emphasis on disinfection and engineered microbial reduction technologies (Englande et al., 1998). The King County Water Pollution Control Division in Wash. conducted a water-quality assessment for the Duwamish River and Elliott Bay to provide information for making decisions about the future of the CSO program (Munger et al., 1998a). Wash. adopted a long-range standard for CSO control of one uncontrolled overflow per discharge point per average rainfall year. In March 1994, the city of Orlando, Fla. entered into a Joint Planning Agreement with Orange County which would facilitate the annexation of approximately 52 km<sup>2</sup> (20 mi<sup>2</sup>) of underdeveloped land southeast of the Orlando International Airport (Roesner et al., 1998). This planning effort would include the development of a Master Stormwater Management Plan (MSMP) for the annexed area using a "watershed based" approach to the management of the water quantity and quality to provide regional flood control and water maintenance of existing wetlands. Schaefer et al. (1998) described the development of a comprehensive management plan that addresses flooding, protection of environmental

resources, and stormwater management regulations for a study reach within the context of existing and future development conditions throughout the watershed of Tyler Creek, Elgin, Ill.

As part of N. J.'s watershed management approach, water-resource programs, e.g., stormwater management, wastewater management, source-water protection and CSO control, will be coordinated and implemented through a statewide watershed-management process (Cohen, 1998). N. J. has maintained a federally approved coastal-zone management program for 18 years and used the Coastal Management Act to implement the State Development and Redevelopment Plan (SDRP) and the Statewide Watershed Management Plan (Frizzera 1998). The Rock River Watershed Partnership was established to conduct a full watershed study of the Wisc. portion of the Rock River as a result of stricter P restrictions imposed in 1996 (Schroedel et al., 1998). The Partnership is a cooperation of communities that line the Rock River Watershed area and efforts have been made to share information. Rudolph et al. (1998) gave an overview of the Northeast Ohio Regional Sewer District's (NORS) comprehensive watershed investigation of the Doan Brook, which serves the cities of Beachwood, Cleveland, Cleveland Heights, and University Heights and receives CSO during wet weather.

Lexington-Fayette County, Ky. began a watershed-management program that included the use of greenways, establishment of community water-quality standards, stormwater modeling, retrofitting BMP to improve stormwater quality, and stream morphology (Tapp and Uckotter, 1998). The stormwater program of the Lexington-Fayette Urban County Government used chemical monitoring techniques and biological and stream-morphological studies to quantify the current condition of the resources (Robson and Kramer, 1998). The Columbus Water Works of Columbus, Ga. developed a watershed plan to identify and quantify urban and rural wet-weather pollution sources and assess instream results of existing CSO control facilities (Turner et al., 1998). The study area of the Metro Atlanta Urban Watersheds Initiative (MAUWI) in Ga. was divided into subbasins based on factors including basin size, hydrography, land use, impervious surface and location of CSO. Each subbasin was sampled for one or more biological parameters (Hall and Richards, 1998). The MAUWI, a stakeholder driven process, produced a Watershed Improvement Guidance Document which is based on habitat, biotic integrity and water-quality data and assessments of impacts on the watersheds. The information provided communities and governmental agencies, the current state of the urban streams, pollution sources, alternatives for improvements and guidance on implementation (Richards, 1998).

A planning study for the Ile-de-France Region which includes Paris was conducted to meet dry and wet weather water quality criteria in the year 2015 (Renard et al., 1998). A watershed approach was used, and four remedial scenarios were developed including the construction of  $1.4 \times 10^6$  —  $1.6 \times 10^6$  Mm<sup>3</sup> of new retention capacity and 2.5—8.5 m<sup>3</sup>/s of high-rate treatment plant capacity. Fujita (1998) presented examples of restoration of polluted or dried urban watercourses in Tokyo, Japan. Parsons Engineering Science developed the Basin Master Plan for South Creek in Sarasota County, Fla. (Cabezas, 1998) which addressed watershed-management issues. During heavy rain events, South Creek contributed to flooding and violations of levels of service in adjacent basins. A computer model summarized technical information and allowed a citizen task force to make decisions about a cost-effective management plan for development of Lake Sammanish in King County, Wash. (Richey et al., 1998).

### **Effluent Trading and Water-Quality Planning**

Thurston et al. (2004) researched the possibility of using trading allowances for stormwater control in order to promote a more dispersed, smaller-scale use of Best Management Practices (stormwater treatment practices) (compared to the regional stormwater treatment practices typically used). Various scenarios of implementation/use were presented. A multi-agent prototype was proposed to represent the relationships between urbanization dynamics and land and water management in a peri-urban area (Ducrot et al. 2004). The model was developed to look at problems and solutions in a catchment that is the main drinking water reservoir and is subject to urban runoff pollution and increasing development.

Endreny (2004) proposed that stormwater management should incorporate not only the traditional objectives but should also focus on ecological engineering and ecohydrology. Implementation consisted of simulating, monitoring and reporting how storm-water design decisions to infiltrate or directly discharge runoff resulted in a complex set of linked adjustments to the dynamics of the water table, soil chemistry concentrations, plant stress/viability, terrestrial habitat, river loads/flows, and aquatic habitat patterns. EPA evaluated urban runoff control programs and noted that integrated water quality management produced the best long-term results (Ports 2004). Pritts et al. (2004) reviewed the anticipated national benefits of erosion and sediment control regulations. In evaluating the benefits of regulations, EPA attempts to both quantify the degree of reduction of a range of pollutants or indicators, as well as monetize the expected environmental improvements that result.



Schultz et al. (2004) described and applied a reduced-form model of a large-scale water quality model developed for regulatory decision support. The model indicated that it was more important to resolve the loading rates rather than the hydrology when determining how to get a model that best reflects what is occurring in a watershed.

The federal-state partnership undertaken by the Wisconsin Department of Natural Resources was reviewed by Lucero et al. (2004). This article reviewed the evolution of decision support and planning systems based on increasingly complex technological advances, specifically of data provision and modeling. The collaborative approach to managing water quality planning the Greater Milwaukee Watersheds was presented by Bate et al. (2004). Data, models, analysis techniques, stakeholder support, objectives and recommendations will be designed and jointly developed by the three participating agencies to meet the needs of the group as well as of the individual contributors. Breidenbach et al. (2004) examined the development and use a watershed assessment protocol for prioritizing management activities in Sanitation District No. 1 (northern Kentucky). The protocol consisted of four steps: (1) problem identification; (2) source assessment; (3) linking causes and effects through modeling; and (4) source ranking.

The stormwater and urban stream management practices in Ontario (Canada) were discussed by Bui (2004). The paper reviewed the relevant portions of the 1994 Ministry of Environment manual together with changes proposed in a 1999 draft amendment. Corso et al. (2004) examined the need to build consensus in order to enhance watershed stewardship in the Great Lakes region.

The development of a community-based Phase II watershed organization in the Greater Lansing Michigan area was presented by Herrmann and Scholl (2004). A case study was examined to show the committee's inception, participants, legal relationships, structure, funding allocations, evaluation and relationship to the permit application. Quality of life benefits can be successfully integrated with urban stormwater management, according to Kieser et al. (2004). The case study presented for Portage, Michigan showed that stormwater management could result in improved water quality as well as expanding the city's recreational corridor – all at costs similar to or less than traditional practices. Mangus and Stefanski (2004) presented the Water Quality Management Plan for southeast Michigan, which shifted emphasis from end-of-pipe controls to improved planning. Local governments were given a continuum of options for preserving and restoring water resources, including addressing the requirements for stormwater management. Shosh (2004) presented the school-based watershed education and monitoring established in the Rouge River watershed (Detroit, Michigan).

The Standard Urban Stormwater Mitigation Plan compliance at The Port of Los Angeles (POLA) was reviewed by Brown et al. (2004). In addition, POLA researched many types of storm water treatment control devices and determined that a proprietary oil-water separator product was selected as the preferred BMP. Rodrigo et al. (2004) reviewed the Los Angeles experience in integrated watershed management. The anticipated result is that the City can meet its year 2020 needs in a more cost-effective, environmentally sustainable way. The stormwater management plan for Lodi, California, was presented by Sommers et al. (2004). The program was designed to reduce the discharge of pollutants to the Maximum Extent Practicable (MEP), protect water quality, and satisfy the appropriate water quality requirements. Drennan et al. (2004) presented a pilot project constructed in the Sun Valley watershed the Los Angeles region which investigated various alternatives for controlling flooding problems. The alternatives were selected to not only address flooding issues, but also improve recreation and aesthetics, reduce stormwater pollution and prevent habitat degradation.

Hillick et al. (2004) discussed the implementation and initial results from Atlanta's long-term monitoring program for watershed management. The purpose of the program was to collect the needed data for assessing stream and watershed improvements. Turner and Boner (2004) reviewed the monitoring and modeling performed in Columbus (Georgia) in order to comply with federal regulatory requirements. The results obtained demonstrated that significant wet weather data was necessary to establish relationships between land use, water chemistry, aquatic biology and sensor data.

The New England Interstate Water Pollution Control Commission developed a multi-state guidance document to assist sanitary sewer collection system owners, managers and operators optimize the system to prevent overflow events (Jennings 2004). Walker et al. (2004) reviewed the temporary variance obtained for the Charles River (Massachusetts) that allowed the Massachusetts Water Resources Authority more time to study the impacts of non-CSO pollution on the river. These activities included: conducting an assessment of providing additional CSO storage; conducting a performance evaluation of the CSO Facility, which discharges to the Charles River; developing a more detailed stormwater runoff model for areas tributary to the Charles River; and upgrading the receiving water model for the Charles River.

BMP manual development in the Kansas City metropolitan area, a bi-state effort, was reviewed by Jacobs and Henson (2004). The rationale underlying the new approach of multi-municipal cooperation included substantial long-term savings in the development and maintenance of public infrastructure, better natural resource protection, and compliance with new federal water quality regulations. Geomorphic engineering was introduced into standard stormwater designs in the Kansas City metropolitan area (Prager et al. 2004). The purpose of incorporating geomorphic engineering was to better understand and model the effects of channel energy on natural stream features. Nutrient criteria were established in the Santa Margarita River watershed with the unintended consequence of eliminating reclaimed water discharges in the watershed (Rowan et al. 2004). Because of this, governmental agencies are reviewing instead the use of riparian wetlands to reduce the nutrient loads in runoff during storm events.

The stormwater management plans for St. Charles were discussed by Martin et al. (2004). GIS was used to determine locations of outfalls and locate illicit connections and discharges. Peterson and Kacvinsky (2004) reviewed the multi-municipality approach to watershed management plan modeling in Cool Creek watershed (Indiana). These communities have developed a jointly funded, comprehensive investigation of existing and future stormwater management issues. The Pogues Run near Indianapolis (Indiana) has a 2.2 mile box culvert enclosing the lower end of the stream (McCormick et al. 2004). The flood-prevention project for Pogues Run involves adding flood-control basins, removal of several bridges, and conversion of the box culvert into a CSO storage facility.

Job and Korening (2004) reviewed a planning tool, the Site Evaluation Tool, used by Mecklenburg County to assess site development impacts and to ensure that water quality goals are met post-development. The Source Water Protection Program of Loudoun County, Virginia was reviewed by Ryon et al. (2004). The program addressed potential problems near the freshwater intakes and the potential degradation of stream habitat in the watershed.

Obree (2004) examined the shift in thinking in South Africa away from traditional storm drainage systems towards managing stormwater and rivers based on a philosophy of integrated watershed management. The paper reviewed the approach and experience of Cape Town to implement this new thinking. McDonald and Vogelzan (2004) reviewed the need to communicate flooding issues and solutions to the public in KwaZuluNatal. Information is disseminated to the public through direct mailings and word-of-mouth Disaster Management Communities. As part of a need to reduce potable water demand, the Pimpama Coomera region of the Gold Coast proposes to start treating stormwater runoff through the use of swales, bioretention, wetlands and basins (Kalli 2004). Rodrigo and Alonso (2004) assessed and discussed the problems and prospects for water and land-use management and planning within the framework of the European Union.

Armstrong et al. (2003) presented the model Emergency Response Program (ERP) for wastewater utilities in the Denver, CO area. The objective of the program was based on the belief that a coordinated ERP could solve a number of response and notification problems experienced by wastewater utilities during overflow events in recent years.

Bolender and Shuler (2003) reviewed municipalities' shifting perspective in stormwater management design, with a particular focus on infiltration facilities. Cleland (2003) reviewed the duration curves and wet-weather assessments that are crucial to appropriate TMDL development. The increased use of duration curves supported the "bottom up" approach by offering an opportunity for enhanced targeting, both in TMDL development and in water quality restoration efforts. Grippo (2003) reviewed the progress in South Carolina in establishing TMDLs. The process used by South Carolina and the affected municipalities to develop this cooperative and proactive effort to address reductions in fecal coliform loading in the Dorchester Creek and Sawmill Branch watersheds without inclusion of complex and non-obtainable numeric limits was presented.

Bacon et al. (2003b) illustrated how conservation credits could be generated and implemented through a series of case studies developed using a suite of integrated models specially tailored for this application. The suite included CH2M HILL's WISE (Watershed Improvement through Statistical Evaluation) with custom-built trading and banking modules, and relied on selected output from EPA's PLOAD model.

Chavan et al. (2003) reviewed the water quality trading program for TMDL compliance on the Truckee River. The development of the trading program included establishing the technical basis for modifying the TMDLs and Waste Load Allocations (WLAs) and for identifying the optimum mix of structural and nonstructural projects and programs. Bacon et al. (2003a) reviewed the establishment of a market for pollution trading and reduction credits in the Dallas Metropolitan area. The credit market was proposed to more equitably distribute nutrient control responsibilities among point and

nonpoint sources by capturing favorable economics. Thurston et al. (2003) hypothesized that a well-designed, tradable runoff allowance system could create economic incentives for landowners to employ low-cost runoff management practices to reduce excess stormwater flow to more ecologically sound levels. Attributes such as percent impervious surface, soil type, and so on, determined a given land parcel's runoff potential and management alternatives and, by extension, its allowance requirements.

Bloom (2002) provided a national review of known proposed or issued TMDLs or TMDL implementation plans that call for the imposition of numeric effluent limitations in MS4 permits as a means to achieve TMDL-derived load reductions. The paper also highlighted some of the policy implications of this emerging trend. Dors and Tsatsaros (2002) reviewed the determination of a margin of safety for TMDLs for water bodies that are determined to be water quality limited. Freedman et al. (2002) discussed the results of the WERF-funded research project on navigating and improving the TMDL process. The objective of this research was to investigate issues and concerns with the TMDL program, and to develop and identify ways to improve the TMDL process. Clark (2002) used the Cascade Reservoir TMDL Implementation Plan as an example for the development and application of a database project tracking tool. The tracking system serves as a master summary of all projects and stormwater treatment practices constructed for the purpose of reducing the phosphorus load to the Reservoir, and is used to assess phosphorus load reduction, to analyze cost-effectiveness and to assess the performance of each BMP individually or as a whole.

Bhimani et al. (2002b) presented the findings, conclusion and recommendations for the implementation of a water-quality trading program for TMDL modifications on the Truckee River using a phased-permitting approach. The paper also addressed the viability of a seasonal TMDL and discussed the phased approach toward developing water-quality trading permit language. Al-Ebus and Jacobson (2002) reviewed the protocol for developing fecal coliform TMDLs in New Jersey. Percent-load reductions will be assigned to stream segments based on the use of a geometric mean and the aid of load-duration curves and sources will be identified using one of several reliable bacterial source tracking (BST) methods. Cleland (2002) reported on the use of duration curves in TMDL development in Kansas. The expanded use of flow duration curves has enabled enhanced targeting, both in TMDL development and in water quality restoration efforts. Duration curves also provided a context for evaluating monitoring data and modeling information. Lee and Jones-Lee (2002) reviewed the development of nutrient criteria/TMDLs to manage excessive fertilization of waterbodies. The paper discussed recommended approaches for developing site-specific nutrient criteria that will protect the nutrient impact-related beneficial uses of a waterbody, without significant unnecessary expenditures for nutrient control. The paper by Schechter et al. (2002) presented guidance on incorporating stormwater and other urban wet weather sources into TMDLs. Using a broad-based review of nearly 200 approved TMDLs, combined with interviews of state TMDL staff, and detailed study of selected case studies, the research team developed several key findings related to wet weather sources in TMDLs. The paper provided recommendations for possible improvements for states, dischargers, and other stakeholders to use when confronting a wet weather TMDL. The paper also presented a case for the development of separate and distinct event-related wet weather TMDLs independent of dry weather TMDLs. In many cases, these wet weather TMDLs will have different sources, and often, different water quality endpoints.

Bowman (2002) reviewed the Nutrioso Creek (Arizona) TMDL partnerships between landowners and the state and federal agencies for TSS control. Ranchers received grant money and technical assistance to change the way the land is used and to install land improvement structures and stormwater treatment practices, and efforts have shown improving stream water quality and riparian areas after only a year of implementation. The development of the Ohio River TMDL for PCBs was reviewed by Dinkins et al. (2002). The plan included characterizing the extent and severity of water quality impairment, inventorying potential sources and quantifying source loadings, defining load reductions needed to meet water quality standards, assigning load allocations to the sources, and providing recommendations for actions to address the contamination. Based on the data analysis, direct deposition to the Ohio River may contribute over 40 percent of the allowable load for some segments of the river. O'Dea (2002) presented TMDLs in New Mexico which provided a case study in managing court orders, tribal interests and endangered species in a desert area. In the Middle Rio Grande, point sources and non-point sources are trying to understand what requirements might result from the recently finalized TMDL for fecal coliforms and might require permit holders to implement stringent BMP requirements or numerical standards in the permits.

Jones et al. (2002b) discussed how stakeholders' involvement can positively affect the development of TMDLs using the West Branch of the DuPage River as an example. Mumley and Speare (2002) presented an effort to optimize stakeholder involvement in the TMDL process in the San Francisco Bay Region. Lessons learned in San Francisco Bay Region TMDLs provide useful examples of how to conduct effective stakeholder outreach. Shanks and Grovhoug (2002)

presented a case study of stakeholder involvement in the development of TMDLs in the Sacramento River watershed. This presentation focused on the benefits and drawbacks of the stakeholder process as a forum for problem solving, the approach taken to foster collaboration and connection between stakeholder activities and the TMDL development process, the work products developed by the stakeholder groups, and the lessons learned from the process.

Effluent trading to maintain water quality on a watershed has gained momentum recently, however the method is complex. Kerns and Stephenson (1996) addressed the key elements for a successful trading operation. The EPA (1996d) acknowledged the benefits of pollutant trading among the various sources within a watershed as a means of reducing costs, and a framework for watershed-based trading was drafted (EPA, 1996e). Imbe *et al.* (1996) did a water budget to determine the impact of urbanization on the hydrological cycle of a new development near Tokyo, Japan. A cost-effectiveness study on point sources and nonpoint sources control of phosphorus was conducted in Chatfield Basin, CO (Little and Zander, 1996). Podar *et al.* (1996) summarized progress on trading programs across the nation.

Taff and Senjem (1996) outlined four major classes of regulatory uncertainty of point-nonpoint pollutant trading systems and offered practical measures for these uncertainties.

In planning a water-quality strategy for urban areas, public relations and upfront development of partnerships were found to be critical to facilitate implementation of pollution-control plans as illustrated in the St. Catharines' case study (Toth, 1996). An ecology-based, integrated-stormwater-management approach in relation to the regulatory requirements was initiated in Germany (Schmitt, 1996b). The Rock Creek community development in Superior, CO (Galuzzi and Pflaum, 1996) used an integrated approach for the planning, design, and construction of multiuse drainage systems, including the regional-stormwater channels and detention facilities. Robbins (1996) used GIS for establishing infrastructure-inventory databases for planning and monitoring stormwater-management programs. The City of Detroit's Water and Sewerage Department developed a long-term CSO-control plan, including interconnections of drainage systems between districts and their overflow outfalls to the Detroit and Rouge Rivers (Fujita and Grazioli, 1996).

After more than a decade of research of the Water Industry's Urban Pollution Management (UPM) in the United Kingdom, its products, a UPM Manual and software tools have been widely used by major cities for evaluating their flooding- and CSO-pollution problems (Morres and Clifforde, 1996). The goals for mitigating urban-wet-weather pollution and the fundamental methodologies employed to achieve those goals were determined to be similar, according to a comparative study of urban-wet-weather-pollution-management approaches in the United States and the United Kingdom (Brashear and Drinkwater, 1996).

The Minnesota Pollution Control Agency has allowed the reduction of NPS pollution to be credited to industries' point-source discharges. Now that point- and NPS-trading standards have been established, opportunities exist for industries to take advantage of NPS trading (Wallace and Sparks, 1997). An alternative permitting approach for the release of Pb-contaminated wastewater was discussed (Kratch, 1997a). Innovative stormwater sampling allowed a Pb-acid-battery manufacturer to obtain a new Kentucky Pollutant Discharge Elimination System permit and saved the company two-million dollars.

Schroeter (1997) discussed a methodology (and the databases used) in computing planning-level loading estimates for urban NPS from Ontario, Can. communities. Li *et al.* (1997) described the steps required to develop a preliminary stormwater-quality-management-planning strategy and presented a case study from the city of Scarborough, Ont., Can. Bolstad and Swank (1997) indicated that although most water-quality regulations, legislation, and sampling are promulgated for baseflow conditions, storm-flow conditions also warrant consideration during the promulgation process.

San Francisco, Calif. implemented a proactive water-pollution-prevention program, consisting of > 300 automotive facilities, in order to minimize wastewater- and stormwater- pollutant discharges into its CSO (Rourke *et al.*, 1997). According to Buke (1997), national "green taxes" were environmentally effective and the European Environment Agency in Copenhagen, Den. reported that these taxes were gaining acceptance. Streiner and Loomis (1997) assessed the economic benefits of urban-stream restoration and reported that property prices in areas with restored streams increased by 3% — 13%.

### **Permitting**

Wei (2006) discussed how to avoid having to obtain a stormwater permit. Walker (2006) discussed how to write tight stormwater treatment specifications. White and Boswell (2006) discussed the implementation of the NPDES Phase II

program in California and Kansas. The study found that fiscal resources, a well-educated public, positive perceptions of the federal policy, and co-operative planning efforts lead to better compliance with the mandate and a higher quality response. Stidger (2006b) reviewed current and projected stormwater regulations, including low-impact development strategies for highways.

Mark and Parkinson (2005) advocated an integrated approach as the future of stormwater management. The goal was to propose alternative approaches for controlling development in flood-management land. Rauch et al. (2005) reviewed the state-of-the-art and current implementation of integrated approaches in urban storm drainage. Integration was being implemented at two conceptual levels: (1) integrating the storm drainage system with the receiving environment, and (2) considering the interaction and influence of stakeholder participation on the performance and development of the storm drainage system.

Lee and Stenstrom (2005) compared three stormwater permit programs to determine their effectiveness in assisting agencies in meeting their NPDES permits. The land-use monitoring program appeared to be more successful than the beach-water-quality program or the industrial monitoring program. Urbonas and Doerfer (2005) advocated master planning for stream protection in urban watersheds. The paper suggested several general principles that can be used to deal with these emergent problems. Zhou and Beck (2005) described the difficulties of managing stormwater runoff in sinkhole and karst areas. Mixing cell models were used to predict the impact of the runoff on the karst aquifer. Obropta and Goodrow (2005) reviewed the New Jersey process of establishing Regional Stormwater Management Plans. The regional plans were required in order to minimize flooding, eliminate nonpoint source pollution, and promote groundwater recharge. They were also designed to provide a better measure of the impact of on-site stormwater management practices on downstream sites and to aid in TMDL development and implementation. The paper by Orlins et al. (2005) presented the challenges faced by New Jersey entities in developing regional stormwater management plans in southern New Jersey. Many of the challenges related to the fact that watershed boundaries often contain many municipalities and counties, each of which have local control of planning, zoning and land use.

Lewis (2005) highlighted the move to holistic stormwater management in the city of Charlotte (North Carolina) by reviewing two projects. The first project used the old approach to address stormwater issues, i.e., replace the pipes and stabilize the channel banks. The second project used the holistic approach; it addressed the problems and infrastructure, but also included BMP and stream restoration projects. Lien et al. (2005) presented an overview of the watershed agreement signed by Baltimore City and County. The purpose of the watershed agreement was to ensure that both jurisdictions established and worked toward a common set of goals.

The Staten Island Bluebelt was created as an interconnected set of stormwater treatment practices to improve drainage (Deb-Moorjani et al. 2005). stormwater treatment practices were combined with a traditional drainage structure to address the issues of water quality and flooding. Thomas et al. (2005) reviewed two watershed management plans in James City County (Virginia). The plan-specific strategies being implemented included acquisition of priority conservation and buffer areas, demonstration projects, development of special stormwater criteria, existing BMP retrofits, regional stormwater treatment practices, stream restorations, better site design initiatives and formation of a County water-quality education program.

Maimone et al. (2005) outlined the watershed plan for a suburban/urban creek in the Philadelphia (Pennsylvania) area. The program includes hydrologic and water quality analysis, as well as biological, wetland and habitat assessments. The plan has prioritized areas for potential restoration. Merly and Shoberg (2005) highlighted the Glen Oaks Stormwater Management Project in Clearwater, Florida. The project combined an integrated system of stormwater treatment practices with stream restoration and educational and recreational areas. O'Connell and Palmer (2005) reviewed the California Ocean plan, which has set bacterial water-contact standards. A plan reviewer compared the environmental fate of total coliforms, fecal coliforms and enterococci based on historical monitoring data. The results showed that all indicators behaved similarly in terms of fate and transport.

Shen and Jiang (2005) reviewed the changes needed in the separate institutions involved in water management in China. The reforms will be designed to reduce the barriers between the separate management of parts of the hydrologic cycle and improve communications.

Du Bay et al. (2004) reviewed two policy memos issued by the US EPA – “Committing EPA’s Water Program to Advancing the Watershed Approach” and “Watershed-Based NPDES Permitting Policy Statement.” As a result,

Implementation Guidance has been developed and the paper focused on the complex issues raised during the public comment period for the Guidance. Bradley et al. (2004) reviewed the holistic strategy to wet-weather events under development by the US EPA. The purpose of the new strategy is to provide required flexibility for stormwater, CSO and SSO discharges covered by NPDES permits.

Clements et al. (2004) reviewed the use of the Site Evaluation Tool (SET) developed for Mecklenburg County. This tool will allow the user to show the county and the municipalities that the site development plans meet the goals of the county in terms of water protection, since it calculates pre- and post-development loads.

Hall et al. (2003) reviewed the perceived primary problems with EPA's current approach to regulating wet weather flows: its piecemeal fashion. The authors felt that this created an approach that is fraught with regulatory and technical inconsistencies. The authors argued that EPA has done little to ensure that the legal and technical flexibility in its NPDES permit regulations and described in guidance documents is actually allowed by regional offices. Abron (2003) presented the legal aspects of NPDES permits. All new NPDES permits issued will need a capacity, management, operation, and maintenance program; a prohibition on discharges to the waters of the U.S. that occur upstream of the treatment plant; and reporting, public notification, and recording requirements for discharges from a municipal sanitary sewer collection system. Kime et al. (2003) summarized the Watershed-Based National Pollutant Discharge Elimination System (NPDES) Permitting Policy Statement issued by US EPA in January 2003. The Policy represents EPA's commitment to watershed management and support for a holistic watershed approach to water quality management. EPA is working to move watershed-based permitting beyond a concept to an implementation phase. Fernandez et al. (2003) presented the pre-CMOM study employed by Coral Springs, FL, including the methodology used to conduct a preliminary study (not begin the full CMOM study, but to assess the current status of compliance). The results of the Pre-CMOM Study as compared to the CMOM requirements became the scope of work of the full CMOM Study.

Cook and DeBell (2002) reviewed EPA's focus on improving the management of urban wet weather flows under the NPDES program. The methods of particular interest are methods for improving urban wet weather flows, watershed management, best management practices, innovative funding mechanisms, and locally-developed TMDLs. DeBell and Weiss (2002) reviewed the development of a Federal Register notice to provide guidance, policies and regulations to clarify NPDES requirements for municipal sanitary sewer collection systems and sanitary sewer overflows. The paper provided an overview of the Agency's approach. EPA's watershed approach to managing urban nonpoint source pollution was discussed by Frederick et al. (2002). EPA's guidance contained a set of management measures that EPA recommends to states, local governments, and community groups to incorporate into their urban pollution control programs to protect surface and groundwater quality. For each management measure, EPA has provided a list of practices that can be used to implement the objectives of the management measure. Cost and effectiveness data are provided for most practices and references to the most up-to-date and useful publications and web sites are cited.

Barnard (2002) reviewed the Phase II regulations that were published by EPA on December 8, 1999, and that address stormwater discharges from small municipal separate storm sewers and construction sites between one and five acres. The affected municipalities are required to develop stormwater control programs to address the pollution problems. Collins et al. (2002) discussed the compilation of regulatory requirements for stormwater runoff. The analysis suggested the usefulness of conducting qualitative and quantitative assessments about available control technologies. Hall et al. (2002) discussed the EPA's developing of numerous requirements for the design and permitting of facilities intended to manage wet weather flows properly. These requirements have been issued in a number of contexts and have, at times, been subject to widely varying interpretation across the country, leading to dramatically different treatment requirements. The paper by Swietlik (2002) discussed the statutory background and essential elements of water quality standards and how biological assessments and criteria can be used to define appropriate aquatic life goals for urban water bodies. This will also allow for a better focus of scarce resources on restoration efforts that are attainable.

Kosco and Keefe (2002) discussed the EPA requirements of the Phase II regulations to develop measurable goals for each BMP in the stormwater program. These markers will be used to track the progress and effectiveness of stormwater treatment practices, and are enforceable elements of the permit. Woelkers (2002) reviewed the Phase II NPDES stormwater regulations as the deadline nears for implementation. There are six minimum measurement requirements of Phase II and these will be met using best management practices and associated goals rather than analytical testing. The six measurement requirements relate to public education and outreach, public participation and involvement, elicit discharge detection and elimination, construction site run-off control, post-construction run-off controls and pollution prevention and good housekeeping. The paper by Briglio and Macrina (2002) reviewed the consultants' role in developing NPDES

Phase II programs. Bateman (2002) reviewed the outsourcing of the bulk of Florida's NPDES program activities. Private contractors write and monitor permits, and inspect construction, industrial and municipal permittees.

Schrimeck (2002) presented Michigan's General Storm Water Permit and Phase II Stormwater regulations and the innovative approach for the Rouge River. The permit incorporated some of the better aspects of the Phase I Federal Storm Water program, such as the Illicit Discharge Elimination Program and the Public Education program, without the onerous aspects of the intense sampling found under that program. The permit also mandated that the communities/agencies within the various subwatersheds of the Rouge cooperate together to format a plan for public involvement in the restoration process and, most uniquely, required that the various parties within the subwatersheds develop a comprehensive watershed management plan for their separate areas that will be linked together to form a basin wide Remedial Action program for the Rouge River.

Harrison (2002) reviewed the municipal perspective on zero-impact policy issues and the concerns that it raises. While the inventory of stormwater quality management measures to reduce pollutant discharges is growing, they do not achieve the zero-discharge mandate and do not reduce the vulnerability to statutory enforcement action.

Under Phase I of the NPDES permit requirement, permits were required for stormwater discharges associated with industrial activity (Daniel 2001). Typically these discharges were material handling and storage areas at certain industries. Authorized dischargers were required to develop and implement stormwater pollution prevention plans to prevent the discharge of pollutants in runoff. Pollution prevention has been the key for stormwater discharges associated with industrial activities (Duke 2001). However, evidence suggests the pollution prevention approach is widely failing. In targeted case studies, evaluation of chemical constituents in runoff shows no evidence of pollutant reduction over time. Effective implementation of the pollution prevention approach may require more resources by regulators compared to classical command-and-control approaches, but instead agencies have devoted far fewer resources and relied on voluntary compliance. Therefore, it is important for the Industrial community to understand what these regulations are trying to accomplish and how these regulations will be locally specific. The paper by Gates and Resiak (2001) discussed when the State of Indiana will implement the Phase II regulations, who will need to apply for Phase II permit coverage, and what requirements will be in those permits. These were illustrated by a specific case study.

Georgia EPD and the Board of Natural Resources have to decide how and who should do watershed protection (Scarborough 2001). Georgia concluded that POTWs should be the responsible party since the County/City controls land use in Georgia. The purpose of the Gwinnett County Watershed Assessment was to evaluate stream conditions within the County and recommend a watershed protection strategy to improve the streams which were not meeting the designated use. Patel (2001) provided a general background and state perspective for municipalities to approach the regulatory requirements for the new EPA Phase II Stormwater regulations. The description of the proposed Pennsylvania State Strategy summarized what the Phase II regulations will require of the regulated communities, and answered basic questions of who is affected, what is required, when permit applications are to be submitted, what permitting options are available, what types of permits may be available, what minimum information on permit applications may be necessary, and what, if any, funding assistance may be available. The CMOM approach in the SSO Rule will require "a dynamic system management framework that encourages evaluating and prioritizing efforts to identify and correct performance-limiting situations in the collection system" (Ruggard 2001). The goal of the ultimate elimination of any type of overflow from the sanitary sewer system was established at the Stege Sanitary District in 1996. The paper reviewed the improvements to the District's management, engineering, maintenance and data management systems in order to achieve that goal.

Stormwater discharges associated with industrial activities must be characterized for effective analysis of pollutant loads in urban watersheds. Regulatory compliance lists and inventories developed for other purposes may be poor identifiers of discharging facilities and poor estimators of discharges. In 1996, the General Electric Plastics (GE Plastics) resin production facility located in Bay Saint Louis, Mississippi, embarked on a capital program to improve stormwater management at the facility by permitting and installing a structural BMP consisting of a *first flush* capture and treatment system for critical areas of the facility that had a potential to contribute acrylonitrile to stormwater discharges from the facility. Bennett et al. (1999) discussed the issues encountered during the permitting, implementation, and operation of the first flush system. A number of small cities across the United States were finding it difficult to comply with the national CSO policy issued by the EPA and have proposed alternative solutions to the CSO problem such as the site-specific designated-use reviews. In response, the EPA has begun to develop guidelines for designated-use reviews and provide technical and financial aid to several states (Mealey, 1999).

WWF control often involves unfamiliar institutional alliances, diverse groups of stakeholders, varied goals, and social or institutional resistance to new approaches. Bateman et al. (1999) reviewed the institutional framework the state of Florida has implemented to address stormwater problems associated with land uses. Karaitiana et al. (1999) discussed a partnership between the City Council of Christchurch, New Zealand and the indigenous Moari people to sustainably manage the wetlands and waterways of Christchurch. The partners have identified six generic values, including ecology, landscape, culture, heritage, recreation and drainage, which will replace only drainage as the goals of the management approach. The government of New South Wales (Australia) has initiated a stormwater management planning program to mitigate the environmental impacts of stormwater runoff from urban areas throughout the State (Sharpin et al. 1999). The urban stormwater management plan addresses environmental protection issues, including stormwater quality, river flow, riparian vegetation and aquatic habitat management, and was tailored to the state's climatic, ecological, social, land use and administrative characteristics. Nielsen and Elle (1999) argued that current infrastructure hold a considerable momentum, and this momentum was a barrier to transformation to newer more sustainable technologies. The sewage sector in Denmark was an example of a technical infrastructure system whose technical, economic, and social momentum acts as a barrier to the implementation of small-scale stormwater infiltration.

Geldof (1999) discussed the impact of "qwerties" on the implementation of source-oriented approaches to stormwater management in Holland. A qwertie was an ingrained pattern that occurs in a complex process which can be eliminated only by taking measures which have sufficient critical mass and doing so at the right moment. Nine qwerties were detailed, including those of conservatism and the use of different languages. McElroy (1999) outlined efforts in the Palestinian West Bank and Gaza Strip to develop sustainable water use and reuse practices and to improve wastewater treatment so that water quality standards and regulations can be adopted that will be meaningful, measurable and enforceable. Cooperating agencies included the Palestinian Water Authority, the Palestinian Ministry for Environmental Affairs, and The United States Agency for International Development. The development of a stormwater management strategy for the City of Clarence in Tasmania illustrated a number of difficulties faced by local government agencies and communities seeking to be more environmentally and socially responsive to ecological sustainable development goals, and the strategies available to address these difficulties. Philips et al. (1999) outlined a number of innovative approaches to the technical analysis which were used by the City of Clarence, and the principles guiding the selection of particular options. In 1994, Northern Kentucky's three counties, including 28 cities, consolidated their sewer collection systems under Sanitation District No. 1, creating the second largest public sewer utility in Kentucky, which maintained more than 1,200 miles of sanitary sewer lines. Many participating jurisdictions believe that the Sanitation District were now looking to the District to take over the operation and maintenance of Northern Kentucky's stormwater drainage systems and controls (Higdon and Eger, 1999). Because of the diverse, multi-agency and interactive nature of the watershed management approach model, both drinking and wastewater utilities often found it difficult to establish and define their role in a watershed management program. Shablen and Lauria (1999) outlined how the city of Columbus, Ohio, Division of Water and corresponding watershed stakeholders have adopted unique roles integrating federal, state and local resources to develop a source water protection partnership.

In March 1998, Portland Oregon became the first major urban area with a threatened salmonid listed under the United States' Endangered Species Act (ESA). This marked the first time the ESA has been applied in a major urban area and would result in new challenges in how best to apply and meet the Act. It would also require fundamental changes in a broad suite of activities conducted in planning, developing, and maintaining a city (Abrams and Prescott, 1999). The city of Indianapolis, Minnesota was currently fighting state permitting provisions that would make it illegal for the city's treatment facility to discharge combined sewer and stormwater flows without secondary treatment. The new regulations could cost the city \$2 billion over the next decade (*Civil Engineering*, 1999). Odeal (1999) described efforts by the Northeast Ohio Regional Sewer District to fashion a program to develop future employees and leaders for the district, which provides wastewater conveyance, CSO control, and wastewater treatment for the Greater Cleveland area (Ohio). After years of failing to meet WWTP discharge requirements, the city of Waterton, South Dakota evaluated the existing treatment process, to determine whether or not the City was truly on a path to compliance, and to assist with making any projects affordable. Schroedel and Boerger (1999) presented the success of one of the resulting recommendations, using a program manager to track all required activities to achieve compliance. Van der Heijden (1999) discussed a system of BMP intended to reduce the phosphorus loading from an area of new development and existing commercial and mixed land use. This effort was part of the New York City Department of Environmental Protection's pilot phosphorus offset program.

The Mich. Department of Environmental Quality initiated a limited Voluntary General Storm Water Permit until the U.S.



EPA Phase II stormwater regulations become effective (Cowles, 1998). The Wis. Department of Natural Resources recognized that a comprehensive urban stormwater permitting program was needed for the Milwaukee River Basin as water quality in area streams and the near-shore area of Lake Michigan did not meet state standards. Aggressive voluntary efforts to control sources of rural and urban NPS pollution did not achieve desired results (D'Antuono, 1998a and 1998b). Wayne County's Rouge River National Wet Weather Demonstration Project (Rouge Project) is a comprehensive program to restore the water quality and beneficial uses of the Rouge River, a tributary to the Detroit River in southeast Mich. with significant sources of pollution from industrial and municipal point sources, stormwater runoff, and CSO (Murray, 1998). One of the Rouge Project's key findings was that major barriers to effective pollution control and water resources management are often institutional, not technical. The Rouge Project supplemented the existing regulatory program with a general permit for a sub-watershed policy in an effort to control NPS pollution (Ridgway, 1998). The NORSD service area contains approximately 20 000 ha (50 000 acres) of combined sewer area and 125 CSO for which it has an NPDES Permit (Greenland, 1998). Part of the CSO Permit requires completion of CSO control plans before 2002 and an outline was given for the plans to meet these requirements. The Community Discharge Permit Program was established as a result of grant conditions (U.S. EPA funded) for the NORSD's Heights-Hilltop and Southwest interceptors (Duke, 1998). Member communities made significant expenditures to control and alleviate SSO and the program has increased community awareness for the need for BMP to meet the performance objectives stated in the permit.

On January 9, 1998, the U.S. EPA published in the Federal Register "Proposed Regulations for Revision of the Water Pollution Control Program Addressing Storm Water Discharges" or the NPDES Storm Water Phase II proposed rule. The proposal designated two classes of facilities for automatic coverage on a nationwide basis under the NPDES program, small municipal separate storm sewer systems located in urbanized areas (about 3 500 municipalities) and construction activities (pollutants include sediment and erosion from these sites) that disturb between 0.4 and 2 ha (1 and 5 acres) of land (about 110 000 sites per year) (Kosco, 1998; EST, 1998). The U.S. EPA considered a framework for "watershed permitting" as an alternative to separate permitting of individual pollutant discharge sources which, in urban areas, would include a coordinated approach to addressing many sources in one permit or few permits, including both urban wet weather and continuous sources of pollution (Cook et al., 1998). This system of permitting helps to highlight the most critical pollution control needs of a watershed and community and allows those needs to be addressed in the most effective and least costly manner consistent with the goals of the Clean Water Act. The Mass. Department of Environmental Protection revised the state's water quality standards to include water body classifications that reflect a range of circumstances under which combined sewers discharge and issued a new CSO Policy and Guidance Document, incorporating increased flexibility for permittees to demonstrate the combined sewer discharges were being controlled to the maximum extent feasible (Hornbrook et al., 1998a). This revision came in response to the U.S. EPA's publication of its final CSO Control Policy in April of 1994.

The EPA is adopting an interim-permitting approach for regulating stormwater discharges under its NPDES program (EPA, 1996c). The EPA developed three stormwater-discharge-permit options for industrial facilities: (1) an individual application, (2) a group application, or (3) a notice of intent for a general permit. The facility should be more cautious to select a general permit versus a multisector NPDES stormwater permit (Espey *et al.*, 1996). Stormwater discharged from iron and steel industries are regulated by the EPA Industrial Stormwater Permits Program that require the submission of a notification as soon as possible to the EPA under the Clean Water Act (Chalfant, 1996; Bralower, 1996).

Dinnison (1996) discussed the EPA's regulatory requirements for stormwater discharges and offered a practical approach to compliance with the complex federal and state stormwater regulations. A guide for obtaining a stormwater permit for construction activities at Army installations provides detailed administrative procedures for environmental staff regarding their compliance duties (Dzuray and Tang, 1996).

The California Water Resources Control Board has developed an industrial facilities database to identify the status of compliance with a facility's General Industrial Permit conditions (Duke and Chung, 1996). The Rouge River National Wet Weather Demonstration Project provided an opportunity for alternate watershed-wide NPDES permit programs to municipal stormwater discharge regulation under the Clean Water Act (Murray *et al.*, 1996).

Roth (1996) reviewed the current German law that exists for municipalities to promote alternative stormwater management, including changes in the sewage regulations and wastewater fee assessment.

### ***Cost Analysis and Financing***

Helfand et al. (2006) discussed the economics of using native plants in residential landscapes and the resultant impacts on

environmental quality. King et al. (2006) described a Texas Department of Transportation tool that collect, stores and retrieves information on stormwater compliance. Lee et al. (2006d) provided a life-cycle optimization for highway stormwater controls. The model can be integrated with spreadsheet optimization tools to find the least-cost options for implementing controls. Thurston (2006) presented the opportunity costs of residential for stormwater controls.

Benson and Whetham (2004) presented a case study integrating technical and management sciences to develop the best solution for addressing an SSO consent order. The three tools used in the evaluation included: (1) residual asset life analysis; (2) business case analysis; and (3) weighted decision tables. The use of satellite imagery and GIS in Denver (Colorado) was reviewed by Blossom (2004). The results of this analysis were used to fairly distribute stormwater fees to the contributing entities in Denver. Blackwell et al. (2004) reviewed the methodology developed to determine the capacity of the existing sewer system and the needs for future growth. It also included confirming dry- and wet-weather flows to address CSO and SSO issues.

Klemens (2004) reviewed the financial and engineering aspects of rebuilding the Atlanta region's water and sewer systems, including the decision to replace combined sewers in some areas with separate storm and sanitary sewer systems. Miles et al. (2004) presented the framework for a financial model to be used by utility managers to demonstrate the business cases for funding sewer rehabilitation. The model includes traditionally accepted financial considerations such as savings from infiltration and inflow (I/I) removal through reduced transport and treatment costs and savings from deferred capital expenditures, and includes savings in other operation and maintenance costs through reduced costs for cleaning, root removal, and crew time spent on emergency responses to sanitary sewer overflows (SSOs) and blockages. A System-Wide Hydraulic Evaluation and Capacity Assurance Plan was implemented by the City of Folsom to identify, assess and prioritize deficiencies (Knapp and Eising 2004). The purpose was to cost-effectively manage the city's collection system.

Nemura and Moore (2004) reviewed the concerns with the costs of meeting the "fishable and swimmable" goals of the Clean Water Act. The role of water quality standards in setting policies for wet weather discharges was presented, along with an update on advances being considered in the standards program. Turner et al. (2004) related the financial difficulties faced by the City of Columbus (Georgia) Water Works due to increasing regulations and aging infrastructure. The use of a consultant to develop a financial plan was reviewed.

Nemura et al. (2004) reviewed the tools used in the St. Joseph River (Indiana) watershed initiative. The stakeholders have to identify cost-effective source controls that will meet water quality criteria within the Indiana portion of the river and at the Indiana/Michigan state line. Otherwise, revisions to the water quality standards may need to be pursued. Spicer (2004) discussed the establishment of a formal remediation program for the Greater Cincinnati sewer system to prevent SSOs and CSOs.

Anderson and Iyaduri (2003) advocated the need for integrated urban water planning and a view of the "big picture" as seen in New South Wales (Australia). The process linked urban water management objectives to overall catchment and river management objectives. Bowen et al. (2003) presented the methodology used to develop the engineered productivity standards and improved work methods for crews performing collection system maintenance activities.

Burden et al. (2003) compared costs to communities of on-site wastewater treatment systems (OWTS) versus municipal sewer systems as part of an evaluation of OWTS upgrade alternatives. Comparisons were performed based on relative cost-effectiveness, treatment performance and land area requirements. The design, construction, and operation of central sewers proved to be the most cost-effective option for the Phillippi Creek study area.

Bowen (2003) reviewed the impact small MS4s face with the Phase II stormwater regulations. Stormwater management programs in Stephenville, TX; Chapel Hill, NC; and Dallas, TX, were outlined. Eshelman and Williams (2003) reported on the problems that an increasing population put on Wentzville, MO's drainage plan and limited budget. The authors also discuss the development of a master plan inexpensively and quickly. Braun (2003) proposed use of Middletown, OH's strategy, which involved coordinating the capital improvement plans of utility engineers and transportation engineers. Integration of the knowledge management systems among governments, public utilities, and even private businesses would be expected to lead to smarter asset management decisions.

Cantu et al. (2003) reviewed Austin, TX's Clean Water Program which addressed problems with the wastewater collection system leading to increasing numbers of sanitary sewer overflows (SSOs). Donovan et al. (2003) presented the Lowell, MA CSO abatement program. The city argued that the cost of the CSO program advocated by regulatory

agencies (approximately \$100 million) could not be justified by its benefits. While committed to CSO reduction, Lowell proposed a more cost-effective approach tied to the watershed-wide study and currently, Lowell's CSO program is a test case balancing costs and environmental impacts. Gribbon et al. (2003) discussed the methods used by the City of Portland Oregon's Bureau of Environmental Services (BES) to procure and compensate the contractor for the West Side Willamette River Combined Sewer Overflow (CSO) Project. The paper focused on pre-construction phase lessons learned from the development of the contract general conditions, establishment of a construction budget and cost control program, incorporation of contractor recommended design changes, and development of a subcontractor procurement program for construction.

Lachmayr and Haves (2003) reviewed the cost incentives for the Town of Weymouth, MA to implement a CMOM program. Weymouth pays for treatment based on the amount of flow sent to the plant. Landers (2003b) reviewed Nashua, NH's plans to revamp its campaign to disaggregate its combined sewers. Instead of disaggregating additional combined sewers, Nashua is proposing to build storage tanks and make other improvements to increase its system's collection capacity. Landers (2003a) reviewed Atlanta, GA's plans to address its CSO and SSO problems through the construction of tunnels and separation of combined sewers into two systems.

Hagekhalil and Farhang (2003) presented the City of Los Angeles's CMOM program that was developed to meet the proposed EPA regulations. The program included a collection system planning business plan which integrated various elements of the collection system into a whole. A Fats, Oils, and Grease (FOG) control program, a roots control program, and a wet-weather overflow reduction program were also major components. Hagekhalil et al. (2003) then reviewed the challenges faced by the City of Los Angeles as it implemented the CMOM program. Humphrey and Delizo (2003) used a reliability-centered maintenance and asset management program to implement the CMOM program for the Stege Sanitary District. The Stege System Rehabilitation Plan was a management information system linked with mapping and condition assessment tools that enable management and operations staff to improve system performance and reliability.

Little (2003) examined the point-source versus nonpoint source loads of phosphorus to the Chatfield Basin southwest of Denver, CO from a cost perspective. The authors used mathematical optimization methods to develop cost-effective TMDLs. Mumley et al. (2003) reviewed the guidance developed by the California State Water Resources Control Board and Regional Water Quality Control Boards to manage California's impaired waters. The phases of the process ranged from defining and planning the project to data collection and analyses to regulatory action and implementation. Palhegvi et al. (2003) compared stream segments in the Thompson Creek Watershed (Santa Clara, CA) upstream of development, which continue to be stable and do not show excessive erosion, with stream segments downstream of outfalls that drain impervious areas. The results indicated that the increase in runoff as a result of urbanization (hydromodification) was the most plausible cause of erosion. Salgaonkar et al. (2003) reviewed the Santa Monica (CA) experience in sustainable water management of urban runoff and the development of the urban runoff reclamation facility. The objective of the Santa Monica Urban Runoff Reclamation Facility (SMURRF) is to eliminate pollution of Santa Monica Bay caused by urban runoff during dry season (dry-weather flows).

Minamide et al. (2003) described the regulatory framework for the City of Los Angeles' Integrated Resources Plan (IRP). The IRP integrated facilities planning for the wastewater, storm water, and recycled water systems with the being specific water quality goals to be used in the facility planning process. Lo et al. (2003) presented the Los Angeles County's perspective on pretreatment programs. Policy shifted recently from focusing on industrial to municipal source control, turning attention from the highly regulated and compliant industrial sector to the creation of alternative controls for the virtually unregulated residential community. Mowery et al. (2003) showed how conducting financial planning in an integrated resources planning for the Los Angeles' wastewater, stormwater and water systems increased the range of funding options for meeting future utility system needs in an affordable manner.

Neff et al. (2003) described the City of Clearwater's CMOM self-audit which had a goal of achieving environmental improvements and regulatory compliance more quickly and in a less adversarial setting than with the traditional enforcement approach. Oppenheim et al. (2003) reviewed the Miami-Dade County (FL) Water and Sewer Departments existing CMOM program. The results of the CMOM activity determined where MDWASD will focus its efforts for improvements. The paper compared how Miami's CMOM efforts met with the draft EPA's proposed National Pollutant Discharge System Regulation. Roberson (2003) reported on the San Bernardino County Special Districts Department (SBC SDD) Optimization Study, Water and Sewer Rates Study, and Capital Improvement Program, which allowed SBC SDD to make its first attempt to close the competitive gap that existed in the management, administration, and operations Divisions. Rothman and Heijn (2003) outlined the measures taken by the City of North Miami Beach to comply with the

CMOM requirements. The CMOM framework had the benefit of supporting system operators, both by affirming the importance of their role in system management and by encouraging appropriate funding levels for the implementation of comprehensive preventive maintenance programs. Wilson (2003) reviewed the needs of areas like the Puget Sound to create sewage management solutions for communities that do not require sewers.

Bacon et al. (2002) reported on an initiative of the Joyce Foundation that is investigating how conservation development projects could create tradable/bankable credits for nutrient reduction as part of a TMDL or other watershed protection program in the Great Lakes region. The two pilot projects for this are located in the Kalamazoo River – Lake Allegan watershed and in the Saginaw Bay watershed (Michigan). Fischer (2002) discussed the Governmental Accounting Standards Board's 34<sup>th</sup> Statement (GASB-34) that has the stated purpose of having units of government in the U.S. make annual reports more comprehensive and easier to understand and use. One of the most revolutionary requirements in GASB-34 is the reporting of infrastructure assets (roads, bridges, traffic signals, sanitary and storm sewer systems and public water supply systems).

The paper by Benson (2002) reviewed the recent survey by Black & Veatch Corporation of North American user-fee-funded stormwater utility financial practices. It profiled current practices and potential future trends. Ambrose et al. (2002) presented the approach of Wheeling, West Virginia, to separately identify system wastewater and stormwater allocation costs and then to share the costs equitably between residential and commercial customers. This study was beneficial because it identified what the services actually cost, it verified whether customer classes were paying their fair share, and it provided useful information for forming a separate stormwater enterprise fund. An update of the City of Jefferson, Missouri's stormwater management program was provided by Brizendine et al. (2002). A funded integrated stormwater management program was developed to address capital improvement needs, program needs, and regulatory needs in order to prevent water quality degradation and reduce flooding. Foster et al. (2002) reviewed the integrated partnering approach that was used to determine cost responsibility for Detroit's investment in combined sewer overflow facilities. Rothstein et al. (2002) discussed the development of the strategic financial planning model that was created to support Atlanta's CSO-SSO program implementation. The SFP model enabled program planners and policy makers to efficiently construct and evaluate financing plans and rate increase projections associated with alternative capital programs and schedules involving hundreds of individual projects. Salem, Oregon's strategic financial planning was reviewed by Galardi et al. (2002). The \$1 billion planning process followed four main tracks of analysis: system development charges, long-term financial planning, cost-of-service analysis, and public education and involvement.

Stormwater controls and Best Management Practices (stormwater treatment practices) were evaluated within a land development context (Sample et al., 2001a). Costs were developed from published literature and standard cost estimation guides. Data gaps and research needs were then explored. Many communities across the country have developed user-charges – and their delivery vehicles, stormwater utilities – as the primary funding source for expanded maintenance and new infrastructure (Rose 2001). With the implementation of a new funding source (e.g., user fee or special assessment) for stormwater management programs, a municipality imposes a new financial burden on the public (McClelland 2001). Therefore, the key to a successful stormwater utility implementation is public approval. The article presented methods for public education and approval, particularly the shift in focus from the fees to the stormwater service the new revenue will provide. Sound rate methodology should draw upon key concepts from public finance, utility theory, economics, law and engineering science. Most rate structures have been built around the “runoff” theory. Within this “runoff” theory are four related but different basic models: (1) the “impervious area” model, (2) the “weighted pervious plus impervious area” model, (3) the “land use” or “density” model, and (4) the newly emerging “pollutant loading” model. Fitting a basic model to a community is largely a matter of community political context.

Hall et al. (2001a and b) reviewed EPA's development of requirements applicable to design and permitting of wet-weather flow management facilities. These include issuance of various combined sewer overflow policies, development of regulations to require elimination of SSOs, enforcement actions against municipal entities, objections to state program permits; informal guidance to Regional Offices, and Regional Office initiatives. The paper reviewed the major inconsistencies in current program implementation, evaluated the applicable federal regulations and permit approaches, and recommended broadly, how communities with SSOs and CSOs should approach state and federal agencies to resolve these matters. Salo (2001) reported on the comprehensive assessment of the City of Atlanta's water and wastewater operations. Internal and external management approaches were considered after it was found that a substantial rate increase would be required to fund a Capital Improvement Program. The adopted plan combined approaches through contract operation of the entire Water System, contract operation of the largest wastewater treatment plant, and reengineering of the other City wastewater and sewer operations.

Present worth is often used to select among alternatives in the public works arena (Bate et al., 2001). This is adequate if the options are technically equal and operations and maintenance costs are controlling, but it overlooks intangible criterion such as social impacts, meeting the design criteria, construction, traffic and utility impacts, constructability, as well as service life and reliability. "Paired comparisons" allow comparisons of intangible criterion that impact the project. Case histories illustrated the use of the "paired comparison" process. Booth et al. (2001) reviewed a survey of residents in the Oak Creek and Menomonee River watersheds, both located in Milwaukee County, Wisconsin to determine the willingness to support ecological restoration of urban streams. One purpose of the project was to assess the willingness to pay (WTP) of urban watershed residents for urban stream restoration and to identify the underlying economic, psychological, and social motivations for WTP. The basic hypothesis tested here was that psychological variables, environmental attitudes, and ethical values are more important than strictly economic phenomenon.

In the future, systematic and ongoing asset management programs are expected to influence evaluations by bond rating agencies, budget allocations, decisions by enforcement authorities, and acceptance of rate increases (Morgan and Wagner 2001). This approach incorporates life-cycle analysis, longer planning horizons and more intensive tracking of asset conditions. Of the nine primary program components in the CMOM/SSO guidance, most are related directly or indirectly to asset management activities. The privatized operation of the Milwaukee Wisconsin, sewerage facilities has lowered costs of operation (\$14 million per year) and increased service performance (Tobel and Jankowski 2001). Additional benefits include increased asset and performance accountability and state-of-the art operations and maintenance (O&M) technologies. The Kansas City Missouri Water Services Department (WSD) developed a Competitive Business Plan (CBP) (Salo and Turner 2001). The CBP identified how WSD will improve service levels and minimize annual operating costs. Implementation of this CBP will require significant additional capital investment. O&M savings are expected to be between \$129 and \$217 million over the next 10 years.

New federal funding sources have become available in the US for WWF control activities. The proposed budget for the U.S. EPA in fiscal year (FY) 2001 will continue the agency's efforts to reduce funding of traditional clean water infrastructure and boost spending for projects addressing nonpoint source pollution (Calamita 2000). The Water Pollution Program Enhancements Act of 2000 (S 2417), introduced to congress in April 2000, would significantly increase federal funding for states to implement programs to address nonpoint source pollution, to assess the quality of their rivers and streams, and to collect the data needed to prepare TMDLs (Anonymous 2000d).

Several authors examined the costs of stormwater and non-point source pollution control programs. Butt and Brown (2000) report that over \$3.5 billion were spent toward nutrient controls in the Chesapeake Bay watershed between 1985 and 1996. Despite nutrient reductions, no significant improvements in dissolved oxygen levels at the bottom of the Chesapeake Bay were detected along the Bay mainstem during the warmer months, and the mouth of Bay showed marginally significant degradation during the 11-year-period. It was determined that dissolved oxygen conditions were influenced more by nitrogen than phosphorus reductions and that nutrient controls aimed at the mid-Bay region had the greatest potential for improving low dissolved oxygen conditions in the Bay's bottom waters. Fan et al. (2000a) presented a critical review of information on the costs of stormwater pollution control facilities in urban areas, including collection, control, and treatment systems. Jorgensen and Syme (2000) examined contingent valuation (CV) surveys that were used to evaluate public support for stormwater pollution abatement efforts. Their study revealed that attitude toward paying underpinned protest beliefs regarding the role of government in stormwater management and individual rights to unpolluted waterways. They cautioned that censoring protest responses in the present study would bias CV samples toward those individuals who were favorably disposed toward paying for environmental public goods and those from higher income households. Kalman et al. (2000) explored the potential value of benefit-cost evaluation for stormwater quality management decisions at a local level. A preliminary benefit-cost analysis screening method was used for a maximum extent practicable (MEP) analysis, identifying promising management practices, and identifying societal and economic tradeoffs for local stormwater problems. In the case of Ballona Creek, a major urban storm drain in Los Angeles, California, USA, benefit-cost analysis was found to be useful for evaluating and understanding stormwater management alternatives despite the uncertainties in characterizing stormwater quality and the effects of stormwater management on improving receiving water quality (Kalman et al. 2000).

The Clean Water State Revolving Fund is the United States' largest source of continuing financing for water quality projects. The 50-state managed funds are specifically authorized to, among other things, finance nonpoint source water quality projects that implement the states' nonpoint source water quality management plans that they have developed pursuant to Section 319 of the federal Clean Water Act. Steinborn (2000) described the Clean Water State Revolving

Fund program and discusses potential uses of the funds for nonpoint source water quality projects. The Minnesota Legislature commissioned a six-month study to investigate the framework for a cost-benefit model to analyze water quality standards through a watershed-based approach that evaluates both point and nonpoint pollution sources (Laws of Minnesota 1998, Chapter 401, Section 59). Although watershed management has been practiced in Minnesota for decades to protect and restore water quality, this study was undertaken because of the growing understanding of the complex and often conflicting choices facing those who live in, use, and manage watersheds if watershed integrity is to be maintained over the long term (Ward 2000).

The costs for controlling sanitary sewer overflows (SSO) and combined sewer overflows (CSO) have also been examined. A problem common to many SSO equalization facilities was that the planning level cost estimates were significantly less than the final implementation costs. Keller et al. (2000) presented guidance for developing the costs of SSO equalization facilities so that their cost-effectiveness can be properly evaluated during the planning phase. New regulations governing discharge of untreated combined sewage (defined as wastewater consisting of both sanitary and storm flows during rain events) to the nation's receiving streams have challenged the traditional methods for determining cost responsibility and sewer rates for municipal wastewater utilities for the City of Detroit and Southeastern Michigan (Foster and Fujita 2000). A number of asset management tools and techniques that have been used in utilities, including wastewater utilities, were discussed by Morgan and Wagner (2000). The authors outlined a new approach for integrating these tools called Infrastructure Capital Assets Management (ICAM). The approach included modeling tools, decision support tools, and rational methodology to provide decision-makers the tools needed to develop strategies and justify retaining revenues as part of informed management of their assets (Morgan and Wagner 2000). Spartanburg Sanitary Sewer District (SSSD) in Spartanburg County, South Carolina, experienced rapid growth during the last decade, occurring primarily in rural areas. This growth created a demand for investments in all types of infrastructure. Through the use of an innovative and unique financing structure, SSSD was able to raise the required capital to finance significant sewer system improvements with minimal rate impact on existing customers, while contemporaneously improving wastewater treatment facility permit ("NPDES") compliance and reducing pollutant loading into area streams (Rich et al. 2000). In January 1998, the Milwaukee Metropolitan Sewerage District approved a ten-year Operations and Maintenance service contract with United Water Services. Tobel and Jankowski (2000) discussed the ongoing success of this award-winning project.

A survey conducted by the U.S. EPA showed that \$140 billion is needed to build, upgrade and maintain publicly owned WPCP and control stormwater and other runoff sources during the next 20 years (Christen, 1998). The mid-1999 extension of the U.S. EPA's stormwater protection scheme to 3 600 cities with populations below 100 000 will involve considerable cost. These "Phase II" cities will have to implement BMP in six different areas to receive the stormwater permits. According to the U.S. EPA, BMP implementation will cost between \$19.5 million and \$351.4 million per year, besides project start-up costs (Barlas 1998). Experiences from the city of Malmö, Swed. have shown integrated stormwater facilities are cost-effective means of achieving both quantity and quality control of urban stormwater runoff (Larsson and Kärppä, 1998 ). The Comprehensive Stormwater Management Plan (CSWMP) was initiated to bring various stormwater issues together so that an effective and economical policy framework and management approach could be developed for the city of Eugene, Oreg. (Andersen, 1998 ).

England (1998a) evaluated maintenance costs of BMP including wet ponds, dry ponds, exfiltration and infiltration trenches, porous pavement, baffle boxes, inlet weirs, grate inlet baskets, curb inlet baskets, and sediment sumps. In order for stormwater retrofit projects to successfully remove pollutants on a long-term basis, the type of maintenance needs should be considered in their design and construction. Baffle boxes were found to be effective for removal of sedimentation in small to medium size drainage basins when installed inline with existing pipe and required minimal easements and utility relocation, while grate inlet baskets and curb inlet baskets are more appropriate for small flows and drainage basins (England, 1998b). The tradeoff for these low-cost treatment methods are the perpetual maintenance expenses.

A case study of Ballona Creek in L.A., Calif. (Wilchfort-Kalman et al., 1998) showed that benefit-cost analysis helped in stormwater quality management decisions. Flexible CSO facilities that integrated the controls into the whole system have the greatest potential for cost savings from the tradeoff potential between centralized and de-centralized treatment and between the storage and treatment level (Geiger, 1998a and 1998b). Switalski (1998) documented the Hilltop Interceptor Contract for Greater Cleveland (Ohio) from its beginning in 1991 to its completion in 1993. Six biofilters each 1 m (3 ft) deep with a treatment bed 27 m (85 ft) long and 8 m (25 ft) wide will be used to counter odor problems on the Heights-Hilltop and another interceptor with maintenance costs including periodic replacement of the substrate projected at \$0.6 million per biofilter. Up to 18,400 Singapore dollars a month could be saved in the north spine of the Republic of

Singapore with the use of a dual-mode system (DMS) which uses collected roofwater for nonpotable uses. This amounts to 12.4% the current average monthly expenditure on water (Appan, 1998).

In Columbus, Ohio, (El-Hosseiny et al., 1998a) uncertainty of model results increased as model complexity decreased for small and medium storms (25—50 mm/d), however system performance was unpredictable for high hourly intensity, e.g., 100 mm/h. In determining the optimal complexity level, there was no difference between using total cost of an alternative versus design costs plus uncertainty costs. The city of Indianapolis, Indiana performed traditional sewer system evaluation surveys to eliminate I/I, costing between \$8.20 and \$9.80/m (\$2.50 and \$3.00/ft). An alternative approach addressed wet weather collection system overflows in two phases costing \$2.80 and \$1.50/m (\$0.85 and \$0.45/ft), respectively (Westropp and Bellucci, 1998). A Nashville, Tenn. study indicated that an I/I removal of approximately 14 700 m<sup>3</sup>/yr /100 m of lining may be expected from rehabilitating deteriorated sewers (Kurz et al., 1998).

The U.S. EPA (1997g) published a catalog of Federal funding sources for supporting local governments to implement watershed projects. Financial capability, along with other factors listed, may be used to negotiate reasonable compliance schedules for implementation of CSO controls (U.S. EPA, 1997h). Austin, Tex. implemented a trenchless-sewer technology, the installation of U-liners. Along with a new maintenance agreement, this will permit the city to repair approximately 35,000 ft/yr and reduce its per foot sewerline-rehabilitation cost by 44% (Water Eng. Manage., 1997a).

A general Benders'-decomposition model, which deals with solving mixed-variable problems, was developed to optimize the repair and replacement strategy for a sewer network. The model determines the least-cost solution by minimizing combined-wastewater treatment and repair associated with I/I (deMonsabert and Thorton, 1997).

Sarnia, Can. planned to upgrade its WWTP, to install four CSO-storage tanks, and to intercept stormwater runoff to upgrade, restore, and protect water quality in the St. Clair River. The first CSO tank has been installed with a cost-effective-cleaning system (Parente and Stevens, 1997). Underflow baffles were identified as a potentially cost-effective alternative for controlling CSO floatables at relatively inactive CSO outfalls by the Massachusetts Water Resources Authority. A study indicated that underflow baffles could provide up to 70% capture of floatables under a wide range of flow conditions (Walker *et al.*, 1997).

Battenfield *et al.* (1997) revealed some of the lessons learned in the development and implementation of a cost-effective solution to control the excess WWF of the Houston, Tex. sanitary system. Ahyerre *et al.* (1997) summarized three main difficulties of sewer-quality models, i.e., doubtful mathematical formulation, uncertainties on input and calibration data, and difficulties and cost of calibration. They further recommended that a clear distinction be made between management tools and research models.

Cost analysis. Onsite detention (OSD) of storm runoff decreases catchment peak flows through the routing effect of temporary storage; onsite retention (OSR) achieves the same objective by abstracting part of the urban flood wave and passing the retained water to disposal on site. Comparisons were made on the basis of site storage required (SSR) to achieve the same global peak flow reductions, environmental aspects and cost. OSR practice was shown to out-perform OSD generally in medium-large (14 ha to 210 ha) catchments with respect to SSR and, hence, cost; however, Scott et al. (1999) cautioned against use of OSR in unsuitable circumstances.

Koch et al. (1999) described an approach to the determination of flood frequency as a function of moneys that could be spent to address a road flooding problem caused by runoff from a 2-m<sup>2</sup> residential area near Washington, DC. Flood mitigation options included both culvert resizing and the provision of detention areas upstream. Challenges faced in completing this project included establishing a practical limit on the number of detention sites to be considered, and right-of-way issues in an area fully developed for single family homes.

Kreeger et al. (1999) presented a methodology for determining drainage system costs as the function of design storm recurrence interval. The Manning equation and sewer and swale cost data were combined to yield a relationship giving the cost per unit length of sewer or swale as a function of design flow. A typical residential development was created and a stormwater modeling computer program (Rational Method and Manning equation) along with derived cost functions were repeatedly used to design and cost the drainage system for a range of recurrence intervals.

Mangarella et al. (1999) described the retrofitting of a flood control basin in Sunnyvale California and subsequent monitoring to evaluate the pollutant removal cost effectiveness of the retrofitted basin. Costs, and particularly benefits, of

WWF control were often hard to quantify. Bond (1999) examined the benefits of basic infrastructure investment - water and sanitation systems, new electricity lines, roads, stormwater drainage, and other services provided at municipal level - to South African society. The direct economic benefits of infrastructure for low-income people have long been recognized, and include construction jobs, improvements in work productivity; and the growth of small enterprises. Indirect benefits include more time and resources for women; dramatic environmental benefits, public health benefits (which require infrastructure of a sufficient quality so as to enhance rather than endanger health), and the desegregation of urban society (with respect to enhanced employment, educational and cultural opportunities). McDonald and Johns (1999) use an example from Bogotá, Colombia to demonstrate how Social Benefit-Cost Accounting (SBCA) can be used to value the benefits and costs of a watershed restoration and protection project. By addressing the benefits and costs to all stakeholders, the design of watershed management programs can be improved to achieve goals in a cost-effective manner.

Rein (1999) evaluates environmental costs and benefits of implementing vegetated buffer strips (VBS) at Elkhorn Slough, Monterey Bay, California, both to the grower and to society as a whole, as a means of capturing nonmarket ecosystem values and informing decision making. The results support installing VBS as a management strategy in an erosion-prone watershed to protect water quality and preserve soil fertility, as well as to protect economic interests.

Various authors examined the costs and benefits of new or rehabilitated sewer and storm drainage systems. Backstrom et al. (1999) compared resource use in a conventional buried pipe system and a grassed swale system. Based on usage of both physical and financial resources, the grassed swale was a more economic alternative than the pipe system in areas with moderate land prices. Hasegawa et al. (1999) presented a system for assessing the need for repair and improvement of sewer pipe networks based on: 1) Decrease in flow capacity of the sewer pipe, 2) Possibility of road collapse, 3) Sewer overflow and flooding by Infiltration/Inflow (I/I), 4) Increase of treatment cost by I/I. Hirai et al. (1999) applied the Analytic Hierarchy Process procedure to prioritize portions of a drainage system reconstruction project. This system was effective because it can take into account both quantitative and non-quantitative measures of reconstruction needs. An analysis of historical development and present status of urban drainage in Switzerland and Germany conducted by Krejci and Borchardt (1999) clearly indicated that according to identified problems the current practice was associated with a high risk of misdirected investments and was not consistent with optimum system operation. The authors identified research objectives and conclude that for the near future cost efficiency should be an important issue in urban drainage. Prato (1999) presents multiple attribute decision-making (MADM) as a means of evaluating and selecting land and water resource management systems (LWRMS). Advantages of MADM were that it facilitates community-based collaborative decision making, avoids some of the ethical, theoretical and practical shortcomings of conventional economic approaches, does not require assigning monetary values to ecological services, allows consideration of multiple attributes and was not culturally biased.

McCleary (1999) discussed the costs and savings of the stormwater banking approach adopted by DeiDOT and provided useful information regarding program implementation. Doll et al. (1999) provided examples of stormwater utilities with credits for onsite stormwater management, including credits for peak runoff controls, implementation of water quality BMP, and proper maintenance of onsite stormwater facilities.

Taxes or charges for stormwater discharges were becoming a more widespread method of funding WWF control efforts. The Augusta (Maine, U.S.A.) Sanitary District was facing a projected capital expenditure of roughly \$30 million for CSO abatement alone over the next fifteen years. Recognizing that the costs for wet-weather controls could not be equitably distributed using its current system of charges, a new system was developed during 1998 and implemented in 1999 which took into account impervious areas as a means to generate appropriate levels of stormwater-based revenues (Freedman et al. 1999). Haarhoff (1999) reported on the introduction of a rainwater tax on runoff from sealed surfaces into receiving waters that was implemented by the Land (German Federal Region) of Schleswig-Holstein. The reactions of the communal authorities and their administrators responsible for the disposal of the wastewater including rainwater, and the level of success achieved by the District Water Authority in enforcing the creation of facilities for the treatment and retention of surface runoff was discussed.

The greatest obstacle to implementing a storm-drainage plan is often lack of funds to support construction and operation of drainage facilities. Fort Bend County, TX created financial alternatives by issuing tax-exempt-revenue bonds and collecting impact fees to finance its drainage-improvement projects (Gilligan, 1996). Financing a stormwater-management program is a challenge for local governments. Collins (1996) described detailed plans for basinwide-capital-improvement plans for implementing a stormwater-management program. The establishment of an urban-stormwater-utility authority is one of the important alternatives for funding the implementation of stormwater-pollution-control



systems (Benson, 1996; Reese, 1996). Roesner *et al.* (1996) described a stormwater-master plan that formulates an integrated way to finance necessary stormwater infrastructure for a new development near Orlando, FL. The EPA's Environmental Financial Advisory Board (EFAB) and Environmental Financing Information Network (EFIN) are valuable sources for creating a financing strategy for implementing Comprehensive Conservation and Management Plans (Henkin and Mayer, 1996). The EPA State Revolving Fund provides loans to local governments for financing surface-water-related infrastructure projects with 0% interest rate and could cover 100% of eligible costs (Singelis, 1996). In New Jersey, funding for CSO projects is provided through a grants- and low-interest construction-loan program jointly administered by the New Jersey Department of Environmental Protection and the New Jersey Wastewater Treatment Trust (Binder, 1996). The mechanisms used by Prince William County, VA to fund its Watershed Management Program include a county-wide-stormwater-management fee, development fees, and grants and cooperative agreements (Pasquel *et al.*, 1996).

The purpose of cost-benefit analysis of environmental projects is to assure that any development project with net environmental cost be off-set by projects with net environmental benefits. In reality, the processes are complex and their credibility is subject to question as a decision-support tool (George, 1996). A newly developed stormwater-management strategy (Mulden-Rigolen-system) that was designed to be both an ecologically and socially acceptable stormwater-drainage method was demonstrated and evaluated in the City of Zwickau, Germany (Huhn, 1996). Rudolph and Balke (1996) analyzed the cost-benefits of the new alternative stormwater-management systems for new residential developments in the cities of Dortmund and Zwickau, Germany.

## **Control and Treatment Technologies**

### ***General***

Zumwald (2006) described the expansion planned by a northern Kentucky stormwater utility. The district is demonstrating a dozen stormwater control practices.

Stidger (2006a) reviewed potential stormwater controls for road runoff. Dreelin *et al.* (2006) tested the effectiveness of porous pavement on clay soils. Porous pavements were found to be viable in clay soils for reducing runoff and some pollutants from small storms or the first flush from large storms. Zhang and Lulla (2006) evaluated the bacteria removal efficiency, resuspension and survivability of indicator organisms in stormwater controls. Zhang and Lulla (2006a) investigated the distribution of pathogen indicator bacteria in structural stormwater controls. The indicator bacteria were mostly associated with particles smaller than 106  $\mu\text{m}$  in the sediments and 50  $\mu\text{m}$  in the water column.

The inclusion of compost-based or compost-enhanced materials on the US EPA's BMP list was reviewed by Goldstein (2006). These products were included in one or both of the construction and post-development BMP lists. Trojak and Goldstein (2006) describes the recycling of wood and yard waste trimmings for use in stormwater and erosion controls. Trejo-Gaytan *et al.* (2006) described the urban runoff treatment at Lake Tahoe – a low-intensity chemical dosing using coagulants. Polyaluminum chlorides modified with silica or sulfate, with low to medium basicity, were consistently the best performers. Yamada *et al.* (2006) studied purification mechanisms used in the soil for road runoff. The results included a model of the removal effectiveness of soils receiving road runoff under changing rainfall conditions.

Williams and Wise (2006) investigated the hydrologic impacts of alternative approaches to stormwater management. The combination of land preservation and infiltration-based storm water management yielded the hydrologic response closest to existing conditions, although ponds were required to control peak flows for the design storms.

“Ecological sanitation” – the technologies that promote sustainable water development – were reviewed by Matsui (2004). In particular, the idea addresses how to provide adequate clean water, adequate sanitation, and how to prevent degradation from runoff.

Lenhard and de Ridder (2004) reviewed many of the sampling issues that arose when verifying performance of stormwater treatment devices. Specifically, the issue of percent removal versus meeting a verifiable effluent concentration was addressed. Sansalone (2004) addressed the need to control metal pollution in urban runoff and proposed that the knowledge by stormwater managers of the partitioning between dissolved and particulate fractions would improve water quality because stormwater treatment practices would address that relationship. The paper presented specific field and lab studies that integrated these concepts in determining the required structural and non-structural controls.

The paper by Shaver and Ridley (2002) discussed a number of tools that were recently developed to reduce stormwater-related impacts. These tools could include low impact design approaches from an individual and comprehensive catchment perspective, recognition of urban stream values, offsetting mitigation approaches when adverse impacts are unavoidable, and the establishment of regional criteria for stormwater discharges.

Growing demands on drainage still challenge designers with respect to runoff quantity and quality; landscape aesthetics, ecology and beneficial uses; and operation of existing urban wastewater systems (Chocat et al., 2001). Integrated approaches, optimal operation of the existing infrastructure, advanced pollution and runoff source controls, improved resilience of receiving waters, and adaptive water management can achieve further advances in water quality protection. Specific research needs include new technologies and strategies for stormwater management, advanced treatment of urban wet-weather effluents, and tools for analysis and operation of drainage systems. Smith et al. (2001a) investigated a range of process technologies to assess their suitability for the treatment of different water sources for non-potable reuse. For this study, a large scale water reclamation evaluation and demonstration facility was constructed at the Millennium Dome, London, UK. Greywater, rainwater and poor quality groundwater were treated by a combination of processes including biological oxidation, constructed wetlands, chemical oxidation, adsorption, ultrafiltration and reverse osmosis. Chemical and bacteriological results for each process were presented and discussed.

The WERF report on controlling pollution at its source documented the application of effectiveness measurement tools at demonstration projects that controlled wastewater and stormwater pollution at its source (WERF 2001a). The report described the demonstration projects, the tools tested, identified the costs involved, and assessed the feasibility of measuring a source control program's impact. The Minnehaha Creek Watershed District has funded a multi-component project focused on improving the water quality in Lake Nokomis (part of the chain of lakes in Minnesota) (Hettiarachchi et al., 2001). The project components included constructed wetlands and grit chambers to treat runoff from surrounding residential neighborhoods, an inflatable weir to prevent Minnehaha Creek water from flowing back into the lake, and rough fish removal and alum treatment to reduce the internal phosphorus loading.

Patty and Ahmed (2000) described the watershed assessment and protection plan being implemented in Peachtree City, Georgia, including both wet-weather and dry-weather sampling. These samples were to be used to ensure that standards are met and for model verification, where the model will be used to anticipate impacts from land development in the water.

Stinson et al. (1999) presented an overview of the EPA's Environmental Technology Verification (ETV) program which was established to overcome the numerous impediments to commercialization experienced by developers of innovative environmental technologies. The purpose of ETV was to provide such data and information to the customer groups that require them in order to accelerate the real world implementation of improved technology. This publication described the ETV approach and two recently initiated pilot programs for verification testing of WWF and source-water protection technologies.

A case study was reviewed which applied urban design planning for a commercial redevelopment project in the City of Vista, California involving the replacement of a 1950 concrete flood control channel into a restored natural "river walk" linear park. The proposed creek restoration would provide the focal point for an economic revitalization of the downtown area that includes restaurants, shops, and entertainment center, with the creek providing the common linkage (Phillips, 1999). Wong et al. (1999) discussed the various issues and performance considerations associated with the comparisons of ponds and wetlands for stormwater pollution control. Ponds and wetlands were commonly used in urban design to meet a number of urban planning objectives including the management of urban stormwater for water quality improvement.

Brashear et al. (1999) described a project to deliver stormwater management information through the World Wide Web. The Texas Nonpoint SourceBOOK was a Web-based stormwater quality guidance document for public works professionals in the State of Texas. The SourceBOOK allowed users to access a wide variety of stormwater management information including the applicability and cost-effectiveness of stormwater management practices, legal authority issues, funding mechanisms for stormwater programs and local water-quality information. Most importantly, a database of over 100 BMP was available for users to access, allowing a diverse audience to become familiar with BMP principles and application procedures (sizing, design principles, etc.).

The site planning and design phase of land development projects presented the best opportunities for, and was critical to, reducing the impacts of development on the quality of the nation's waters. Recognizing the need for guidance in site

planning and design, the San Francisco Bay (California) Area Stormwater Management Agencies Association (BASMAA) published the document "Start at the Source - Residential Site Planning and Design Guidance Manual for Stormwater Quality Protection" and a second edition in 1999 that also included guidance for industrial and commercial development. The manual communicated basic stormwater management concepts and illustrates simple, practical techniques to preserve the natural hydrologic cycle (Richman and Bicknell, 1999).

### ***Erosion Control***

Cazzuffi et al. (2006) evaluated slope stabilization using the perennial "gramineae", a deep-rooted plant. The authors linked the root tensile strength of the plants to the increase in soil shear stress.

Xu et al. (2006) evaluated the effectiveness of erosion control measures along a highway in China. Engineering measures were effective in the short-term, but revegetation was effective once the vegetation was established. Rickson (2006) evaluated erosion control geotextiles at construction sites. The results showed that some products are successful at controlling rainsplash detachment and transport, but are less efficient at controlling the erosivity of overland flow. Other products had the opposite effect. Cleveland and Fashokun (2006) monitored a highway construction site to determine the effectiveness of a rock-filter dam. The results showed that the rock-filter dam had limited effect on the solids leaving the site.

Sepaskhah and Bazrafshan-Jahromi (2006) examined the use of PAM to control runoff quantities and erosion on sloping land. The effect of PAM in reducing erosion was greater than in reducing runoff quantities. McLaughlin and Brown (2006) evaluated erosion control products with and without added polyacrylamide (PAM). PAM did not produce repeatable significant improvements in runoff water quality, but did increase vegetative coverage overall. Shrestha et al. (2006) evaluated the effectiveness of polymers and additives on reducing suspended sediment in runoff. The effectiveness of the polymers to reduce suspended sediment was related to sediment load and polymer concentration.

Ziegler and Sutherland (2006) examined the effectiveness of a coral-derived surfacing material for reducing erosion on unpaved roads in Hawaii. After the initial application, sediment generation was reduced substantially; however, repeated traffic caused the covered roads to behave similar to bare soil.

### ***Drainage Design and Hydraulics***

Abdullah and Sivaligam (2006) reviewed the project criteria for developing a SMART stormwater management facility in Kuala Lumpur to reduce flooding. Kuang et al. (2006) studied a storage scheme in Hong Kong that was designed to address the flooding problem. The studies resulted in an optimal design of the flood storage scheme. Crist (2006) reviewed the improvements being designed for the Norfolk (Virginia) International Terminals to address limited stormwater drainage and management capacity. Guo (2006a) described the design of street curb openings using a decay-based clogging factor.

Ashley et al. (2005) evaluated the effect of potential climate change on the sizing, and design, of drainage systems in the United Kingdom. The results of the modeling showed that the uncertainty factors in the design will increase greatly and that traditional engineering measures are not likely to provide protection against climate change effects. Vrees and Radoszewski (2005) reviewed the feasibility of using a corrugated high-density polyethylene pipe for a water-tight storm drainage system. The Dry Creek (Colorado) Drainage Improvement Project was reviewed by Rogers and Glunz (2005). The project consisted of constructing two uncontrolled earthen detention dams and implementing a computer control system to move floodwaters in specially selected canals for storage and later release.

Inlet inefficiency was assessed by Despotovic et al. (2005) as a source of additional stormwater runoff in urban areas. The authors proposed that many inlets and subsequent drainage systems are not getting the design quantity of runoff leaving the remainder as potential flood water.

Horner (2004) reviewed two drainage projects constructed by Seattle Public Utilities that had the goal of reducing the quantity of stormwater discharged to Pipers Creek, resulting reduced channel erosion and pollutant loadings. The stepped pool design reduced the influent volume by 33% and the reconstruction project to reduce impervious area prevented all dry season flow and reduced wet-season flows by 98%. Cheng et al. (2004) compared the hydrological response from low impact development with that from a conventional development in Prince Georges County (Maryland). Summaries of the

results to date were presented in the paper.

Clark (2004) reviewed the use of a flood-alert system which combines real-time NEXRAD radar with hydrologic models. The goal was to improve the prediction of flooding flows – when they occur and where they will affect – in addition to predicting the effects of new development on flooding potential.

Nehrke and Roesner (2004) evaluated the effects of flood control design and stormwater treatment practices on the flow-frequency curve. Comparisons were made between pre- and post-development flows assuming that peak-shaving techniques, a common requirement in urban drainage design, are used. In addition, the use of detention ponds was examined for their impact on the curves. Peak-flow reduction targets based on habitat and geomorphic (median grain size mobilization potential) was examined by Dierks et al. (2004). It was proposed that in sand and gravel bed streams, peak flow targets based on that mobilization threshold could serve as a surrogate for maintaining intact benthic and macroinvertebrate habitats, even in urban streams.

Rahman and Weber (2003) reported on the use of a holistic context in Brisbane City to address stormwater management. One key initiative included facilitating Water Sensitive Urban Design (WSUD) components within an Integrated Water Management Strategy that looks at policy formation, planning strategies, design option, community marketing and acceptance, maintenance programs and finally evaluation of various WSUD approaches.

Rowe et al. (2003) advocated using water quality criteria as the basis for hydraulically sizing conveyance systems under the proposed SSO rule. The fundamental problem that most municipalities' struggle with was how much capacity would be sufficient. Turner-Gillespie et al. (2003) studied the regional flood response in the Charlotte, NC metropolitan area. The regional flood response strongly reflected urbanization effects – increased flood peaks and decreased response times – and geologically controlled attenuating reaches, which decrease flood peaks and increase lag times. Roy et al. (2003) reviewed the solutions used by Littleton, MA and that were based on LID techniques to reduce the effects of stormwater runoff on the highly developed watershed of Long Lake. These solutions included grass and vegetated swales, constructed wetlands, bioretention cells, landscaping features that encourage the on-site infiltration of stormwater, the redesign of the boat ramp and parking area, and controls on private residential lots within the watershed.

Funayama et al. (2002) reported on the approach of the Tokyo region for using storage pipes and interconnecting network pipes to provide storage and prevent flooding, with the result being that this approach was cost-effective.

Woods et al. (2002) reviewed the balancing of the water budget in the Ipswich River (Massachusetts) watershed. The framework of the “water balance” policy is a no net loss policy for water resources within the watershed, which will require each town to develop a hydrological budget. The tools under consideration to achieve this goal are water conservation measures, increasing stormwater recharge from new development within the basin at a 2:1 or 3:1 ratio, protection of recharge zones, encouraging either decentralized wastewater or sewerage waste to stay within the basin or importing sewer from outside the basin.

As part of the Clean Water Act, EPA required local governments to control urban storm water runoff (Ports 2001). asked the General Accounting Office (GAO) to report on the amount of runoff from urban areas, particularly from roads and other impervious surfaces, and its effects on water quality, and to perform an overall evaluation of the urban runoff control programs that federal regulations require, including their cost and effectiveness. The results from the GAO evaluation were summarized in a report titled, “WATER QUALITY, Better Data and Evaluation of Urban Runoff Programs Needed to Assess Effectiveness.” The paper by Pazwash and Boswell (2001) presented an overview of design methodology of various stormwater management systems, including detention basins, wet ponds, infiltration beds and underground detention/retention chambers. It discussed shortcomings in design and recommended improvements. The paper also described differences in local and state stormwater management regulations in New Jersey and offered suggestions for unifying the regulations.

Parsons Engineering Science, Inc., as part of an EPA project, reviewed industry and state practices for sizing both new and rehabilitated sanitary sewers (Mauro et al., 2001). Several new tools for estimating peak flows with reflect current technology and water use habits were identified. The research has found that peak flows in sanitary sewers depended on a complex set of variables. Tools used by communities to evaluate the operation of sewer systems were identified through interviews with experienced practitioners, research on federal and local regulations and industry guidance documents. The wastewater industry has been performing detailed I/I studies for the past 25 years (Lyon and Nelson 2001). The lessons learned can be applied to sanitary sewer design criteria to reduce the future occurrence of SSOs. Data from I/I studies for 20 wastewater agencies in six states (Kansas, Kentucky, Minnesota, Missouri, Ohio, and Texas) were compared, and

guidelines for appropriate sewer design criteria were developed. Due to the complex hydraulics in the vicinity of the Jackson Pike WWTP and as part of the West Columbus (Ohio) Local Protection Project (WCLPP), a detailed dynamic model was developed to assess the sewer system performance under different operating conditions (El-Hosseiny et al., 2001). The model used the sewershed approach to maximize system storage without affecting the current services and to satisfy the regulations. The sewershed approach and the developed model allowed the determination of the optimum operating conditions by maximizing in-line storage while meeting all required constraints (e.g., overflow, pumping capacity, control flow devices, sewer capacity). The paper by McConico et al. (2001b) described a mechanical flushing system located in the confined space of the CSO Outfall Structure for the Shockoe Creek Basin in Richmond, Virginia. Over time, deposition of solids in the twin river crossing has reduced the flow capacity of the inverted siphon pipelines, reducing transfer capacity to the wastewater treatment plant. The mechanical flushing system was designed to store and release a large volume of wastewater to flush the twin river crossing with a high volume, high velocity stream while avoiding accidental releases of dry weather overflow to the river.

Many areas in the United States have established stormwater detention pond ordinances that require the postdeveloped outflow from a site to discharge at a rate equal to or less than the predeveloped peak flow rate (Glazner 2001). The impacts of increased stormwater runoff volume due to development were reviewed. Using a hypothetical catchment in Chicago, Illinois, Guo (2001b) compared three different approaches for the hydrologic design of flood control detention ponds that service urban catchments: (1) design storm approach; (2) continuous simulation approach; and (3) analytical probabilistic approach. While all three approaches generated similar results, the results from the design storm approach were shown to vary by 40% to 50% depending on the choice of models and design storms. The results further verified the suitability of the analytical probabilistic approach for the hydrologic design of urban flood control detention ponds. Hsieh et al. (2001) evaluated the flood mitigation performance of various long-term regulated plans (protecting banks, pumping stations, diversion works, and retention reservoirs) for the middle-upstream of Kee-Lung River Basin in northern Taiwan through simulations of both 1-D unsteady flow and 2-D overland flow. The models evaluated the flood mitigation effect of each measure based on three criteria, including flood stages, runoff peaks, and inundation depths and ranges. The results showed that none of proposed regulated plans was best at resolving the flood and inundation problem. Storm water detention pond design is frequently part of each site or land development project (Ovcharovichova 2001). One critical aspect of the design is the determination of the boundaries of drainage areas for both existing and future conditions. The paper compared two different models of the same pond, with the only difference being in the existing and future drainage area delineation. Consequently, the results are different. The paper suggested which approach should be preferred to simulate the basin as it truly functions in the field. The paper by Wong (2001) contended that for drainage design to be based on a consistent theory, the kinematic wave time of travel formula for channel flow ought to be used in conjunction with the kinematic wave overland time of concentration formula. The paper contains the kinematic wave time of travel formulas for channels of seven different cross sections. A model of a hydrologically isolated section of the M6 motorway in the United Kingdom was used to calculate the times of travel in a channel with a vertical curb section for rainfall intensities ranging from 20 to 100 mm h<sup>-1</sup>. A comparison of the time of travel estimates from the computer model, and from the time of travel formula, shows that the differences are less than 5%. The derived time of travel formulas could be used to design drainage channels whose properties fit the kinematic wave approximation.

An exponential relationship exists for underflow baffles between the vertical velocity and the turbulent component of the horizontal velocity. Dimensioning analysis indicated that long chambers with intensive designs would be required for an 80% floatables removal efficiency (Cigana et al., 1998a, 1998b and 1998c).

A nine year, \$186 million rehabilitation program in Dallas, Tex. used trenchless technology for the smallest pipes and 3 m (120 in.) diameter diversion pipes with the ability to throttle flow (Almeida, 1998). During wet-weather events the city now has the ability to fill pipelines in the wastewater collection system without creating overflows. The Rouge Project used several methods to identify illicit connections. Data suggested there were 5 260 illicit discharges and 3 600 failing on-site sewage systems in the watershed (Johnson and Tuomari, 1998). Evanston, Ill. conducted a large-scale project to reduce the frequency of backups of combined sewers into residents' basements. An inlet control project increased the protection against basement backup to 50 to 100 year recurrence levels while significantly lowering cost (50%) over traditional solutions (Figurelli et al., 1998). A study conducted in the city of Salem, Oreg. revealed modification of interior plumbing of homes and installation of backwater valves, and the modification of the interior plumbing of the homes and installation of new service and ejector pumps the most effective solution to flooding of residential basements with raw sewage during storm events (Roley, et al., 1998).

In Houston, Tex. a 15% reduction in the peak rainfall-dependent I/I was factored into the design of all overflow control

projects as a credit for I/I estimated to be eliminated by structural rehabilitation. Because of the inherent variability of I/I, response in sewer systems flow reductions due to rehabilitation generally cannot be definitively quantified and at best, a range in reduction can be established (Samson et al., 1998). A slipline pipe was installed on the NORSD Westerly Interceptor project (Dell'Andrea, 1998) to relieve I/I and exfiltration at a cost significantly less than a total replacement would have been. A slightly smaller diameter pipe section is inserted inside the existing sewer and the annular space between the two is filled with grout. Montgomery, Ala. monitored the rehabilitation of manholes in a sanitary sewer system and found that a cementitious mortar, in places covered with a coal-tar epoxy liner effectively sealed out I/I from the system (Holmberg and Rowe 1998). Their experience also indicated that proper surface preparation is vital to ensure adhesion between the mortar and substrate for lasting benefits of the work. The NORSD assessed the condition of the interceptors and CSO (Duke and Knott, 1998). Guidelines for manhole and pipeline defect classification were established and procedures for condition assessment were also developed. Anderson and Curtis (1998) discussed how a hydraulic model can be developed that will ensure the level of accuracy that should be required as part of any hydraulic evaluation of wastewater piping systems involving technologies such as the Global Positioning System (GPS).

Because SSO and CSO pumped-relief force mains are normally emptied after use to prevent odors and deposition, the volume of air to be vented with each start up may exceed the capacity of typical air relief valves. Typical air relief designs include venting of full force mains where small amounts of entrained air are vented from the pipe while operating at the design working pressure (Cavaliere and Devlin, 1998). Hydraulic modeling indicated that a 1 m (42 in.) relief siphon with a 170 000 m<sup>3</sup>/d (45 MGD) capacity for Braintree and Weymouth, Mass. should result in a 78% reduction in overflow volume per year, with number of overflows reduced from 38 to 15 (Spearin et al., 1998). Flowmeters installed in the siphon at the Green Bay (Wis.) Metropolitan Sewerage District's Fox River Crossing and at three locations along the upstream interceptor sewer provided data used to develop projected peak flows to be expected during design storms ranging from 5 to 50 year frequencies. The evaluation showed that the siphon's existing capacity was inadequate to handle the projected peak flow from even a five-year storm (McCarthy and Blauvelt, 1998). Although traditional studies interpreted Bellmans Creek near Jersey City, N.J., to be dominated by tides, Sela (1998) found that fluvial flooding from storm runoff was dominant on most of its length and that the corresponding design flood level exceeded estimates of previous studies by approximately 1 m (4 ft).

Several days of heavy precipitation induced flows which exceeded the capacity of pipes and basins at a site in Wash., causing a road failure, and 227 000 m<sup>3</sup> of wastewater were discharged to Puget Sound. Emergency measures were undertaken to repair the damage within three weeks of the failure (Langer et al., 1998). An underground utility in Lynchburgh, Va. was restored to full capacity after a blockage was removed. Before the cleaning, any rain longer than ten minutes would cause raw sewage to bypass into the Blackwater Creek and James River (Water Engineering and Management, 1998). Stop-ups or backups caused by trash or grease accumulations have a significant probability of being caused by backwater effects in the collection system, rather than by illegal discharges (Conegliano, 1998). Gow (1998) reviewed the NORSD wastewater collection system which includes 334 km (207 mi) of intercepting sewers within the boundaries of Cuyahoga County, Ohio.

Faced with declining water quality as a result of uncontrolled inflow of poor quality runoff from within the watershed, managers of Sweetwater Reservoir opted to construct the Sweetwater Urban Runoff Diversion System (URDS), a diversion system to intercept and divert poor quality runoff upstream of the reservoir and convey it downstream of the reservoir (Bottcher et al., 1998).

Roesner (1998) discussed the impact urbanization has on water runoff intensities and effects to the receiving waters. A guidance manual for WWF drainage systems in newly urbanized areas is being developed and will examine the history of WWF management and present some recommended strategies for newly developing areas (Pitt et al., 1998a). A related study (Heaney et al., 1998a and 1998b) presented some highlights of the initial phases of innovative urban stormwater managements systems for the 21<sup>st</sup> century with results of an extensive literature review and preliminary evaluations of alternative future scenarios. The development of a combined sewer network for new urbanized areas, associated with inline retention and RTC was cheaper than separate sewers (despite provincial regulation providing new urban developments have separate sanitary and storm sewers) and reduced the impact of stormwater to the environment for Montreal, Can. (Charron et al., 1998).

The drainage system of Port St. Lucie, Fla. is made up of roadside swales, a series of drainage right-of-ways, and canals and waterways that eventually lead into the north fork of the St. Lucie River. To address swale drainage problems, the city purchased various types of all-terrain excavators including three 'Swamp-Meisters' which have large, powerful

mulching/cutting heads (Thacker and Gonzales, 1998).

Grace (1997) described four case studies of marine-outfall rehabilitation and maintenance where obstructions had caused serious problems in wet-weather- and wastewater-effluent drainage. Larsen *et al.* (1997b) reported that after construction costs of 6.8 million dollars for regional-sewer rehabilitation in the Broward County, Fla. Southern Regional Wastewater Collection System, I/I is still a problem. The repair project eliminated 5.64 million gallons per day (mgd) of extraneous flow but an estimated 10.5 mgd still enters the system. An evaluation of eight basins in Seoul, Korea revealed that every five meters the sewer systems needed repair and this was made worse by I/I, resulting in poor operation of the WWTP. Trenchless-rehabilitation technology was recommended as a solution (Parks, 1997). Guajardo and Gogers (1997) developed a roadway drainage plan with improvements on existing discharge flows to the receiving stream in the Houston, Tex. Pazwash and Boswell (1997) presented specific methods to collect and use roof runoff for lawn and landscape watering, car washing, and deck and driveway cleaning.

Bhaskar *et al.* (1997) used a physically-based-rainfall-runoff-estimation method. The geomorphological-instantaneous-unit hydrograph (GIUH) estimated flooding from wet weather and obtained results comparable to observed events. Bonta (1997) derived frequency distributions as an alternative method for determining watershed curve numbers from measured data, treating rainfall and flowrate data as separate frequency distributions.

Over 7,900 ft of 24 in. — 54 in. diameter failing sewer pipe was repaired using sliplining and cured-in-place-lining techniques in Baton Rouge, La. (Water Eng. Manage., 1997b). Ahmed *et al.* (1997) evaluated the performance of subdrainage systems for the mitigation of WWF and found performance to be dependant on pavement and drain types. Young (1997) presented a methodology for the identification, assessment, and novel solution of the stormwater-overflow-pollution problem in a typical small urban catchment.

The U.S. Department of Transportation, Federal Highway Administration (U.S. DOT) (1996a and 1996b) published a two-volume report on the evaluation and design of highway- stormwater-runoff-control facilities.

Burrows *et al.* (1997) reported on the development of a low-cost system based on monitoring the behavior of flap valves on numerous major outfalls along the Thames River in the United Kingdom. The modeling approach was based on the principle of conservation of angular momentum and its application to experimental data for circular gates. The recommended calibration offered  $\pm 20$  — 30% flow prediction accuracies for gate openings angles  $> 20^\circ$ .

Djebbar and Wisner (1997) compared three unit hydrographs based on the ability of each to reproduce observed stormwater runoff in urban watersheds that had different hydroclimatic conditions. The study addressed the frequently reported problem of time-step selection in hydrological modeling. Pruski *et al.* (1997) developed a procedure to determine the maximum-surface-runoff (MSR) volume by employing a constant infiltration rate after prolonged wetting of the soil. This procedure is applicable where the rainfall intensity/duration/frequency relationship is known.

Holmberg (1997) addressed the techniques for proper project execution and quality control when applying cementitious coatings (in a sewer environment) performed in a sewer-basin-manhole-rehabilitation project in order to meet three goals: the elimination of I/I, limited structural rehabilitation, and general corrosion protection. Rajaratnam *et al.* (1997) performed physical-model studies on the hydraulics of stormwater-dropshafts. The energy loss in the dropshaft was about 80% — 95% of the total hydraulic loss.

O'Loughlin *et al.* (1996) presented examples of design problems and research and development work on small stormwater drainage systems, relating these to scale effects in space and time. There is a potential for extending the lower boundaries of current design methods through detailed studies of small drainage systems. Blaszczyk and Ashley (1996) presented new approaches for the design and operation of combined sewers to control sediment problems. Results from a field study conducted in Poland and how application of these criteria aids in the development of self-cleansing velocities for full and partially-full flows were discussed.

### ***Stormwater Treatment Practices***

Marsalek *et al.* (2006b) characterized the trace metal levels in sediments trapped by several stormwater controls, including detention ponds, constructed wetlands, an infiltration basin, a biofilter, a stormwater clarifier and a three-chamber oil-and-grit separator. With respect to individual controls, severe pollution was found in sediments from oil and grit separators (for Cd, Cr, Cu, Pb and Zn), the stormwater clarifier sludge (Cu, Mn and Zn), a biofilter (Cu and Mn), an

industrial area stormwater pond (Cu only), and a commercial/residential pond (Cr only). Landers (2006a) presented the University of New Hampshire's Stormwater Center's test setup to compare stormwater control practices side-by-side in cold climates.

Scholz et al. (2005b) reported on a Glasgow project to assess how sustainable urban drainage systems contribute to reducing combined sewer overflows. The feasibility tool demonstrated the preferred selection of stormwater treatment practices for two drainage areas. Barrett (2005) proposed a methodology for evaluating the performance of structural stormwater treatment practices where the performance was not reported as a percent reduction. Regression curves were presented for different structural stormwater treatment practices that allow the user to predict performance based on a known influent concentration.

Weinstein and Herricks (2005) explored how low impact development can be used to address many of the limitations and impacts of end-of-pipe approaches to stormwater management. The implications for watershed master planning and restoration were presented. Low impact development was promoted as a methodology/development technique to assist in restoration of the Anacostia River watershed in Maryland and the District of Columbia (Cheng 2005). Restoration efforts include the implementation of stormwater treatment practices, three LID projects and a National LID conference. Stanford et al. (2005) discussed the incorporation of low-impact development principles into the redevelopment of a property. The paper reviewed the procedures used, the constraints imposed since this project was a redevelopment, and the low-impact development principles that would be most applicable.

Army case studies in LID in the Chesapeake Bay Watershed are reviewed by Bullock and Merkel (2005). The project included the installation of bioretention facilities at Fort Meade and the development of workshops on LID design and implementation. The implementation of Low Impact Development in the Fredericksburg, Virginia area was reviewed by Beisch et al. (2005). The plan integrated the viewpoints of various stakeholder groups – clients, U.S. Army Corps of Engineers, the regulatory agencies, the municipality, the neighbors and the local watershed groups.

Bengtsson (2005) evaluated the ability of extensive green roofs to reduce peak flows. The storage capacity of these roofs was also examined. The water quality from the same extensive green roofs was reported by Berndtsson et al. (2005). With the exception of nitrogen, the roof was a source of materials and recommendations to avoid easily-dissolvable fertilizers were promoted. Villarreal and Bengtsson (2005) examined the response of a Sedum green roof to individual rain events. A unit hydrograph for the green roof was developed and was able to predict peak flows and runoff volumes for any rain input. Roof slope had no effect on the direct runoff hydrograph, although antecedent moisture conditions had a substantial impact. The rain retention and runoff delay of green roofs was investigated by DeNardo et al. (2005). In addition to the delay of runoff peak by 5.7 hr, the green roof abated temperatures in both the summer and winter. VanWoert et al. (2005) examined the effects of roof surface, slope and media depth on green roof stormwater retention. For all studies and conditions, vegetated green roofs reduced the total quantity of stormwater runoff. They also extended the runoff duration well beyond the actual storm event. Sherman (2005) reviewed the media currently being used in green roof mixes. Of particular focus was the lack of leaching of nitrogen and phosphorus from the media.

Sutton-Grier et al. (2005) examined the use of compost in urban restored wetlands. The purpose of the compost addition was to increase the growth of planted vegetation and improve water quality in North Carolina.

Vranayova and Kosicanova (2005) evaluated the feasibility and benefits of a rainwater harvesting system for buildings in the Slovak Republic. The purpose of the rainwater harvesting was to reduce the stress on the local water systems of both non-potable supply uses and the increased runoff due to urbanization. list (2005) described the use of a Rainstore3 as a collection device for rainwater that can be later used for irrigation and toilet-flushing. Rainwater harvesting tanks were installed in a Sydney shopping center (Anonymous 2005h). The tank design, piping and risers were reviewed.

Stidger (2005a) reviewed the ultra-urban stormwater treatment practices used by Alexandria, Virginia, to meet its discharge requirements. Stephenson (2005) advocated the incorporation of structural stormwater treatment practices, such as a Hydro-Brake Flow Control, with the nonstructural stormwater treatment practices that are integral to sustainable urban drainage systems. Stidger (2005b) reviewed the stormwater control systems that could be considered as part of a stormwater management plan.

Chapman and Lau (2004) advocated using volume-based runoff controls, rather than peak-shaving requirements, in stormwater management decisions. This volume-based approach provides the appropriate control of local peak flows to



prevent increases in flow associated with increased runoff volume downstream in the watershed. Parson et al. (2004) assessed the performance of stormwater treatment practices for the construction and development industry. The results showed the following: (1) the performance efficiency of most stormwater treatment practices to control pollutants in storm water runoff has not been tested to the extent sufficiently to show that they are the best available technology on a widespread basis; and (2) the actual impact of treated storm water discharges on aquatic systems is largely undocumented. Ellis et al. (2004) reviewed the multi-criteria design approaches used to select sustainable drainage systems for highway and urban runoff. A French case study was presented to illustrate the approach and to highlight the inherent constraints and subjectivity embedded in the decision-making process.

Jones et al. (2004) reviewed the difficulties encountered in trying to acquire reliable data on the actual performance of stormwater treatment practices. The factors contributing to the difficulty of BMP monitoring were listed. General considerations in BMP design were reviewed by O'Connor et al. (2004). Sullivan and Borst (2004) reviewed the state-of-the-knowledge and the research activities on urban stormwater treatment practices. The paper focused on the research work sponsored by the US EPA and other key organizations. Bowles (2004) described the field operations yard of the County Special Service District in Washington County, Oregon. The project goals called for the site to be a demonstration project so contractors, engineers, plan review staff, and the public could see these innovative stormwater management techniques in action.

Perez-Pedini et al. (2004) used a distributed hydrologic model to optimally locate stormwater treatment practices in a northeast-U.S. urban watershed. The results found that more than 20 percent of the peak flow reduction could be achieved by installing fewer than 200 stormwater treatment practices, with the maximum peak flow reduction of 31 percent. Mathematical optimization was demonstrated by Volkening (2004) as a tool for selecting cost-effective stormwater treatment practices. If the primary goal was that a user-defined percentage of annual TSS must be removed from runoff, the model would select an optimal management program from three available best management practices: wet detention ponds, street sweeping, and settling/vortex devices.

Clar (2004) presented the fundamental principles behind Low Impact Development (LID). In addition, the paper summarized the results of demonstration projects that showed the effectiveness of LID both in new developments and in limited retrofit applications. Cheng et al. (2004) reported on an HSPF module developed to assess the effectiveness of the stormwater treatment practices incorporated in an LID design. Process-based algorithms are used to simulate BMP function and removal efficiency. BMP effectiveness can be evaluated and estimated over a wide range of storm conditions, site designs, and flow routing configuration approaches.

LID was implemented as a requirement in Mecklenburg County (North Carolina) (Fisher et al. 2004). The paper discussed how the water quality goals and performance standards were used in the case study site designs and the findings of the four case studies. Gerold and Sear (2004) reported on the use of LID design practices at the African American World Cultural Center in Milwaukee, Wisconsin. Low Impact Development (LID) applications included pervious pavement, grass swales, rain gardens, a green roof, a wetland, and an underground cistern. The hydrologic/hydraulic analysis of the existing and proposed conditions using XP-SWMM 2000™ concluded that the 2-, 10-, and 100-year storm peak flows would be properly attenuated by the proposed LID facilities. The Low Impact Feasibility Evaluation (LIFE™) model was used to design low-impact developments (Patwardhan et al. 2004).

Lampe et al. (2004) compared and contrasted the stormwater treatment practices implemented in the U.S. versus in the U.K. Schuster and Grismer (2004) reviewed the water quality projects underway in the Lake Tahoe Basin. They concluded that the preliminary data show that some stormwater treatment practices are effective in reducing the nutrient flux to the lake, although further investigations are needed.

Continuous simulation was used by Loucks et al. (2004) to evaluate the effectiveness of stormwater volume reduction practices. Two issues were identified: (1) how well do specific practices work in the field and (2) what are the long term 'end of pipe' benefits of a broad implementation program. Myers et al. (2004) also used continuous simulation to evaluate the effectiveness of twelve stormwater treatment practices in southeastern Pennsylvania. Wet retention, wetlands, infiltration basins, and rain barrels are among the most cost-effective options in separate-sewered areas. In highly urbanized areas, storage under parking facilities may be the only practical option to achieve large storage volumes.

The implementation and evaluation of Adelaide's greenway (River Torrens Linear Park) was presented by Mugavin (2004). Tree planting and low impact approaches have been implemented in Roanoke (Virginia) to address flooding

concerns (Brzozowski 2004). The goal is to restore the natural hydrology and reduce the impacts of urbanization on streams and flooding potential. Vellidis and Lowrance (2004) evaluated the effectiveness of riparian forest buffers as a way to reduce nonpoint source pollution. These riparian systems were found to reduce the concentrations of solids in surface runoff and nitrates in shallow groundwater.

Rowan University was charged by EPA to assess two creeks in New Jersey in relation to watershed characterization, water quality, modeling and outreach (Jahan et al. 2004). The deliverables include an interactive website and a CD-ROM for local government planners, environmental specialists, developers, and citizens.

Oost (2004) examined the Rainstore<sup>3</sup>, Grasspave<sup>2</sup> and Gravelpave<sup>2</sup> systems. The systems were developed to better address problems of poor stormwater management. In order to improve water quality in the Alna watercourse (Oslo, Sweden), a study was carried out to rank subcatchment areas for their existing and potential degradation, as well as to assess possible corrective measures (Nordeidet et al. 2004). The highest 15 ranked catchment areas accounted for 70% of the total load of heavy metals; all were strongly influenced by three major highways. It was estimated that wet ponds could remove a substantial portion of the total solids and around half (or more) of the heavy metals. Inner city (Malmo, Sweden) control of stormwater was achieved through the use of combinations of structural stormwater treatment practices (Villareal et al. 2004). It was found that the green-roofs are effective at lowering the total runoff from Augustenborg and that the ponds should successfully attenuate storm peak flows for even the 10-year rainfall.

Figola (2004) examined the use of Storm Water Quality (SWQ) unit to treat runoff from an old gas station. Settling of grit, sediment toxins and heavy oils was the primary treatment mechanism. A Continuous Deflective Separation (CDS) unit was used to treat urban runoff in Florida (Rushton 2004). The CDS unit was effective at removing litter, trash and larger sediments. A treatment train approach was implemented at the Miami International Airport to treat stormwater runoff from the facility (Schmidt et al. 2004). Peck (2004) reviewed the new passive stormwater treatment facility installed in South Lake Tahoe, California, to replace the ineffective lined detention basin.

The use of composted recycled materials in erosion control by the Texas Department of Transportation was investigated by Barkley (2004). Compost was shown to prevent erosion and reduce water contamination due to stormwater runoff. Demars et al. (2004) investigated the required thickness of wood waste materials that were used as erosion-preventing mulch. The results showed that 0.75 inches of wood waste material is sufficient to reduce the erosion to levels below commonly used treatments such as silt fences. Emerson and Goldstein (2004) examined the acceptance by the Minnesota Department of Transportation for the use of compost in erosion control for highway projects. Polyacrylamide (PAM) was proposed as a method for reducing erosion from construction sites (Soupir et al. 2004). At a low application rate, both liquid and dry PAM were effective in reducing TSS and nutrient losses in runoff.

Carr and West (2004) reviewed the activities of the grassroots organization in Johnson Creek (Wayne County, Michigan) which is heavily involved in public education. The paper discussed the evolution of the organization and the current structure to illustrate how the organization is meeting its goals of promoting clean water. Salt Lake County's stormwater media outreach campaign was outlined by Hartman and Way (2004). The five steps of the campaign were the following: 1) evaluation, 2) problem identification, 3) brand identity creation, 4) message targeting to an identified audience, and 5) media and method delivery selection.

Barrett et al. (2003) reported on the study, Post-Project Monitoring of stormwater treatment practices/SUDS to Determine Performance and Whole-Life Costs, which is jointly funded by the Water Environment Research Foundation, the United Kingdom Water Industry Research, and the American Water Works Association Research Foundation. Lai et al. (2003) described the initial phase of the EPA's research project to develop a decision-support framework for placement of stormwater treatment practices in urban watersheds. The integrated watershed-based stormwater management decision-support framework (ISMDSF) was based on a geographical information system (GIS) watershed/BMP database, cost, and hydrologic, hydraulic, and water quality modeling to achieve desired water quality objectives.

Quigley et al. (2003) reported on the revised analysis of the water quality and quantity data collected in the National Stormwater Best Management Practices (BMP) Database Project. Specifically the results of the statistical analysis conducted as part of the project could be used as the basis for probabilistic modeling of BMP effluent concentrations and loads. This paper provides specific examples from the results of the analysis of the database and presented applications of those results for watershed modeling, BMP selection, and potential stormwater design. Lee et al. (2003) researched the techniques that would be suitable for evaluating and optimizing decentralized urban BMP controls. General approaches

for conducting detailed spatial analysis, long-term precipitation data analysis, an explicit runoff routing model, and a prototype optimization model for functional land development strategies were included.

Gardiner et al. (2003) presented the idea of regional stormwater treatment practices as a solution to meeting future TMDL allocations in southern California. The authors argued that regional BMP facilities, such as detention and/or infiltration basins or wetlands, could provide higher levels of treatment more reliably and were easier to construct and maintain when compared on a cost per acre basis. O'Connor et al. (2003) reviewed current municipal practices to implement low-cost stormwater treatment practices to address stormwater pollution. The paper presented the factors to be considered in the design of treatment stormwater treatment practices to improve water quality. Sample et al. (2003) presented new methods to calculate costs of stormwater treatment practices and associated land for urban stormwater control. The method assigned stormwater control costs at the parcel level. Sullivan et al. (2003) focused on the complications associated with monitoring structural stormwater treatment practices and provided an overview of the drawbacks of existing monitoring systems, limitations of monitoring devices and methodologies, inadequacies of commonly used monitoring parameters and their impacts on the performance and design of treatment stormwater treatment practices. One complication of existing monitoring systems is that standard parameters are measured instead of those pertinent to pollutant removals.

Heckler (2003) reviewed the water quality in New York-New Jersey Harbor due to the implementation of best management practices (stormwater treatment practices) to control wet and dry weather discharges from New York City's (NYC) sewer systems. These stormwater treatment practices are related to CMOM requirements in the proposed SSO rule.

Landers (2003c) reported on the testing of the effectiveness of residential stormwater treatment practices in Waterford, CT, by the EPA. The study evaluated stormwater runoff from two adjacent neighborhoods in Waterford, Connecticut, one that had stormwater treatment practices designed to reduce the quantity and improve the quality of storm-water runoff and one that did not. Lin and Hsieh (2003) described the effort by Taiwan Water Resources Bureau, the City of Taipei, and the Bureau of Fei-tsui Reservoir Management to protect the water quality in the Fei-tsui Reservoir, which has been threatened by siltation and eutrophication. Practices being considered included nonstructural measures such as nutrient management, and structural measures such as swales, detention basins, and wetlands, in addition to erosion and sediment control methods.

Anonymous (2003b) presented the results of a study of the continuous deflective separation unit installed by Nashua, NH to protect the Merrimack River from stormwater discharges. The CDS removed 100% of the floatables and 80% of TSS from stormwater runoff. The outlet baffle trapped most of the oils and greases. Anonymous (2003c) reviewed the problems of the debris and litter in stormwater runoff which clogged an oil-water separator installed to protect the Sammamish River in Redmond, WA. Fantozzi et al. (2003) investigated an EcoDrain™ for cleaning stormwater runoff through field monitoring in Sydney, Australia following laboratory testing in Australia and Italy. In the tests performed in a marina near Sydney, Australia, oil and grease concentration were reduced more than 95% and metal concentration (particularly Cu, Pb, and Zn) were reduced close to 98%.

Benik et al. (2003) evaluated five erosion control products (wood fiber blanket, straw/coconut blanket, straw blanket, bonded-fiber matrix that was hydraulically applied, and disk-anchored straw mulch) using natural rain events. The blanket treatments had less erosion than straw-mulch plots, but no significant difference between blanket types. Glanville et al. (2003) evaluated the performance of compost blankets to control erosion. The performance of compost-treated and conventionally treated roadway embankments was compared. Parameters considered included runoff quantity, runoff quality, rill and interrill erosion, and seasonal growth of planted species and weeds.

Parmelee (2003) reported on the use of part of Sedgefield Park in Charlotte, NC as a stormwater holding area. The money saved on the original plan to upgrade the problem culverts will now be used to upgrade the park.

The paper by Claytor (2002) presented a common nomenclature for structural stormwater treatment practices and discussed several general elements for consideration in evaluating BMP pollutant removal effectiveness in the context of TMDL assessments for urban and suburban watersheds. In addition, the results and usefulness of the Center for Watershed Protection's BMP pollutant removal database were presented.

Clary et al. (2002) reviewed the procedures used to develop, evaluate and maintain a standardized stormwater BMP

effectiveness database. The national stormwater BMP data clearinghouse continues to screen and post new BMP data to the database, as well as respond to inquiries from the public. An overview of both of the database software and results of the data evaluation were provided in this paper.

Strecker et al. (2002) presented the Urban Stormwater BMP Performance Monitoring Manual that was developed by integrating field experience of ASCE's Urban Water Resource Research Council and the development of the ASCE/EPA National Stormwater Best Management Practices Database. The Manual was intended to help achieve stormwater BMP monitoring project goals through the collection of more useful and representative rainfall, flow, and water quality information.

General stormwater control objectives and sustainable drainage design. Vaes et al. (2002) reviewed the impact that moving storms can have on combined sewer designs. They noted that when a storm moves over an urban catchment in the same direction as the main flow direction of the sewer system, higher peak discharges and water levels often result. The paper presented a procedure to simulate moving design storms over a combined sewer system in different directions. Waugh et al. (2002) reviewed the 2000-2001 Denver Urban Storm Drainage Criteria Manual. This was an update of the original 1969 manual.

Reference flow and water levels meters were field verified under the EPA's ETV Program (Pelletier et al., 2002). The accuracy of three meters was verified: one four-path transit-time flowmeter and two level meters, a bubbler and an ultrasonic level meter. The Field Testing Organization recognized that the four-path transit-time flowmeter and both the bubbler and ultrasonic level meters did not meet the accuracy requirements specified in the Generic Protocol in order to be validated as the reference meters. Nevertheless, since the results obtained using the revised flow accuracy margins and considering the low accuracy of the tracer dilution analysis, as well as the good fit with the flow rates estimated with the "flow under the gate" equation, the four-path transit-time flowmeter was validated as the reference flowmeter to verify the vendors' flowmeters.

Silveira (2002) presented the problems of establishing modern urban drainage in developing countries, including a 19<sup>th</sup> century philosophy on drainage, legal and clandestine settlements that limit the space for the system; contamination of stormwater by sewage and garbage; climatic and socio-economic factors, including water retention for flood-avoidance and infiltration; lack of technological basis for drainage management and design; lack of interaction between citizens and the government.

Harremoes (2002) presented a review of the status and perspectives on integrated urban drainage in general and as a professional discipline. New paradigms were introduced – risk of pollution due to system failure, technology for water reuse, sustainability, new architecture and greener upstream solutions.

stormwater treatment practices can range from management operations (such as street sweeping or reducing pesticides used on urban lawns) to structural treatment options (such as detention/retention ponds, swales, filter/buffer strips and constructed wetlands) (Sullivan and Borst 2001). This paper focused on structural stormwater treatment practices and reviewed the state of the knowledge, the unknowns, and research programs being undertaken by the U.S. Environmental Protection Agency and other key organizations to address the unknowns.

The final report will document the effectiveness of these stormwater treatment practices to improve water quality and will address BMP stability, longevity, and operation and maintenance issues. BMP manuals have been developed that address the control of urban runoff to protect receiving water quality (Roesner et al., 2001). Investigations of both design practices and effectiveness revealed that there is a lack of knowledge in the scientific and engineering community about what constitutes a properly designed BMP and what the BMP should achieve. This paper discussed the state-of-practice in BMP design in the US and pointed out the strengths and weaknesses with respect to water protection. An approach to design criteria development for a wide variety of climatologic, topologic, and geologic conditions was recommended to protect receiving waters systems. Strecker et al. (2001) reported on the EPA-funded cooperative research program with the ASCE to develop a more useful set of data on the effectiveness of stormwater stormwater treatment practices in urban development. The paper described the comparability problems encountered between different BMP effectiveness studies and the considerations that affect data transferability, such as methods used for determining efficiency and statistical significance. Finally, it recommended that effluent quality be used to measure BMP efficiency. In the paper by Yu and Zhen (2001), a methodology is developed to assist in the determination of stormwater treatment practices placement strategies at the watershed level. The Agricultural Non-Point Source Pollution Model 2001 (AGNPS 2001) developed by

USDA, was used for BMP placement analysis, and the relative effectiveness of stormwater treatment practices at three different spatial placement levels, i.e., on-site, sub-regional and regional levels, were compared. Based on the model simulation results, a BMP placement optimization approach was developed to determine a most cost-effective BMP placement strategy at the watershed scale.

Development projects in the high-altitude mountain environment of the Rocky Mountains such as Colorado often require innovative best management practices (stormwater treatment practices) due to challenging runoff conditions, the relatively short growing season, vegetation and wildlife habitat considerations, and the high level of water quality of receiving waters (Earles and Jones 2001a). This paper described a variety of stormwater treatment practices and stormwater/dewatering discharge management strategies that have been successfully employed on development projects. Case studies were presented for addressing runoff from snowmelt; shallow groundwater; soil erodibility, mobilization, and suspension; water chemistry; and regulatory requirements related to water quality and wetlands protection, and included examples of structural stormwater treatment practices. Yamada et al. (2001a) analyzed the mass balance of pollutants during both dry periods and storm events on Lake Biwa and discussed the effects of pollutant removal systems, land use planning and new drainage systems by simulation. The project included estimation of influent pollutant loadings from existing data, collection of additional samples from road surfaces, house roofs and parking lots, and evaluation of ongoing BMP projects. Hambridge and Stein (2001) studied a 33-acre lake in Duke Power State Park where lake water quality is deteriorating. The EPA "Simple Method" screening model was used to estimate the contribution of pollutants from each land use category, and a goal for stormwater treatment practices to reduce phosphorus loadings by 34% was determined. Restoration options included dredging; developing an in-lake wetland; and carp eradication. Watershed stormwater treatment practices included regional stormwater treatment; parking lot bioretention; wetland treatment at a local high school; strengthening stream buffer restrictions; agricultural stormwater treatment practices; education; and septic maintenance programs. In Onondaga County, an Amended Consent Judgment required the County to perform a NPS environmental benefit project (EPB) in Onondaga Lake watershed (LaGorga et al., 2001). stormwater treatment practices were implemented on three farms and at two urban sites in the Onondaga Lake watershed. The Staten Island Bluebelt Program represents New York City's first large-scale use of stormwater stormwater treatment practices to alleviate chronic flooding and provide drainage infrastructure (Vokral et al., 2001). The stormwater treatment practices used by the t Program included constructed wetlands with extended detention, stilling basins, underground sand filters, and meandering streams. These stormwater treatment practices were effective on a large scale (even preventing flooding during Hurricane Floyd). The enhanced wetlands and improved water quality greatly promoted biodiversity. Public support was enthusiastic and valuable educational/recreational resources and cost-effective drainage infrastructure resulted.

Low Impact Development (LID) combines hydrologically-functional site designs with pollution prevention measures as compensation for land development impacts on receiving waters (Clar 2001). This paper summarized the results of a number of demonstration projects, and introduced a strategic framework for the application of LID technology to ultra urban areas. It reviewed the hydrologic characteristics of ultra urban areas and related them to identified stormwater management goals in ultra urban areas. LID combines conservation strategies, distributed micro-scale source control stormwater treatment practices, and pollution prevention to control the volume and peak runoff rate, and to treat the pollutants (Weinstein et al. 2001). LID practices can be incorporated into buildings, sidewalks, streets and landscaping. Because they are small scale, the issues associated with conventional large-scale, end-of-pipe controls, such as large-scale traffic and property disruptions, utility conflicts and large capital costs, can be avoided. The paper documented the issues and efforts of a multi-year monitoring and construction effort of the Maryland State Highway Administration (MSHA) to determine the effectiveness of LID at addressing regulatory and ecological protection goals for highway construction. The development and use of environmentally sensitive construction materials as a low-cost component to stormwater management has gained interest recently (Pitt and Lalor 2001). However, there is little data for specific alternative building materials, although information exists targeting selected sources, especially the role of roof runoff as a significant source of zinc and other metals. Relative pollutant contributions from construction materials themselves are also a concern that has not been adequately addressed. Due to the common use of these materials in the urban environment, material substitution would seem a good place to start in implementing source reduction.

To assess the effectiveness of sedimentation and erosion controls during highway construction, the impact on water quality in adjacent wetlands was monitored (Huang and Ehrlich 2001). Downstream measurements were equivalent statistically to upstream measurements except once when erosion controls were neglected and when culverts were constructed. Attention to sedimentation and erosion controls and seasonal scheduling of highway construction were advocated to protect adjacent wetlands. Clopper et al. (2001) reported on an erosion control study that examined the

benefits of two different erosion control mulches; blown straw and a manufactured biodegradable erosion control blanket. Sprinkler-type simulators were used to create rainfalls having intensities of 2, 4, and 6 in/hr. The collected data indicated that some surface cover treatments consistently reduced soil losses, while others can actually increase soil losses under some test conditions. They concluded that the Revised Universal Soil Loss Equation can be used to estimate the benefits of mulches at construction sites. Shammaa and Zhu (2001) presented a state-of-the-art review of TSS removal techniques. Three main techniques were reviewed: infiltration, filtration and detention. Infiltration trenches, infiltration basins and porous pavements were the common infiltration practices. Filtration systems included filter strips, grassed swales and media filters. Wet and dry detention ponds (including polymer-assisted ponds) and constructed wetlands were the most common detention practices. The function, performance and suitability of each technique were discussed, and a comprehensive review was provided to guide the selection of a suitable TSS control technique. Levee sump systems have been used by many riverine communities for temporary storage of urban wet weather flows (Smith et al., 2001d). This paper presented a case study that demonstrated a procedure for assessing the hydraulic performance of flood control sumps in an urban watershed. A hydrologic modeling package was used to estimate the flow hydrograph for each outfall as part of the flow balance for the sump. In addition, these sumps may function as sedimentation basins. Yu et al. (2001b) monitored several ultra-urban stormwater treatment practices: manhole-type treatment structures (such as the Stormceptor), a bioretention area, and the Vortechs Stormwater Treatment System. Resuspension of sediment during large storm events has been a concern for these stormwater treatment practices. A cost analysis showed that bioretention might be the most cost-effective in terms of cost per unit pollutant removal. However, the bioretention area may export pollutants before the soil-plant system stabilizes.

NPDES Stormwater Phase II and TMDL regulations have placed additional pressure on industrial facilities to reduce stormwater pollutant levels by implementing source controls and stormwater treatment (Mas and Curtis 2001). This paper presented an overview of the assessment and planning phases of industrial stormwater treatment evaluations, with a focus on structural control measures for removal of dissolved metals and other industrial stormwater pollutants common to the Northeast U.S. Chang and Duke (2001a) evaluated actions taken by auto dismantling facilities in the Los Angeles, California, region to comply with industrial stormwater discharge regulations. The research evaluated a sample of complying facilities, and involved stormwater sampling at a smaller number of case study facilities. The study found that a large proportion have measured effluent concentrations that exceed U.S. guidelines for stormwater. Estimates of pollutant loads contributed by the dismantling industry appear substantial. The Ford Rouge Center complex on the Rouge River is undergoing dramatic revitalization, including substantial redevelopment of the existing plant structures and the addition of several new buildings (Houston et al., 2001). Cahill Associates developed a stormwater master plan that provides providing the facility with onsite stormwater storage and water quality improvement for the smaller, more frequent storms. A general strategy of retention and treatment through water quality swales was adopted. The two-year storm volume was used as the minimum storage volume required for each system.

The Dubai International Airport expansion plans required a stormwater management strategy that met international regulatory authority requirements, addressed time-sensitive milestones, and remained cost-effective (Darnell et al., 2001a). The stormwater management system must achieve the minimum drainage requirements and also provide a multitude of management options that could address the unpredictability of desert-climate storms. When modifications were done to the Camarillo (Ventura County), California, Airport in 1997, a high efficiency oil-water separator was installed to treat the stormwater runoff from the area where the refueling trucks were filled (Mohr et al., 2001). The system included a precast concrete separator vessel with multiple-angle enhanced gravity separator plate packs. Performance tests were performed on the system as part of the acceptance procedure. The results were presented along with the results of three year's operations and maintenance.

A variety of projects employed stormwater control as part of a larger environmental restoration effort. Aichinger (2000) reported on a stormwater BMP program that included the construction of three stormwater treatment basins, implementation of a watershed education program, and completion of an alum injection system for removal of phosphorus from stormwater. The application of alum treatment had several unique features: its design to address treatment of base stream flows, storm event flows, and seasonal changes in stormwater temperature and pH; its off-line system design; its thorough bench-testing to address dosing for optimal phosphorus removal under various conditions; and its design to comply with specific dissolved and total aluminum discharge standards. Mecklenburg County North Carolina's Department of Environmental Protection (MCDEP), has undertaken a comprehensive restoration in the Edwards Branch watershed. The basin-wide BMP plan included design and construction/implementation of wet ponds, multiple pond/marsh systems, sand filters, bioretention areas, riparian forest buffers, level spreaders, filter strips, stream bank stabilization, stream channel restoration, constructed wetlands, and targeted public education programs. The

physical structures had to be designed as retrofits of existing facilities in the developed watershed or integrated into the existing land uses. Baseline, construction, and post construction monitoring, using EPA stream habitat assessment protocols, ambient water quality monitoring, fish and benthic macroinvertebrate surveys, and channel cross section monitoring, have been and continue to be used to collect data to justify implementation of successful practices (Baker et al. 2000). In Portage, Michigan, a storm water treatment system currently under design will significantly increase the quality of life for city residents while meeting and exceeding regulatory requirements. This new regional facility is to be linked to a recreational trail way system, provide treatment for runoff from 1.9 km<sup>2</sup> (463 acres) within the highly developed urban core targeting 80% pollutant removal rates, and double the length of existing trail ways in the city (Jacobson et al. 2000). Mattson et al. (2000) presented a study of urban stormwater impacts in the Severn Sound Area of Ontario, Canada. The study objectives were (1) characterization of dry weather and runoff quantity and quality; (2) monitoring effects of stormwater runoff on the bacterial concentrations at an urban bathing area; and (3) development of pollution control plans for the participating urban municipalities in the Severn Sound watershed with an overall goal of a 20% reduction of stormwater phosphorus loads.

The City of Rockledge, Florida developed and implemented a Stormwater Management Program using a watershed-wide management approach, which included stormwater facility inventory maps along with necessary hydrologic, hydraulic, and water quality data (Schmidt et al. 2000a). The Stormwater Master Plan for Miami International Airport (Florida) included comprehensive evaluations of hydrology, hydraulics, water quality, stormwater treatment practices, and facility planning in phases to allow cost-effective implementation of the plan while aircraft operations continued and increased. A variety of constraints were identified, including the protection of aircraft passenger safety (no fog or bird attractants) and the environment (water quality, manatees, and hazardous material cleanups) (Schmidt et al. 2000b). Lake Macatawa, near Holland, Michigan, was listed by the Michigan Department of Environmental Quality's 303(d) nonattainment list; high phosphorus concentrations from nonpoint sources and excessive turbidity were found to be the main contributors to poor water quality. A list of 44 stormwater treatment practices were considered as controls for reduction of the nonpoint phosphorus load. An objective and quantitative procedure, based on economic production theory and marginal cost analysis, was developed to assign the proposed level of effort and subarea watershed locations for each BMP (Scholl 2000). In order to comply with the County's MS4 Stormwater NPDES permit, the Anne Arundel County (Maryland) Department of Public Works (DPW) had to field locate all storm drain outfalls and stormwater management ponds, assess their structural condition, perform a general assessment of stability of downstream channel conditions, and identify stormwater management retrofit opportunities for implementation as County capital improvement projects. A relational database has been developed for data management and analysis, with a direct link to GIS coverages (Smith et al. 2000b). Templeton (2000) presented an overview of the Nutrient Management Strategy for point source dischargers to North Carolina's Neuse River and the State's experience in implementing the Strategy thus far. Whitman et al (2000) described two efforts to test new stormwater retention technologies in the Los Angeles, California watershed. These efforts were designed to better manage stormwater and to address the impacts of urbanization and imperviousness. The efforts included reducing impervious cover and planting trees at public schools. The state of Florida was developing urban stormwater treatment practices to control urban runoff impacts on the Everglades (McPherson et al. 2000).

Treated stormwater has been suggested as a candidate for irrigation water or similar reuses. Heggen (2000) reviews the challenges of rainwater catchment in sustainable development. Fan et al. (2000a) discussed current urban stormwater control and treatment technologies, and the feasibility of reclaiming urban stormwater for various purposes, including a hypothetical-case study illustrating the cost-effectiveness of reclaiming urban stormwater for complete industrial supply. In connection with efforts to restore water quality in Santa Monica Bay, The City of Santa Monica, California has diverted its major dry-weather stormwater flows from the Pico-Kenter and Pier Storm Drains to the City of Los Angeles' Hyperion Wastewater Treatment Plant located a few miles to the south. Recently the city concluded that the dry-weather flows could be treated and economically reused in place of potable irrigation water and has begun design and construction of the Santa Monica Urban Runoff Reclamation Facility (SMURRF). Perkins and Shapiro (2000) reported that the City of Santa Monica, California is using both a micro- and a macro-scale approach to watershed BMP implementation. Reuse of stormwater and treated sewerage effluent, previously regarded as waste, has begun in South Australia through the innovative aquifer storage and recharge technique. After pretreatment in wetlands, this water was stored in otherwise-unused brackish aquifers for summer irrigation of parklands. Barnett et al. (2000) presented several case studies where the aquifer storage and recharge technique has been successful, with savings in water and infrastructure costs, as well as providing environmental benefits. Domestic harvesting of rainwater as a source of water for flushing toilets and watering gardens was assessed in Berlin, Germany. Rainwater harvesting relieved demand on potable water supplies and rainwater drainage in Berlin's urban districts (Koenig 2000).

Urban streams are often badly degraded from their pre-development, natural state. Restoration of these streams is becoming a widespread practice, and is often done in conjunction with WWF control efforts. Athanasakes et al. (2000) described the holistic stream restoration program which was developed by the Louisville and Jefferson County, Kentucky, Metropolitan Sewer District. Their discussion focused on issues involved in developing and managing a streambank stabilization/stream restoration program, such as getting a program started, a brief overview of stream restoration techniques, items to consider during construction and a summary of items learned throughout the development of the program. Stormwater management in an urbanized basin near Dallas, Texas included channelization of a creek which was eroding private property (Amick 2000). Since the watershed was nearly fully developed, areas where mitigation could be accomplished were limited. Mitigation was required - leading to some restoration of another urban stream that had previously been channelized. The creeks in the Kelowna, British Columbia, Canada area, like those throughout North America, have been impacted by human development. The City of Kelowna initiated the Lower Mill Creek Watershed Program in 1997. Objectives of the program included (1) improvement of Mill Creek water quality by preventing streambank erosion and creating riparian areas; (2) restoration and enhancement of instream and streamside habitat; and (3) education of the public, private landowners and developers on the importance of Mill Creek (Gow and Kam 2000). The U.S. EPA has allowed local governments to establish natural vegetative buffers (greenways) along stream corridors in lieu of incurring other EPA enforcement actions associated with violations of the Clean Water Act. Kleckley and Kung'u (2000) identified the role of greenways in protecting water quality and aquatic and stream corridor habitats, and described an on-going greenways project in Jefferson County, Alabama. Rodriguez et al. (2000b) presented a pool-riffle design for straight urban streams where existing infrastructure has prevented channel planform re-alignment. The proposed structures fulfilled four main requirements: (1) increased flow variability during low and moderate flows; (2) produced minimal increase in the water levels during high flows; (3) self-maintained in terms of bed erosion and sediment deposition, and (4) provided in-stream habitat for fish. Von Euw and Boisvert (2000) presented two case studies that focused on the partnership process, design and implementation, and lessons learned from the construction of two riffle weirs in urbanized streams in Vancouver. Key conclusions were that partnerships are an effective tool for implementing stream improvement projects in a cost-effective manner; and that riffle weirs can function effectively in an urban setting to mimic natural stream morphology, thereby improving fish habitat and channel stability.

Urban watershed managers are increasingly investigating stormwater control programs as a whole, rather than focusing on individual stormwater treatment practices. Chocat et al. (2000) described the evolution of urban drainage, noting that even though urban drainage has been practiced for more than 5000 years, many challenges arising from growing demands on drainage still remain with respect to runoff quantity and quality, landscape aesthetics, ecology and beneficial uses, and operation of existing urban wastewater systems. In Lulea, Northern Sweden, Backstrom and Viklander (2000) investigated which integrated stormwater system components might be suitable in cold climate regions. The authors found that porous pavement, grassed waterways (swales, ditches), wet pond, and percolation basin were the most suitable integrated stormwater system components in cold regions whereas dry basin, stormwater infiltration surfaces, and stormwater reuse seemed to be less suitable. The Delaware Canal, a unique, 60-mile long, 167-year-old man-made waterway, was built and operated commercially to haul coal and other goods from Bristol, Pennsylvania to Easton, Pennsylvania. Environmental Liability Management, Inc. prepared a map of the Delaware Canal Watershed, analyzed potential strategies to reduce accelerated erosion and sedimentation in the canal watershed, and produced a report intended to educate local residents and township and county officials on land use/management practices that could be incorporated into local ordinance to reduce the excessive sedimentation in the canal (Brussock et al. 2000). Barrett (2000) discussed the potential for stormwater treatment practices to adequately address receiving water impairments in southern California. He concluded that pollutant removal rates for conventional stormwater treatment practices will not enable stormwater treatment practices to reverse adverse receiving water impacts.

Several innovative watershed management approaches are attempting, in combination with a system of stormwater treatment practices, to preserve the natural runoff-controlling features of a site. Low Impact Development (LID) is rapidly being recognized as an ecologically sustainable and cost effective strategy to protect receiving waters from the water quality, volume, magnitude, and frequency effects of stormwater runoff. The LID strategy is based on creating hydrologically functional equivalent design features that replicate the pre-development conditions through the use of pollution prevention, precision engineering, and integrated micro-scale stormwater treatment practices throughout a site. Coffman et al. (2000) presented the management strategies, protocols, and technological approaches incorporated in the development of an LID management strategy for the control of WWF in urban areas. Two publications that describe LID are the *Low-Impact Development an Integrated Design Approach* and *Low-Impact Development Hydrologic Analysis* (obtainable from the National Service Center for Environmental Publications (NSCEP) 1-800/490-9198). Daniil et al. (2000) presented general design considerations and principles for flood protection and related stormwater design, based



on an integrated environmental approach and involving less technical works and preservation of the physical condition of streams and creeks. The application of the above mentioned consideration was illustrated in two specific case studies from the suburbs of Athens, Greece. Hall and Scarbrough (2000) reviewed the development and implementation of new-development requirements aimed at watershed protection in Gwinnett County, Georgia, USA. The approach presented is simple to use and encourages site design that takes advantage of the natural site amenities and minimizes impervious surfaces. Kauffman and Brant (2000) advocated amending existing zoning codes to establish watershed-zoning districts based on percent impervious cover thresholds in the Christina River Basin of Delaware.

The Storm Water Phase II Rule, published in the Federal Register on December 8, 1999, will bring approximately 5,000 small municipal separate storm sewer systems (MS4s) and over 100,000 small construction sites into the National Pollutant Discharge Elimination System (NPDES) permitting program by 2003. USEPA is supporting implementation of this rule through the development of a 'tool box.' This tool box will consist of fact sheets, guidance, a menu of stormwater treatment practices, an information clearinghouse, training and outreach efforts, technical research, support for demonstration projects, and compliance monitoring/assistance tools (Kosco 2000). The City of Portage, Michigan, pioneered a comprehensive approach to storm water management in light of the Phase II Storm Water regulations. The approach has served to define the application of the now elusive "Maximum Extent Practicable" (MEP). Breidenbach et al. (2000) presented the approach for selecting design parameters to define MEP and identified how the minimum control measures for Phase II regulations are incorporated into the passive storm water treatment system design.

Once a watershed management study has been conducted and a plan adopted, local planners and engineers are often faced with the questions of how to practically translate these recommended management strategies or best management practice recommendations into zoning and subdivision regulations, capital improvement plans, and assistance programs, how to encourage effective site design and also provide flexibility in meeting environmental objectives, and of finding a practical, economical way to track how the design and best management practices are performing. Brewer et al. (2000) documented Rockdale County's innovative Development Performance Review, including its procedures, and program cost/staffing requirements. Fernando et al. (2000) described the development of effectiveness indicators for stormwater and watershed management programs and the development of a regional monitoring program. The study was conducted for the jurisdictions encompassed by the Hampton Roads Planning District Commission, with specific focus on the six cities that currently have Virginia Pollutant Discharge Elimination System stormwater permits. New Jersey developed a rule proposal to standardize its approach to the watershed planning process, and to goals and objectives for watershed planning. Van Abs (2000) proposed a conceptual basis for watershed planning objectives and thresholds, and then described how New Jersey's planning and regulatory system currently and prospectively addressed the issues. As part of the stormwater planning process for the Greater Vancouver area, a watershed classification system was developed to help evaluate the current and future impacts of stormwater discharges on the receiving environment. The system was designed to easily communicate these impacts along with potential mitigation strategies to stakeholders and decision-makers. Woods et al. (2000) described the watershed classification system, presented the classification results for 1996 and 2036, and outlined some of the experiences with developing and using this watershed management tool.

The California Department of Transportation (Caltrans) constructs, operates, and maintains the state highway system in California; the runoff from which is subject to the federal Clean Water Act and its associated NPDES permit program. New permit requirements have required methods that achieve higher levels of pollutant control than conventional stormwater treatment practices. As a result, Caltrans initiated an extensive research and pilot-testing program to identify new technologies that can be used to meet water quality standards (Krieger 2000). Prior designs assumed that street drainage was designed to collect stormwater as fast as possible, and therefore, the street stormwater capacity was defined as its hydraulic conveyance and was estimated by Manning's formula. Guo (2000) found that the street stormwater capacity at a sump was actually dictated by the storage capacity rather than the conveyance capacity. A new design methodology was developed that considered the street depression storage as a criterion when sizing a sump inlet. In 1999, two oil-water separators at Mobil de Colombia's terminal facilities in Cartagena, Colombia were replaced in order to bring the facility into compliance with environmental law. Using a proprietary computer program it was found that the existing pits were large enough to meet the national environmental regulations for effluent oil content if fitted with multiple-angle coalescing plates. Gutierrez et al. (2000) presented the legal requirements, operating conditions, the new internals, and a discussion of how the new internals will affect the quality of the water exiting the facility. Patwardhan et al. (2000) briefly outlined the Best Management Practices (stormwater treatment practices) and reporting modules of the Hydrological Simulation Program – FORTRAN (HSPF) model in relation to its application to the Camp Creek and Little River Watershed Assessment Project (Fulton County, Georgia).

Stovin and Saul (2000) described an extensive laboratory and computational fluid dynamics study into the hydraulic performance and sediment retention efficiency of tanks. The results showed that (1) using computational fluid dynamics, it was possible to predict the flow field that was measured in the laboratory, and (2) a critical bed shear stress could be used to determine the extent of sediment deposition. The study also showed that the length to breadth ratio of the chamber was the most important parameter to influence sediment deposition, and that changes to the benching and longitudinal gradient of the tank had minimal effect. Intensity/duration/frequency (IDF)-relationships of extreme precipitation have been widely used for design of stormwater facilities. Because the properties of extreme precipitation may be very different for different storm types and different seasons, IDF-relationships which permit decomposition into different components and scaling properties were established by Willems (2000). Hydrologically functional landscapes integrated principles of maximizing infiltration, contouring the landscape to encourage temporary detention, and the use of stormwater to reduce demand for irrigation water. Wright and Heaney (2000) reported on the design and monitoring of a hydrologically functional landscape in Boulder, Colorado, and presented a simulation that evaluated the performance of the system. Low Impact Development (LID), a micro-scale runoff control strategy for WWF, has been based on a combination of conservation to reduce hydrologic impacts and incorporation of distributed micro-scale stormwater treatment practices throughout the subcatchment. LID has resulted in a need to develop new models or modify existing ones. Wright et al. (2000) explored the potential and limitations of existing models in order to evaluate the effectiveness of this design approach. An extensive review of some 50 designs for litter traps which are recommended for urban drainage designs indicated that only seven showed much promise for South African conditions. A preliminary assessment of the seven most promising trapping structures concluded that three designs - two utilizing declined self-cleaning screens and the other using suspended screens in tandem with a hydraulically actuated sluice gate - are likely to be the optimal choice in the majority of urban drainage situations in South Africa (Armitage and Rooseboom 2000a and 2000b).

According to Herr and Harper (2000), stormwater treatment using flow-weighted injections of alum achieved high removal rates of nutrients, heavy metals, and bacteria while proving to be an extremely cost-effective retrofit. Two case studies using alum injection in Florida were presented. A National Cooperative Highway Research Program-funded research project was described by Stein et al. (2000) and included both a synthesis of current information and a plan to guide future research on management of runoff from surface transportation facilities. The issues to be studied included regulations and permitting, runoff water quality characteristics, best management practices, receiving water impacts, and habitat impacts. Insufficient space, high land values, topography, maintenance, aesthetics and liability issues were given as reasons why underground detention has been considered more frequently. Finlay (2000) presented the development of a computer program for designing underground stormwater detention tanks. The program had four main functions: (1) develop or allow the direct input of an inflow hydrograph, (2) size the structure and develop a stage-storage relationship, (3) design the release structure and develop the stage-discharge relationship, and (4) route the inflow hydrograph through the structure. Boyd (2000) presents a collection of pre-programmed hydraulic and hydrology-related functions that have been compiled as an add-on module for use in computer spread sheets to aid in BMP and urban drainage design. Results from the modules are similar to results given by widely-used modeling software.

BMP performance can be verified only through expensive field testing, making published testing results a valuable resource for planners and engineers. Strecker et al. (2000) reported on a research program funded by USEPA and ASCE to develop a more useful set of data on the effectiveness of stormwater treatment practices used to reduce pollutant discharges from urban development. They described some of the comparability problems encountered between different BMP effectiveness studies, considerations that affect data transferability, such as methods used for determining efficiency and statistical significance, efforts used to establish and analyze the currently available data and proposes protocols for future analyses. The authors recommend that effluent quality would likely be a much more robust measure of BMP effectiveness and performance than the currently used "percent removal" metrics. Ball et al. (2000) evaluated the effectiveness of stormwater treatment devices installed on a roadway in Australia, including detention tanks, a Continuous Deflective Separation (CDS) GPT, and a sand filter. It was concluded that the devices were improving the quality of stormwater flowing from the road drainage system into the general catchment stormwater system. Greb et al. (2000) evaluated the water-quality benefits of a new urban best management practice design called the multichambered treatment train. High reduction efficiencies were found for all particulate-associated constituents, such as total suspended solids (98%), total phosphorus (88%), and total recoverable zinc (91%). Dissolved fractions had substantial but somewhat lesser removal rates (dissolved phosphorus, 78%; dissolved zinc, 68%). The Washington State Department of Ecology's efforts to reduce the flow of pollution to Commencement Bay sediments, a federal Superfund site, caused metals concentrations in the bay to decrease by a factor of 10 between 1984 and 1997. This accomplishment demonstrated that major water quality improvements were possible in a heavily industrialized area (Smith et al. 2000c). Wang et al. (2000) sampled stream physical habitat, water temperature, and fish and macroinvertebrate communities at multiple paired watersheds in

Wisconsin before and after BMP installation from 1993 to 1999 to examine the responses of stream quality to watershed-scale BMP implementation. Results clearly demonstrated that watershed and riparian BMP implementation improve overall stream quality. A CDS unit would be expected to separate the following pollutant loads from a stormwater system: suspended solids, bed loads, floating solids, free oil & grease. Field studies verified removal efficiencies for gross solids to be greater than 95%, with particulate phosphorous removal of greater than 30%, and TSS removals greater than 70% (Kohzad 2000).

Non-structural stormwater treatment practices, such a reduction in the use of pesticides and fertilizers, often have been suggested for WWF control; however it is often difficult to assess the impact of such stormwater treatment practices. A project in Sydney, Australia assessed the effectiveness of a directed community education program for non-structural management at stormwater sources through detailed monitoring of both the community and the stormwater volume and contamination. Ball et al. (2000) outlined how the community education program focused on issues of concern to the local community and how changing practices could impact the problem. Also outlined were the monitoring program developed to evaluate the effectiveness of the program and the availability of stormwater contaminants. Henning (2000) outlined the development and work of "WaterShed Partners," a coalition of more than 40 public, private and non-profit organizations in the Minneapolis/St. Paul, Minnesota metropolitan area. "WaterShed Partners" developed and implemented a variety of public education programs to educate the public about changing household behaviors such as water usage, lawn care practices and proper disposal of household hazardous waste.

The pollutant loads conveyed by street cleaning waters, by street runoff and the maximum pollutant load removed by street washing were measured for three streets in central Paris, France. For suspended solids and organic matter, the pollutant load removed on a daily basis from street surfaces by street cleaning waters was found to be similar to that removed during one rainfall event. However, it was five times lower for heavy metals. It was also shown that the total mass of pollutants stored on the street surface is significant, and that the effects of street cleaning may be limited. An unexpected effect of street cleaning was found - it induces sediment erosion inside the sewer during dry weather periods, thus reducing the stock of pollutants available for wet weather flow (Gromaire et al. 2000).

Current turfgrass management practices in the U.S. have contributed to environmental problems, generated large amounts of solid and hazardous waste, and used large amounts of water during the summer months when fresh water supplies are lowest. These practices, including home lawn care, have included intensive use of water-soluble fertilizers, herbicides, insecticides, and fungicides, which may be harmful to human health and to aquatic ecosystems. McDonald (2000) presented an alternative approach based on observation of the entire soil and grass ecosystem, appreciation that turfgrasses are sustained by the activities of soil-dwelling organisms, and understanding that this grass community is a dynamic equilibrium among many plants, invertebrates, and microbial organisms. Pauleit and Duhme (2000) developed a method to delineate urban land cover units to establish the relationship between, on one hand, the socio-economic performance of the urban system and its different sub-units (i.e. housing schemes, commercial and industrial developments, services), and on the other, the environmental impacts of these sub-units. A case study on urban hydrology was presented to characterize aspects of the metabolism of the urban system. A multi-stakeholder group, was formed to address and to remediate nonpoint sources of bacteriological pollution threatening the economic and environmental health of Baynes Sound, Vancouver Island, Canada. This work demonstrated that partnerships among government, the shellfish industry, community groups, and citizens can create a powerful force for improving water quality (Pinho 2000). The University of Connecticut Nonpoint Education for Municipal Officials (NEMO) Project developed an educational program targeted at land use decision-makers. The program emphasized natural resource-based planning that prioritizes local natural resources and finds a rational balance between development and conservation. Four simple elements are shared by projects in the group: (1) an educational approach, (2) an emphasis on land use education, (3) a focus on land use decision makers as the target audience, and (4) the use of geospatial technology in the service of education (Rozum et al. 2000).

According to Strecker et al. (1999), the EPA cooperative research program with the American Society of Civil Engineers (ASCE) developed a more useful set of data on the performance and effectiveness of individual BMP and to assess the relationship between measures of efficiency and BMP design. BMP monitoring data should not only be useful for a particular site, but also be useful for comparing studies of similar and different types of BMP in other locations. It suggested some of the ways that data should be collected to make it more useful for assessing factors (such as settling characteristics of inflow solids and physical features of the BMP) that might have led to the performance levels achieved. It recommended efficiency calculation methods and appropriate terminology to be used in evaluating BMP assessment studies. In addition, Clary et al. (1999) stated that the National Stormwater BMP Database included test site location

characteristics, sponsoring and testing agencies, watershed characteristics, BMP design and cost data, monitoring locations and instrumentation, monitoring costs, precipitation data, flow data, and water quality data. The data retrieval, or search engine, portion of the software enabled users to retrieve BMP data sets based on a variety of search criteria such as geographic location, watershed size, BMP type, and water quality parameters.

Ecotechnology was the use of technological methods for environmental management in a way to minimize the harm to the environment. Herein the primary contributors to NPS pollution were presented. Best management practices (BMP) for NPS pollution were reviewed, and ecological engineering measures for NPS control were described and evaluated (Dermissi et al., 1999). stormwaters flow directly into the Matajoki River, which was situated in Southern Finland with a catchment area of 24.4 km<sup>2</sup>, was monitored with a limnograph. Separate sewage systems were present throughout the catchment area; domestic sewage was directed to a sewage plant directly outside the catchment area. During the research period July 1, 1995 to June 30, 1996, water samples from the Matajoki were taken at least weekly (Olli, 1999).

According to Rushton (1999), an innovative parking lot design at the Florida Aquarium in Tampa, Florida, was being used as a research site and demonstration project to show how small alterations to parking lot designs can dramatically decrease runoff and pollutant loads. Three paving surfaces were compared as well as basins with and without swales to measure pollutant concentrations and infiltration. Utilization of parking lots around Hattiesburg, Mississippi was examined to suggest mechanisms for reducing runoff into local streams (Albanese and Matlack, 1999).

Prince George's County, Maryland first introduced the bioretention device (commonly referred to as a "rain garden") in 1990. Utilizing physical, chemical, and biological treatment processes within an aerobic soil media/vegetated filter system, bioretention has been shown to be highly effective in removing pollutants such as heavy metals and nutrients from urban runoff. By capturing, infiltrating or filtering stormwater runoff close to the source, the use of bioretention treatment can also restore hydrologic functions (Winogradoff and Coffman, 1999). Beginning in July 1997, the University of Virginia has been testing a vault/reservoir structure installed at a bus maintenance facility in Charlottesville, Virginia; two larger such structures were later installed in Warrenton, Virginia and were monitored between October 1997 and September 1998. Another ultra-urban BMP, a bioretention area, was installed at a high school site in 1998 and has been monitored since November 1998. A total of 22 storm events were sampled at the vault/reservoir structure sites, and 4 storms have been sampled at the bioretention site; water quality parameters examined included total suspended solids (TSS); total phosphorus (TP); chemical oxygen demand (COD), and oil and grease (OG) (Yu et al., 1999).

No single BMP will prevent all the effects on receiving waters caused by urban runoff, however, through a combination of source and treatment controls, the greatest benefits will be gained. Stormwater management objectives should focus on obvious localized problems for near-term goals and should establish an appropriate scientific and administrative structure for addressing long-term beneficial use protection in a cost-effective manner (Joint Task of WEF and ASCE, 1998). A BMP screening procedure was used to develop a watershed plan for the Bear Creek part of the Clinton River Watershed in southeast Mich. (Paluzzi and Ditschman, 1998). The screening procedure assessed water-quality sampling and habitat inventory, physical suitability, stormwater benefits, pollutant removal, environmental amenities, and institutional constraints and costs. A linear program, which was developed and run on commonly available spreadsheet software, optimized the selection of BMP for a watershed (Lewis, 1998). O'Leary and Clevenger (1998) reviewed the Maryland Department of the Environment's past and present stormwater regulations and plans for a new design manual. De Hoop et al. (1998a) reported the results of a survey of log storage yards in La. that gathered information related to stormwater runoff such as storage practices, soil composition, materials stored, and runoff control practices.

Silt fences removed sediment from runoff at a construction site in Austin, Tex. by particle settling, not filtration and were ineffective in reducing turbidity (Barrett et al., 1998b). Mean sediment removal efficiencies in flume studies ranged from 68—90%, depending on detention time of the runoff, however, large quantities of construction sediment remained in the discharge because initial sediment concentrations were 3 000 mg/L or more. Dee et al. (1998) reported on efforts by the Virginia Department of Transportation to help protect the water quality of the reservoir before, during and after construction of a roadway project located within the Rivanna River Reservoir watershed. The benefits provided by porous and permeable pavements over the last 20 years included flow attenuation, aquifer recharge, pollution control and treatment, stored water reuse and effluent quality enhancement. These pavement have also provided evidence of their sensitivity to environmental factors and changes over time (Pratt, 1998).

Several sources addressed a "new technology" in BMP - Low Impact Development (LID). By reducing the change in curve number (CN), maintaining the pre-development time of concentration (T<sub>c</sub>), incorporating distributed retention and

then, if required, adding detention BMP to maintain the runoff volume and peak runoff rate, (Coffman et al., 1998a, 1998b, and 1998c) LID creates a “functional landscape” that incorporates design features that mimics pre-development, natural watershed hydrologic functions. Runoff may be reduced and controlled at the site by minimizing impacts to the extent practicable by reducing imperviousness, conserving natural resources, recreating detention and retention storage, maintaining pre-development Tc by strategically routing flows to maintain travel time, and implementing effective public education programs that encourage property owners to use pollution prevention measures. Net results for LID stormwater treatment and management mimic the water balance between runoff, infiltration, storage, groundwater recharge, and evapotranspiration (Dep. Environ. Resour., Prince George’s County Md., 1997). LID techniques integrate stormwater controls in small discrete units throughout the site. Distributed BMP reduce the need for a centralized BMP facility. Micro-management of stormwater, which has been used successfully in several communities, stores water temporarily at many locations on and off the street and below the surface and as close as possible to the precipitation source prior to entry into a combined, sanitary or storm sewer system (Carr and Walesh, 1998). Bioretention uses plants and soil to filter runoff from developed areas. Laboratory and field tests showed good removal of metals, P, and NH<sub>3</sub> with little or negative removal of nitrate. A significant mulch layer was found to be important for metals removal (Davis et al., 1998b).

Within the 16.2 ha (40 acre) festival grounds in downtown Milwaukee, Wis. a flow splitter diverted the first flush stormwater from a 1.2 ha (3 acre) area to a constructed landscaped island with a layer of peat over a layer of fine sand and at a hospital in Green Bay, Wis., a pressurized two stage filter system was designed to reduce pollution from a 2.6 ha (6.5 acre) parking lot (Bachhuber, 1998). A swale-infiltration trench system that combined three engineering techniques (infiltration, storage and throttled drainage) to manage rainfall runoff can be applied to new developments or as a retrofit (Sieker, 1998). Urban stormwater was treated by a combination of engineered and natural treatment systems comprised of a wetland perimeter swale and a berm which directed collected surface water runoff to a 30 m wide forested wetland filter strip (Berg, 1998). A sand-filter system and two grassy medians located on highways near Austin, Tex. were evaluated (Barrett et al., 1998c). The grassy areas reduced SS by 85% while the sand filter reduced pollutants by 90%, but was plagued with maintenance problems and detention times exceeded the 48 hour design. The capability of vegetated highway medians for treating stormwater runoff in the Austin, Tex. area was studied by examining pollutant removal efficiencies of two medians on major highways. Removal efficiencies at the two sites were remarkably similar despite being designed solely for stormwater conveyance and differed in slope and vegetation type and were comparable with those observed in structural controls such as sedimentation/filtration systems (Barrett et al., 1998d).

Washington, D.C. required that BMP be required for new and re-development projects to control urban-stormwater-runoff pollution. Dee (1997) retrofitted an existing drainage basin with a sand-filtration system that controlled the 2-yr and 15-yr rainfall events. An innovative BMP system for a recreational farm in Taiwan was evaluated by Wen and Yu (1997). The BMP system included a grassed strip, a swale, wetland vegetation, two check dams, a shallow lotus pond, and two wet-detention ponds. The results indicated that BMP put in series could provide high pollutant removal, especially for particulates. According to Pechacek *et al.* (1997), key components of BMP include good-housekeeping procedures; preventive-inspection and maintenance schedules; management strategies to prevent contamination of stormwater runoff; facilities that manage runoff to prevent contact between pollutants and runoff; and facilities that reduce pollutants in the runoff. U.S. EPA (1997d) addressed some of the unique challenges for designing BMP in cold climates.

Barrett *et al.* (1997) evaluated different types of structural BMP systems for treating highway-stormwater runoff, including grassy swales, extended detention ponds, and sedimentation-filtration systems. As a part of stormwater management BMP, the Maryland Department of Environment applied a groundwater-syphon system to mitigate wet-pond-outflow temperatures in order to comply with the State’s threshold criteria for stream-flow temperatures (O’Leary, 1997). A literature summary documented the benefits analysis associated with an alternative development approached for controlling stormwater runoff (U.S. EPA 1997e). The Baltimore County, Department of Environmental Protection and Resource Management developed a stormwater-management-water-quality-retrofit program to improve BMP performance in an urbanized environment. O’Leary *et al.* (1997) reported the program details, including assessment of water quality, BMP-retrofit options and prioritization, feasibility and cost effectiveness, and aesthetics and neighborhood acceptance.

Livingston *et al.* (1997a and 1997b) developed two separate reports to address institutional aspects of urban-stormwater-runoff management and the operation and maintenance of stormwater-management systems which included sample stormwater-management-inspection forms.

### **General stormwater control objectives and sustainable drainage design.**

Braune and Wood (1999) described how South Africa currently has one of the highest rates of urbanization in the world, causing a significant increase in surface water runoff and attendant increases in flooding and significant decreases in water quality. They presented a method of how the existing problem areas can be identified and ranked, and how the use of BMP can be used to reduce the impacts associated with urbanization. Cutler and Eastman (1999) described two projects in Christchurch City, New Zealand. The first, Regents Park, was an urban subdivision in an area with springs, open drains and a high water table. The City Council worked with the developer to naturalize and enhance the open waterways so that they added value to the landscape, ecology, drainage, and value of the subdivision. The second area, the Tranz Rail transfer yards, was a multi-million dollar development involving extensive areas of roofing and paved surfaces. They developed an integrated stormwater design approach that includes a two-stage settling/treatment/filtration system that retains peak discharges, contains contaminated spills, and alleviates downstream flooding. Hottenroth et al. (1999) examined the effectiveness of integrated stormwater management in Portland, Oregon. The stormwater program encourages innovative, non-structural pollution reduction techniques such as native landscaping, grass swale drainages, ponds, and public involvement and education. The Parkrose Pilot Project was started in 1994 to test the effectiveness of a wide range of these BMP in a small watershed in north Portland.

The Auckland Regional Council (ARC), New Zealand published a manual for design of stormwater quality improvement devices (TP10). Within that manual a modified Rational Method was used for flood estimation. An improved method was developed for estimation of storm runoff to represent the effects of different approaches to land development, including the use of different types of land cover and drainage systems, which could significantly modify the volume, timing and peak rate of runoff (Levy and Papps, 1999). The ARC developed a manual "Low Impact Design for Stormwater Management" (Shaver, 1999). Schueler et al. (1999) described a series of 22 land development principles developed by a consortium of American planning, road, banking, engineering, development and public safety organizations. The environmental impact assessment database being developed for Project Storm consists of a ranking system to provide comparative data for aquatic resources in terms of existing natural environmental values and existing effects (Stevens et al., 1999).

Iwamoto et al. (1999) described the sequence of urbanization, and associated receiving water problems in Japan. River excavation and widening were first used in the suburbs, followed by the raising of levees and overflow spillway to let flood discharges flow into temporary storage areas near rice fields. In the most urbanized areas, drainage channels and pump stations were constructed to handle the increased flows. Contrary to these historical approaches, they feel that "soft" approaches should be tried to encourage the natural benefits associated with reforestation and land consolidation. Kobayashi (1999) described changes that have occurred with development in Nagoya City, Japan. Rapid rainwater conveyance was being achieved by expanding storm sewers and pumping stations, but they were also stressing the use of infiltration facilities throughout the city area. Private infiltration facilities have not been developed as much as they hoped. The authors described an approach to constructing porous pavements; managing the decreased infiltration capacity of the pavements with time; and the needed field inspection and recovery operations to restore the infiltration capacity.

Cutler and Simpson (1999) described the challenge facing the city of Christchurch (New Zealand) to develop sustainable, aesthetically pleasing waterway environments that were environmental assets for the adjacent landowners. Designers were expected to naturalize the artificial drainage channels, or create new realigned reaches in confined urban settings. A range of techniques were being applied to replace the existing drainage system with a sustainable naturalized waterway environment. Stahre (1999) reviewed ten years of different experiences pertaining to sustainable stormwater management in the city of Malmö, Sweden. A basic element in sustainable stormwater management in Malmö was the involvement of ecological processes in drainage and that the technical design, to a great extent, was adapted to the prevailing local conditions.

Zhang et al. (1999) stated that, although separate sewer systems usually were not designed to take full advantage of available NPS controls, a great improvement can be achieved by combining a number of separate control options. Thorolfsson and Sekse (1999) reports that the green trend in urban stormwater management, as demonstrated in the Birkeland test basin in Bergen, Norway, utilizes the capabilities of nature to store huge stormwater and snowmelt volumes and to reduce the pollution content in the receiving water. Thorolfsson (1999a) further described the Sandsli system (an alternative drainage system demonstrated in Bergen, Norway) used for drainage management in the north Atlantic. The goal was to manage the total urban runoff (wastewater, stormwater, and snowmelt) in a way that environmental damage was avoided, and the goals for the receiving water were achieved at reasonable costs. Thorolfsson (1999b) described how non-contaminated runoff was to be handled near the source by percolation and/or detention, while the polluted runoff will be collected and conveyed to an appropriate site for treatment and discharge.

McAlister et al. (1999) found that the fine sediment in urban stormwater was a key cause to many receiving-water impacts. As a consequence of these studies, a total catchment approach has been developed and applied to urban stormwater quality management in Brisbane city (Australia). Mehler and Ostrowski (1999) found that an economically and ecologically sound combination of centralized and source area control measures will be a concept of the future of stormwater management in Germany and elsewhere. Holz (1999) described how engineering solutions have not been effective at avoiding the degradation of receiving waters in the northwest of Washington's Pacific coastal region. They concluded that "hard" engineering methods have little chance of mimicking the stormwater runoff attenuation of forest cover, regardless of storage provided, and that another paradigm for development must be adopted (in contrast to the present "clear, grade, and pave" approach that has not been proven to be mitigatable).

#### **Stormwater treatment effectiveness.**

Chocat et al. (2002) presented the current French and other western European approaches to stormwater management. The paper reviewed BMP analysis, design and performance and was drawn from the available literature on the subject. Stahre (2002) discussed the use of stormwater treatment practices in Malmo, Sweden. All new developments in Malmo have been planned with special consideration of the drainage of stormwater. Wherever possible, new developments will be built up along constructed open drainage corridors, which are laid out at a very early stage in the planning process. Marsalek and Chocat (2002) reported on an international survey of urban stormwater management practices that was conducted for IWA and contained contributions from 18 countries. The main findings of the survey included clear indications of a widespread interest in stormwater management and of the acceptance of a holistic approach to SWM promoting sustainable urban drainage systems (SUDS). Specific implications of this philosophy included emphasis on source controls in SWM, transition from traditional "hard" infrastructures (drain pipes) to green infrastructures, needs for infrastructure maintenance and rehabilitation, formation of stormwater agencies (within larger integrated water agencies) with participation of both public and private sectors, and sustainable funding through drainage fees rather than general taxes. Lawrence (2002) performed a strategic review of Australia's urban water stormwater treatment practices. The review indicated that while substantial advances have occurred, a number of significant shortcomings in the selection and application of stormwater treatment practices remained.

Blaha et al. (2002) evaluated the effectiveness of the principal structural and non-structural stormwater treatment practices used in the United States – stormwater management facilities and forested riparian buffers. The results of the analysis showed that stormwater management facilities do little to offset the effects of urbanization on aquatic communities, while natural riparian buffers appear effective at low to moderate levels of urbanization. Macdonald and Jeffries (2002) summarized monitoring results for BMP performance in Scotland. A porous pavement and two swales were monitored. The results showed that these stormwater treatment practices reduced pollution when compared to the traditional drainage design.

Cave (2002) reviewed an approach in the Rouge River, which links the performance of stormwater treatment practices to receiving water impacts. The approach considers the various stages of the 'life cycle' of the BMP design and implementation. Benefits have included progress in restoration in the Rouge River watershed, and sharing of practical and transferable results with other watersheds. Stribling et al. (2002) investigated the relationships between instream biological conditions to stormwater treatment practices in the watershed. The paper presented findings from two case studies where a "BMP-assemblage" was evaluated without the benefit of calibrated biological reference conditions, and another where SW retention ponds, in isolation, were evaluated with calibrated reference conditions. Strecker and Urbonas (2002) assessed the receiving water effects of urban stormwater stormwater treatment practices. The paper provided a framework to begin discussions regarding potential approaches and methods for assessing the performance of urban stormwater stormwater treatment practices in improving the health of aquatic ecosystems. It also presented potential methods and study approaches along with potential individual physical, chemical, biological, and biochemical measurements/indicators that employed in particular combinations may be useful in assessing downstream BMP performance.

Field surveys of structural stormwater treatment practices in the Pacific Northwest found that, even with a relatively high level of attention, a minority of the developed watershed area was typically served by these stormwater treatment practices (May and Horner, 2002). Those stormwater treatment practices installed are capable of mitigating an even smaller share of urban impacts, primarily because of inadequacies in current design standards. Even with these shortcomings, though, results showed that structural stormwater treatment practices help to sustain aquatic biological communities, especially at moderate-high urbanization levels, where space limits non-structural options. In addition,

structural stormwater treatment practices can be effective in water quality treatment of stormwater pollution "hot-spots" or in "ultra-urban" settings. The most promise appeared to be in the use of low-impact development (LID) concepts that incorporate conservation of native vegetation and soil, minimize imperviousness, and utilize integrated, on-site treatment of stormwater.

Horner et al. (2002) presented a study on structural and non-structural stormwater treatment practices for protecting streams. Intensive study of structural best management practices (stormwater treatment practices) in one location found that, even with a relatively high level of attention, a minority of the developed area is served by these stormwater treatment practices. Those stormwater treatment practices installed were capable of mitigating an even smaller share of urban impacts, primarily because of inadequacies in design standards. Even with these shortcomings, though, results showed that structural stormwater treatment practices help to sustain aquatic biological communities, especially at moderately high urbanization levels, where space limits non-structural options.

Chavez and Cunningham (2002) described the use of sediment removal boxes (baffle boxes) as a retrofit technique in areas where sedimentation basins/detention ponds would not be possible. The performance of three different sustainable urban drainage systems (SUDS) (porous pavement, roadside filter drain, and regional SUDS) in East Scotland were presented by Schluter et al. (2002). The systems were found to perform well at both attenuating flows and pollutant peaks. Modeling of these systems is showing good agreement with field results.

Nandi et al. (2002) presented a spreadsheet-based tool for estimating pollutant load reductions (nutrients, sediments and organic compounds) due to BMP implementation at the watershed levels. The pollutant load and reduction results are presented in summary tables and graphs that are linked dynamically to the data sources. This tool would be expected to assist federal, state, and local organizations in implementing their point and nonpoint source programs, Farm Bill programs, TMDLs, and other water quality-related programs.

Freni et al. (2002) reviewed the catchment-wide efficiency of distributed stormwater management practices (DSMP) in Baerum, Norway. The paper proposed a methodology that allows evaluating the efficiency of complex DSMP packages through the application of detailed rainfall-runoff modeling and sensitivity analyses. In this methodology, variation of hydrological model parameters was used to simulate the presence of different DSMPs. The developed procedure allowed screening and pre-selection of DSMP alternatives, avoiding simulation of numerous alternatives.

O'Shea et al. (2002) studied the role of stormwater treatment practices in mitigating the effects of nutrient over-enrichment in an urban watershed. Structural stormwater treatment practices were found to attenuate stormwater flows and provide some removal for settleable solids and particulate-associated pollutants. The effect of detention and stormwater treatment practices on flow frequency of runoff was investigated by Nehrke and Roesner (2002a). The study examined the effects of the state-of-practice in flow control on the peak flow frequency curve, and how well the postdevelopment flows were controlled to predevelopment levels. Continuous simulation was performed on two climatically diverse locales and detention ponds with a variety of flow control orifices were examined.

Mikkelsen et al. (2002) reviewed stormwater treatment practices used in urban stormwater management in Denmark and Sweden and found that stormwater treatment practices used included structural elements (infiltration, ponds and treatment, wetlands, and retrofitting of river reaches) and non-structural stormwater treatment practices (chemical control, building materials, and street sweeping). The available knowledge of stormwater treatment practices performance in pollution control was inconsistent and the effect of various stormwater treatment practices on receiving water quality was either poorly understood, or not known. A review of recent experiences with selected stormwater treatment practices in Denmark and Sweden was discussed with respect to the current issues related to legislation and the forces driving future development in stormwater management.

James (2002a) investigated removal of suspended material in stormwater runoff by BMP implementation. The USGS reported that the TSS method of analysis to determine concentrations of suspended sediments could result in unacceptably large errors and is fundamentally unreliable and use of TSS data could result in loading errors of several orders of magnitude. Research, development and standardization of new and improved sample collection and sample management techniques and additional analytical methods are needed to better characterize storm water pollutants. The Mass Balance Approach has been proposed to determine the effectiveness of suspended sediment-capture stormwater treatment practices.



Pyke et al. (2002) used a loosely-coupled watershed-water treatment plant modeling technique to provide a screening-level assessment of (1) the impacts of major point and nonpoint source pollutant loads on treatment plant operating costs; (2) the potential of agricultural and urban stormwater treatment practices and best available technologies (BATs) to mitigate these impacts; and (3) the cost-effectiveness of stormwater treatment practices and BATs versus increased treatment at the water treatment plant. The model was used to quantify changes in annual suspended solids and organic carbon loads exported under varying land use and BMP implementation scenarios, and a dynamic water treatment plant model was used to quantify the impact of associated changes in daily raw water quality profiles on water treatment plant operations and costs.

The two interrelated assessments conducted by EPA while developing effluent guidelines for stormwater from new construction and land development activities was presented by Clar et al. (2002). First EPA conducted an evaluation of the environmental impacts attributable to the land development industry. Second it conducted a related assessment of the effectiveness of erosion and sediment controls, post construction stormwater treatment practices and low-impact development practices to determine the ability of these practices to mitigate impacts attributable to construction and development activities which were identified in the first assessment. Schueler and Caraco (2002) reviewed the prospects for LID at watershed levels. Comparisons between baseline rural loads and loads from suburban developments with traditional stormwater treatment practices (STP) were made. Loads from suburban development with STP exceed the baseline rural loads for nitrogen, phosphorus and fecal coliform bacteria. Reininga and MacDonald (2002) presented a case study in simulating the effectiveness of LID techniques for protecting stream corridors. Supplemental management practices for the protection of stream corridors were also evaluated and applied in the case study in terms of costs.

Raghavan et al. (2002) presented the cost data and methods that would support the development of an Internet-based, interactive tool for estimating capital and O&M costs. The cost equations developed from actual cost data provided rough estimates of the actual best management practices (BMP) capital and operation and maintenance costs. Sample et al. (2002) presented new methods for evaluating stormwater controls and stormwater treatment practices in a land-development context. Costs were developed using published literature and standard cost estimation guides. The method had stormwater control costs assigned at the parcel level. Hunt (2002) evaluated the cost-effectiveness of stormwater treatment practices for North Carolina. A tool was presented that links the removal efficiencies of stormwater treatment practices to their associated costs (land, maintenance, and construction). The analysis found that (1) bio-retention was most often the most cost-effective BMP for small mostly impermeable watersheds, (2) the cost-effectiveness of stormwater wetlands and wet ponds were comparable when including land and opportunity costs, and (3) economies of scale existed.

Li and Kyriopoulous (2002) evaluated stormwater retrofit management practices (RSWMPs) for Mimico Creek Watershed. Using a derived probabilistic rainfall-runoff model and a treatment train efficiency model, the cumulative reduction of runoff volume and solids loading of a series of appropriate RSWMPs are determined to be 7% and 18% respectively. In the Mimico Creek watershed, the descending order of cost-effectiveness is: (i) downspout disconnection; (ii) water quality ponds; (iii) stormwater exfiltration systems; and (iv) oil/grit separators. The recommended sequence of RSWMP implementation should follow the descending order of cost-effectiveness.

Leaf et al. (2002) reviewed the guide manual developed for "Heart of the City," Burnsville, Minnesota. The Low-Impact Development (LID) manual was created based upon XP-SWMM2000 goals, stormwater treatment practices and existing permeable soils. Clar and Rushton (2002) presented case studies on low-impact development (LID). This approach results in an ecologically based approach to stormwater management that is usually more aesthetically pleasing, precludes impacts to receiving waters, and is generally less costly to construct and maintain than conventional end of pipe systems. While the emphasis of these projects is the state of Maryland, projects and case studies from other regions of the Country were also included. Strecker (2002) reviewed the inadequacies of the hydrological design procedures used to substantiate the effectiveness of the techniques used in LID. The paper recommended that much more robust hydrological techniques be used to quantify the potential benefits of this development approach. Coffman (2002) reviewed the use of LID as a stormwater management technology. Despite the demonstrated environmental and economic advantages of LID over today's conventional approaches, numerous barriers to its widespread acceptance and utilization remain and they include issues related political agendas, institutional structure and philosophy, lack of professional education and training, competing and vested interests in maintaining the status-quo, regulatory conflicts and inflexibility, lack of funding for research and development and professional / personal beliefs, knowledge and preferences. Rushton (2002) demonstrated how a low impact (dispersed) design of parking lots could reduce runoff and pollutant loads. Storm runoff was treated as soon as rain hit the ground by incorporating a network of swales, strands and a small wet detention pond into the overall

design. Calculations showed that almost all the runoff was retained on site. Basins paved with porous pavement had the best percent removal of pollution loads with many removal rates for metals greater than 75 percent in the basin with a smaller garden area and greater than 90 percent with larger gardens. More phosphorus loads were discharged from basins with vegetated swales than from basins with no swales. Metal and nutrient pollutants in the sediments were not found to be migrating to the deeper strata.

Roesner and Brashear (1999) reported that over the last ten years, a number of BMP manuals have been developed to address the control of urban runoff for receiving water quality protection. They concluded that there was a lot of ignorance in the scientific community about what constitutes a properly designed BMP and what it really achieves, with respect to environmental protection. They therefore recommend a design criteria development approach that can be applied over a wide variety of climatologic, topologic, and geologic conditions to protect receiving waters systems. Roesner (1999) further believes that the conflicting opinions on the effectiveness of various BMP result mostly from: 1) there was no accepted uniform design criteria for BMP; and 2) the objectives of the management practices differ between authors.

Buffer corridors. Crifasi (1999) gave a description of Boulder's (Colorado) instream flow and riparian zone management program, where extensive, high-quality wetlands and riparian areas exist along south Boulder Creek. South Boulder Creek's riparian corridor contains plains riparian cottonwood forests, willow shrublands, freshwater marshes, and alkali wetlands that provide refuge for two federally threatened species, plus other rare species of plants and animals. Haberstock (1999) presented a method used to determine optimal riparian buffer widths for Atlantic salmon habitat protection in Maine. Zone 1 (no-cut zone), closest to the stream, has a fixed width of 35 ft in which no disturbance to soils or vegetation should occur. Zone 2, landward from zone 1, was a variable width zone where only limited uses that do not compromise the desired functions of zone 2, such as light tree harvesting and light recreation, should occur. Resulting total optimal buffer widths (zone 1 plus zone 2) range from a minimum of 70 ft to a maximum of more than 350'. In rare cases (e.g., extensive slopes > 25%), optimal buffer widths can be 1,000 ft or more. The rehabilitation of urban stream channels to protect Pacific Northwest salmon runs were described by Henshaw (1999). In an effort to bolster the survival of salmon returning to the local streams to spawn, land managers have begun extensive programs to rebuild or rehabilitate appropriate habitat that has been lost or degraded due to urban development. Although rebuilt habitat in a stabilized urban stream may not provide the level of ecological integrity required to maintain endangered salmon and other stream biota, physical stability was likely one necessary component of a healthy stream. O'Neal et al. (1999) described hydraulic and biological effects of large woody debris (LWD) and an engineered wood alternative for stream channel rehabilitation projects in the state of Washington. The engineered structures consist of an interlocking complex of small diameter poles that can be carried by hand and assembled on site. The artificial structures have a high hydraulic and surface roughness to trap sediment and debris and caused variations in the pattern of water flow and resultant scour compared to natural LWD. No statistically significant differences were observed in the biological communities associated with these structures compared to LWD.

The city of Austin, Tex. Stormwater Monitoring Program (Glick et al., 1998) monitored various types and designs of BMP over a 15 year period and concluded that large regional water quality BMP tended to be more cost effective even if the treatment efficiencies are moderate because they can treat more runoff. The cost differential indicated that large systems (e.g., wet ponds) may be a more cost-effective option for areas being retrofit with BMP. Alum proved to be the most effective coagulant for stormwater runoff at Mosquito Lagoon located in New Smyrna Beach, Fla. when tested against ferric chloride which was not effective at enhancing settling (Escobar et al., 1998).

### **Stormwater reuse.**

Argue and Pezzaniti (1999) investigated the harvesting of stormwater to replace water supply mains for the irrigation of areas landscaped with grass, flowerbeds, and shrubs in Adelaide, South Australia. Four categories of catchments were recognized according to their levels of pollution production - roof runoff and "low", "medium" and "high" pollution runoff surfaces. Large roof areas draining to gravel-filled trenches provide passive irrigation for grassed surfaces, for example. Dillon et al. (1999) described the development of "new" water resources by using aquifer storage and recovery of stormwater. The reuse of reclaimed water through storage aquifers can lead to more environmentally sensitive design, with reduced requirements for imported water, reduced exports of sewage and stormwater, and lower water supply costs. Dixon et al. (1999) demonstrated the water saving potential of domestic water reuse systems using greywater and stormwater. Monte-Carlo modeling results show that changes in household occupancy, roof area, appliance type, and storage volume, affect the water saving efficiency of a reuse system. Fox (1999) also described a watershed approach for integrated water reuse. Zaizen et al. (1999) described roof-runoff reuse at domed stadiums in Japan, as part of a wider

program for preserving hydrologic cycle characteristics in urban areas. Tada et al. (1999) investigated three alternative storage methods that can be used to assist stormwater reuse. The best method (Type-1) uses a small tank to separate “first-flush” runoff nonpoint pollution loads from the remaining discharges. Type-2 has an overflow weir to separate polluted runoff stormwater, while type-3 has an orifice to separate un-polluted stormwater into the utilization tank. Pratt (1999) described the use of storage reservoirs under permeable pavements for stormwater treatment and reuse. Permeable surfaces for roads and footpaths have been used as a means of disposal of stormwater in developed urban areas and undersealing them to enable them to retain stormwater for reuse for non-potable uses was feasible. However, the stormwater may be degraded where the pavement was used for car parking. Tredoux et al. (1999) described the Atlantis Water Resource Management Scheme that uses artificial recharge of urban stormwater and treated wastewater to augment natural groundwater. The important element was the separation of the stormwater into components of distinctly different quality. Residential and industrial urban runoff was separated into baseflow and stormwater components and utilized for various appropriate purposes.

### **Public education.**

Mashiah et al. (1999) found that raising community awareness of stormwater impacts was a critical component of an effective stormwater management program. The campaign included television advertising, newspaper and radio advertisements, displays, free environmental audits for local businesses, and a stormwater ambassador program for local schoolchildren. Heremaia (1999) described the public stormwater education program used as part of the Christchurch (New Zealand) integrated environmental planning program. The successful pilot program included the development of a web site, audio conferences, a competition, and a drama production. Young and Collier (1999) described the research-based stormwater education of the New South Wales (Australia) Environment Protection Authority. This education program was unique in Australia by providing a comprehensive, integrated, and continuing research-based strategy for involving the community in preventing stormwater pollution.

The needs for linking local-economic and water-pollution problems were discussed from an urban perspective, including (1) access to information, (2) communication and outreach efforts, and (3) advocacy (Alex-Saunders, 1996). The EPA sponsored a number of local public-education programs for cities in abating WWF pollution (Austin *et al.*, 1996; Feuka, 1996). A multimedia public-information campaign helped achieve a 40% reduction of nutrients entering Chesapeake Bay (Leffler and Flagle, 1996). A multilevel cooperative-extension program including workshops, volunteer lawn, and master gardener lawn demonstrations was developed for the education of control of residential-nonpoint-source pollution. A community-action guide on environmental-restoration projects addressing citizen-volunteer participation and methods on how to organize restoration events resulted in a 100% positive experience in Chesapeake Bay areas (LeCouteur and Greenfeld, 1996).

Two new publications that address the causes and problem areas of SSO were released by the EPA (1996a and 1996b) for public awareness.

### **Public Works Practices**

McManany (2004) reviewed the Maine DOT’s use of the federal surface water quality protection plan (SWQPP) to get money to help pay for the engineering, design and construction of innovative stormwater treatment practices to reduce highway runoff and erosion from entering local streams.

The role of street cleaning in stormwater management was examined by Pitt et al. (2004c). The paper provided a summary of various street cleaning research projects conducted over the last 30 years. Pitt and Field (2004) reviewed the use of catchbasins and inserts to control gross solids and stormwater pollutants. Catchbasins with sumps could remove up to 30% of the TSS entering the inlet. Inserts also were able to catch larger particulates but were subject to frequent clogging. Newer designs are showing promise in addressing these drawbacks.

Morgan et al. (2003) investigated the pollutant removal efficiency of several catchbasin inserts that were designed and advertised to improve stormwater quality in regards to TSS and TPH. Results from the testing indicated that at the test flow rate and pollutant concentration, average TSS removal efficiencies ranged from 11 to 42% and for TPH, the removal efficiency ranged from 10 to 19%.

Sutherland and Jelen (2003) discussed a method for accurately estimation urban runoff loads for sediment. The procedure monitored sediment in pilot-test areas that represent the watershed's various land uses, analyzed the sediment's physical and chemical characteristics, and used the data in the simplified particulate transport model to evaluate various cleaning

practices based on an average rainfall year. Results from two watersheds in Michigan show that annual catch-basin cleaning and street sweeping every 15-30 days could reduce annual total suspended solids loadings by 80 percent.

A management study for the Bell Branch and Tarabusi Creek subwatershed of the Rouge River was presented by Sutherland et al. (2002). The goal of the study was to help public agencies develop appropriate management practices. The advisory group for the project recommended stormwater management practices that reduce or eliminate pollutants at their source, such as leaf collection, catchbasin cleaning and street sweeping.

O'Loughlin and Stack (2002) compared four algorithms for pit pressure changes and head losses in stormwater drainage systems. The results were inconclusive with no method being superior.

### **Catchbasins/grit traps**

Memon and Butler (2002) used a dynamic model to assess the impact of a series of water management scenarios on the quality of runoff discharged through catchbasins/gully pots. The simulation showed that the catchbasins/gully pots were effective at retaining solids, but they had an almost neutral performance in terms of removing dissolved pollutants. Model predictions, as against common perception, showed that frequent pot cleaning does not significantly improve the runoff quality. However, considerably improved solid retention was possible if larger pots with modified geometry are introduced into the drainage system. Lau and Stenstrom (2002) investigated the ability of catchbasin inserts to determine their ability to remove particulate pollutants, litter and debris. Laboratory tests with used motor oil showed that the inserts could remove in excess of 80% of free oil and grease. Sand particles larger than the screen mesh were completely removed. Field tests showed that median oil and grease, turbidity and total suspended solids concentrations in stormwater were reduced by 30 to 50%. The inserts were more effective in reducing maximum concentrations than low or median concentrations. Some of the inserts plugged after usage and bypassed stormwater without creating ponding on the street or reducing flood protection.

Because more than 780,000 tonnes of solids washed is washed into the drainage system in South Africa, the Water Research Commission of South Africa and the Cape Metropolitan Council are funding a four year investigation into the reduction of urban litter in the drainage systems through the development of catchment specific litter management plans (Armitage et al., 2001). The results of the litter audits from eight catchments will measure the effectiveness of the various litter management strategies. The California Department of Transportation (Caltrans) conducted a 2-year litter management pilot study in the Los Angeles area to investigate the characteristics of highway litter and the effectiveness of stormwater treatment practices for removing the litter (Lippner et al., 2001). Half the catchments were treated with one of five stormwater treatment practices; the others were controls. The stormwater treatment practices tested were increased street sweeping frequency, increased frequency of manual litter pickup, a modified drain inlet, a bicycle grate inlet, and a litter inlet deflector (LID). Roughly half the freeway storm water litter was paper, plastic, and Styrofoam. Except for cigarette butts, the origins of most litter could not be identified because of its small size. Of the five stormwater treatment practices tested, only increased litter pickup and the modified drain inlet demonstrated some apparent reduction of litter in stormwater runoff, although the data were highly variable.

Some people have advocated annually removing sediment, vegetation and litter from drain inlet vaults as a best management practice to improve the quality of Caltrans run-off before it enters the receiving waters (Dammel et al., 2001). In response, Caltrans implemented an annual drain inlet inspection and cleaning program in selected urban areas, and conducted the Drain Inlet Cleaning Efficiency (DICE) Study to evaluate if this practice improved effluent water quality. Irgang et al. (2001) evaluated the effect of catch basin cleaning on stormwater quality. Catch basins within two of the four drainage areas were cleaned at the beginning of the study, while those within the other two areas were not cleaned. Pollutant concentrations and runoff loadings were compared between the two areas. It was observed that fine particle deposits remaining in catch basins after cleaning could cause higher pollutant concentrations and loadings for several months when compared to control areas where catch basins were not cleaned. Untreated stormwater runoff reaches Santa Monica Bay (Los Angeles, California) primarily through catch basins or inserts to storm drains that terminate at the beach or in shallow coastal areas (Lau et al., 2001). Commercially available drain inlet devices for pollutant capture exist but few have been evaluated by independent parties in full-scale applications. Laboratory- and full-scale tests of inserts were conducted to evaluate their ability to remove trash and debris, suspended solids and oil and grease in stormwaters, with the results providing a basis for future insert development and application. The performance of Drain Inlet Inserts (Fossil Filter and StreamGuard) and an oil/water separator in treating runoff from four California Department of Transportation (Caltrans) maintenance stations was evaluated (Othmer et al., 2001). Drain Inlet Insert results to date showed that reductions in metals, hydrocarbons, and solids were consistent with expectations; however,

frequent flow bypass required more maintenance than anticipated. Oil/water separator results showed no discernable difference between influent and effluent hydrocarbon concentrations at the low levels measured.

Newman (2001) described an analytical framework for the design and/or analysis of baffles to reduce floatables discharges from CSOs. This simple analytical framework, which is supported with a spreadsheet model, was compared to its predecessors and its advantages illustrated. The advantages included ease of use, improved applicability to typical installation configurations, and refined analyses of floatables-removal mechanisms. Model results were compared to previous results and to available laboratory test data for four test cases.

Interest in urban stream restoration has grown (Hession 2001). However, a scientific basis for restoring urbanized streams currently does not exist, although it is known that riparian vegetation along streams significantly impacted stream channel morphology, which in turn influences aquatic ecosystem structure and function. Watershed urbanization also has a significant, but typically conflicting, influence on channel morphology and aquatic habitat.

Grey et al. (1999) summarized the role of catchbasins in the CSO floatables control program in New York City. There were approximately 130,000 catchbasins, distributed over 190,000 acres, in New York City. They found that catchbasins were simple and very effective in controlling floatable material at the source. The most important aspect of catchbasin designs for floatables removal was the presence of a hood that was hung over the basin's outlet. Several studies conducted in the City have shown floatable retention efficiencies of 70 to 90%. Catchbasin hoods were also very cost-effective controls at a cost of about \$100 per acre. The City implemented a catchbasin inspection, mapping, cleaning, and hooding program as part of its CSO control program. Siegel and Novak (1999) reported on the activity of the microbial larvicide VectoLex CG (R) (*Bacillus sphaericus*) for the control of mosquitoes in 346 tested Illinois catchbasins. The tests were deemed successful.

Washbusch (1999) reported on an extensive evaluation of a proprietary urban stormwater treatment unit (the Stormceptor) in Madison, Wisconsin, conducted by the United States Geological Survey (USGS) and the Wisconsin Department of Natural Resources (WDNR). The evaluation was conducted on a 4.3 acre city maintenance yard site over 9 months and for 45 runoff events having rainfall depths ranging from 0.02 to 1.31 in., plus some snowmelt influence from imported snow to the maintenance yard. About 90% of the runoff was treated by the unit, and the remainder flows bypassed the unit during periods of high flows. The overall effectiveness of the unit was 33% for suspended solids, 17% for total phosphorus, 34% for total PAH, and from 20 to 30% for most heavy metals. In general, dissolved constituents were unaffected by the unit. Performance during the early spring events was degraded by high saline snowmelt water, which had elevated conductivity from on-site deicer storage, that significantly slowed particle settling.

Treatment of stormwater runoff from the recently constructed convention center on the shore of Lake Monona in Madison, WI, has recently been achieved with the installation of two vortex separators. The systems were designed to remove >80% of sediments and oils at flowrates of up to 0.48 m<sup>3</sup>/sec (17 ft<sup>3</sup>/sec), with peak 25-year flows of 1.27 m<sup>3</sup>/sec (45 ft<sup>3</sup>/sec) and 1.7 m<sup>3</sup>/sec (60 ft<sup>3</sup>/sec) anticipated at the two system locations (American City & County, 1996a and 1996b).

### **Litter/floatable control**

Armitage and Rooseboom (1999) summarized the results of three years of laboratory investigations sponsored by the Water Research Commission of South Africa into the movement of urban litter through potential trapping structures. They found that once the litter has entered the drainage system it was difficult to remove. They concluded that declined self-cleaning screens showed the greatest promise for the removal of urban litter from most stormwater conduits and streams in the less developed countries. Newman et al. (1999) reported that the City of New York has improved its ability to control one source of floatables and possibly other pollutants to New York Harbor through its newly implemented "Illegal Dumping Notification Program." This program takes advantage of one City Department's field presence to gather and transmit valuable information to another City Department for enforcement and cleanup. They found that this program likely will reduce the number of illegal dumping sites by 15%. Phillips (1999) described how the State Government of Victoria (Australia) provided funding to develop a litter trap (the In-line Litter Separator, or ILLS). The ILLS can be retrofitted into the drainage system downstream of shopping areas.

Two proprietary stormwater control devices were placed at drainage inlets and their performance compared with that of a conventional catchbasin inlet (Pitt and Field, 1998). No significant removals were found in the field tests of the proprietary devices, though large debris was trapped by one device, and a catchbasin retrofitted with a sump provided

good removal of pollutants. A NYC study indicated street litter is a major contributor of floatables to N.Y. Harbor (Grey and Oliveri, 1998). Hooded catchbasins were 80—90% effective in retaining floatables and a city-wide program to inspect, map and hood all catchbasins was reviewed. Based upon a detailed examination of 18 facilities in Ger., Can., and U.S., Pisano et al. (1998) reported the performance of two widely used sewer and tank flushing technologies, i.e., the tipping flusher and the flushing gate.

### ***Infiltration and Biofiltration, including Grass Swales and Grass Filter Strips***

Rain gardens and their design requirements were also reviewed in 2006 (Anonymous 2006b). Heasom et al. (2006) presented hydrologic modeling for a bioinfiltration traffic island in Pennsylvania. Seasonal-variability of the model parameters were used, and the results showed that the model could reflect what was seen in the field.

Hunt et al. (2006c) evaluated the hydrology and associated nutrient removal in three bioretention sites in North Carolina. The results showed that the fill media selection was critical for total phosphorus removal. Davis et al. (2006) investigated whether transport of nitrogen and phosphorus through bioretention media improved water quality. The results showed that the best control of nutrients in bioretention facilities would result from carefully managing the growth and harvesting of vegetation. Dietz and Clausen (2006) reported on creating saturation conditions in a rain garden to improve pollution retention. Saturation enhanced the removal ability of the rain garden for total nitrogen.

Maeda et al. (2006) evaluated the spatial distribution of soil structure in a suburban forest catchment and its effects on soil moisture and runoff fluctuations. The authors presented a simple, physical-contour-based model that can describe topography and spatially heterogeneous distributions, and uses the model to clarify how spatial heterogeneous variability influences long-term rainfall runoff processes.

### **Low Impact Development**

Gregory et al. (2006b) evaluated the impacts of imperviousness in large, developing watersheds. The paper presented methods for estimating the increase in impervious cover and quantifying the resulting impacts of various developments on impervious cover.

Lefers et al. (2005) reviewed how the known information regarding the relationship between downstream flooding, upstream landuse and runoff flows was used to determine the delay in peak time and the need for infiltration at a new development in Madison, Wisconsin.

Traver and Ermilio (2005) presented the continuous monitoring of a bioinfiltration traffic island stormwater treatment practice. Traver et al. (2005) reported on the performance of an infiltration trench designed to capture and treat runoff from a parking garage. Birch et al. (2005) monitored the ability of a stormwater infiltration to remove contaminants from the influent runoff. Removal efficiencies were characterized for total suspended solids, nutrient, trace metals, organochlorine pesticides and fecal coliforms. Stanford and Yu (2005) evaluated the performance of urban and ultra-urban bioretention units. The two units were monitored for their effectiveness in removing nitrogen, phosphorus and TSS. The monitoring conformed to the requirements of the Technology Acceptance Reciprocity Protocol.

Davis and Li (2005) proposed a series of modeling equations to be used to predict suspended solids capture in bioretention. These equations combined deep-bed filtration theory for particles passing through the surface layer with a cake filtration model equation to account for the surficial straining. A model simulation, incorporating dynamic change in storage capacity and infiltration rate and assuming clogging, was able to model the behavior of infiltration facilities to reduce runoff (Furumai et al. 2005). The model was able to account for the dynamic behavior seen during weak-intensity rainfall events.

Sediment transport in grassed swales and grass filter strips were assessed in the laboratory by Deletic (2005) in order to develop new methods for predicting the sediment removal in these grassy areas. The Kentucky model was found to be inadequate to predict the measured sediment transport rates. Simulation of a 10-m or longer vegetative filter strip showed that it was capable of removing most of the larger-sized suspended solids in the runoff flow (Han et al. 2005). For the smaller particles, infiltration loss was the process most responsible for pollutant retention. The condition of the vegetative cover affected the performance of the strip.

The soils below four infiltration basins were sampled and the results analyzed using the traditional soil profile approach

as well as with a Principal Component Analysis (Barraud et al. 2005). Pollutant concentrations were found to decrease rapidly with depth in the soil profile; the statistical analysis showed how pollution affected each sampling depth. Deschesne et al. (2005) investigated the long-term performance of four stormwater infiltration basins in Lyon, France. Pollution migration was seen to a depth of approximately 30 cm, but below that depth, concentrations were less than levels of concern. No relationship was seen between age, hydraulic resistance and pollution. The metals concentration in soil and seepage water in an infiltration device from roof runoff was simulated using long-term numerical modeling (Zimmerman et al. 2005). Concentration increases in the infiltration device were seen for three roof types, but limited movement below the device was seen for all soils except the low-adsorbing one. The hydrologic and water quality performance of four bioretention cells in central North Carolina was investigated by Sharkey and Hunt (2005). Non-agricultural fill soils in the cells resulted in reductions in total phosphorus and total nitrogen. Evapotranspiration was a substantial factor in water removal in the bioretention cell.

Hsieh and Davis (2005a and b) examined the removal ability of several media mixtures suggested for use in bioretention systems. Two media designs were proposed as providing the best removal efficiencies for suspended solids, nitrate, ammonium and heavy metals. They found that the runoff quality was improved after passing through the bioretention column and that the top mulch layer was most effective at removing the TSS. Dietz and Clausen (2005) performed a field study on rain garden flow and pollutant treatment. Total nitrogen and ammonia were the only two pollutants where reduction was seen although substantial water removal was achieved in the system without an underdrain.

Kirby et al. (2005) investigated the hydraulic resistance in grass swales under low flow conditions. The resultant “small-flow” curves extend the Stillwater n-VR curves by approximately one order of magnitude (to smaller values of VR). Munoz-Carpena and Parsons (2005) developed design nomographs for vegetative filter strips. These nomographs were based on the mechanistic hydrology and sediment transport modeling for representative soil types, disturbed area sediment properties, design storm classes and vegetation characteristics.

Lassabatere et al. (2005) showed that geotextiles can affect the movement of heavy metals in stormwater as it passes through an infiltration structure. The factors that caused the greatest effect were the geotextile type, geotextile water content, flow rates, and the number installed. The geotextiles impact is typically through modifying the flow regime. Compost amending of soils to improve infiltration and reduce runoff was advocated by Cogger (2005). A secondary benefit of these amendments is the restoration of organic content and nutrients to the amended soil layer. The use of organic matter such as organic amendments and mulches to protect the native soil and vegetation where possible was promoted by McDonald et al. (2005). For disturbed sites, these organic amendments are promoted as a way to help restore native soil functions and infiltration.

The surface infiltration rate of asphalt permeable pavements was examined by Bean et al. (2005). Maintenance was shown to improve surface permeability and zinc was reduced in the soil profile. The paper by Guan et al. (2005) examined the relationship between the objective void space of porous asphalt pavements and the reduction of runoff. Fach and Geiger (2005) developed a matrix relating the runoff quality from permeable pavements to the specific reactive surface. Batch test results were related to field test results to calibrate the sorption coefficients required for modeling. Aquaflow permeable paving, combined with a stone sub-base, has been installed at a commercial site in Gloucester (Anonymous 2005d). The surface water is passed through the pavement and stone but the lower liner does not allow water to percolate below the surface. Broviak (2005a) reviewed the application of pervious pavement in the urban environment. Huffman (2005) reviewed the types and applications of pervious pavement. Traver and Braga (2005) reported on the continuous monitoring into the performance of a porous concrete stormwater treatment practice.

Traver (2004) reviewed the infiltration strategies incorporated into LID. The relationship between goals and capture volume, placement and general use of infiltration stormwater treatment practices were discussed. The behavior of LID and bioretention areas in cold climates were examined by Nordberg and Thorolfsson (2004). The performance of the bioretention area was evaluated based on peak runoff reduction, detention capabilities, and reduction of total suspended solids (TSS), copper, zinc, and lead in the outflow.

### **Green Roofs**

The role of extensive green roofs in sustainable development was reviewed by Getter and Rowe (2006). Extensive green roofs' effects on runoff water quality was investigated by Berndtsson et al. (2006). Their results showed that, except for nitrogen, the roofs were pollutant sources. Mathew (2006) reviewed the research performed at the Penn State University

Center for Green Roof Research. Hoffman (2006) focused on the use of green roofs to combat CSOs through calculation of the retention/storage capacity of the green roof. Mentens et al. (2006) highlighted green roofs as an integral part of the stormwater management solution. The paper presents an analysis of the results from 18 publications on green roofs.

Carter and Rasmussen (2006) examined the hydrologic behavior of green roofs. Green roofs were able to retain precipitation for small storm events and delay it for 18 minutes on average. Its curve number was estimated to be 86. Compton (2006) investigated the water capture of a green roof that was not allowed to freely drain. The non-draining system was able to retain a two-year frequency storm.

Crushed waste concrete as an aggregate for green roofs was promoted by Fentiman and Hallas (2006).

### **Infiltration**

Mu et al. (2006) discussed enhancing infiltration to reduce runoff. Soil was amended with lignin polymer and zeolite, and showed reductions in runoff volume, COD, TN and TP. Zheng et al. (2006) presented a case study on the design and operation of sustainable infiltration ponds for storm runoff. Three international design guidelines failed in practice. The effect of urban soil compaction on infiltration rate was investigated by Gregory et al. (2006a). Infiltration rates in Florida in disturbed areas were typically lower than the design storm infiltration rate.

Concerns about infiltrating roof runoff from copper roofs were addressed by Athanasiadis et al. (2006). The investigators examined two barrier systems in the field for their ability to reduce copper in the infiltrating water.

Dumont (2004) reviewed the East Clayton stormwater infiltration designs. The infiltration systems designed using conventional techniques, using individual design storms resulted in very promising results. An arch-shaped, open-bottom, corrugated bottom polypropylene tank was developed and the results of design and testing presented by Sharff et al. (2004). The purpose of the tank was to store stormwater and allow it to naturally infiltrate into the soil layer. Brander et al. (2004) modeled the impacts of development type on runoff volume and performance using modified NRCS methods. As expected, infiltration practices are most effective for small storms and in developments with Hydrologic Group A soils, although infiltration can be successful in all development types. Gobel et al. (2004) examined the effects of on-site stormwater infiltration on groundwater levels using three different computer models. It was found that both the precipitation and the infiltration rate are the factors most influencing the groundwater surface/level.

Dussaillant et al. (2004) used the Richards' equation to model stormwater flow through a rain garden. Water flow through the rain garden soil was modeled in three layers: a root zone, a middle storage layer of high conductivity, and a subsoil lower layer. The results showed that a rain garden with an area of about 10-20% of the contributing impervious area maximized groundwater recharge.

The potential of bioretention cells to remove petroleum products, metals and nutrients was modeled by Christianson et al. (2004). Laboratory studies will be performed to confirm the modeling results which showed the removals in each layer of the bioretention cell. Hunt and Jarrett (2004) examined two field bioretention areas in North Carolina for the removal of nitrate. Without an anaerobic/saturated zone, nitrate removal did not occur. The effects of the revised design on the removal of nitrate, total nitrogen, ammonia, TKN, total phosphorus, phosphate, Zn, Fe, Cu, Pb and TSS were still under evaluation. An overview of the Villanova Bio-infiltration traffic island was presented by Emerson and Traver (2004). Over the past three years, the site has infiltration 69% of the annual runoff in the 52%-impervious watershed.

Melloul and Wollman presented a qualitative hydrological and land-use planning tool for the Israel Coastal aquifer. This method assessed the lithological characteristics of the aquifer's vadose zone, indicating potential rechargeability, while weighting factors leading to potential groundwater pollution resulting from some land-uses. Pitt et al. (2003) investigated the ability of compacted urban soils to provide infiltration and the effects of the limited infiltration capability on biofiltration design.

Barber et al. (2003) studied an 'ecology ditch' (a modified infiltration trench composed of compost, sand and gravel with a perforated drain pipe) as a BMP. The peak delay time for larger storms was quantifiable since it depended on the saturated hydraulic conductivity and the distance of the flow path. For larger storms, the ecology ditch reduced peaks between 10 to 50%. Davis et al. (2003) investigated bioretention as a method of improving water quality based on the heavy metals Pb, Cu and Zn. Overall, excellent removal of dissolved heavy metals can be expected through bioretention infiltration. Although the accumulation of metals is a concern, buildup problems are not anticipated for more than 15



years because of the low metal concentrations expected in runoff.

Groffman and Crawford (2003) measured the denitrification potential in urban riparian zones and a suite of related microbial parameters (microbial biomass carbon [C] and N content, potential net N mineralization and nitrification, soil inorganic N pools) in four rural and four urban riparian zones in the Baltimore, MD metropolitan area. There were few differences between urban and rural and between herbaceous and forest riparian zones, but variability was much higher in urban than rural sites. There were strong positive relationships between soil moisture and organic matter content and denitrification potential. Herath et al. (2003) performed a simulation study of the impact of an infiltration facility on the hydrologic cycle of an urban catchment. Infiltration improved the water cycle because increased groundwater recharge and reduced flood flows. Infiltration facility installation options were assessed and changes to the urban water environment over a decade and its restoration potential were modeled.

Datry et al. (2003) investigated the solute dynamics in the bed sediments of a stormwater infiltration basin. Oxidation of organic carbon led to almost permanent anoxic conditions and resulted in the release of ammonium, phosphates and dissolved organic carbon during dry-weather periods. Hydrocarbons and heavy metals were rarely detected in pore water despite their high concentrations in the sediment. Holman-Dodds et al. (2003) described using relatively simple engineering tools to compare three basic development scenarios: an undeveloped landscape; a fully developed landscape using traditional, high impact storm water management; and a fully developed landscape using infiltration based, low impact design. The results showed that manipulating the layout of urbanized landscapes could reduce the impacts on the hydrology relative to traditional, fully connected storm water systems. However, the amount of reduction in impact is sensitive to both rainfall event size and soil texture.

The use of porous bituminous pavement for infiltration as a method to reduce the peak discharge and runoff volume into a receiving water was examined by Adams et al. (2001). In addition, this paper reviews the literature for infiltration meadows, trenches, swales, porous concrete sidewalks, bioretention gardens, etc. The design, installation, and performance of these methods at actual sites, "lessons learned," and the effectiveness of these infiltration methods were reviewed. Infiltration of stormwater in the southeast of France was studied by Bardin et al. (2001) at the Venissieux infiltration basin that drains a 380-ha industrial catchment. The study quantified the effects of the infiltration system in terms of pollutant transport in the groundwater system, including pollutant removal performance of the basin and the pretreatment devices. In-situ performance monitoring of an infiltration system that collected the runoff of a school roof and paved area was reported by Abbott and Comino-Mateos (2001). The resulting data was used to verify the typical design procedures for these infiltration systems. Govindaraju et al. (2001) investigated the difficulty of modeling infiltration through soils that had spatially varying saturated hydraulic conductivities, but which can be represented by a homogeneous correlated lognormal random field. The Green-Ampt equation described the infiltration at the local scale. Approximate expressions based on a series expansion and a parameterization of the local cumulative infiltration were also presented for describing the ensemble-averaged field-scale infiltration.

Gharabaghi et al. (2001) monitored the sediment removal efficiencies of vegetative filter strips. Fifty percent removal efficiencies were seen when the flow length was 2.44 m and were increased to 98% when the flowpath length was 20 m. However, small-sized particulates were not effectively removed in the grass strips. Improved removal efficiency of very-fine sediments was achieved through the installation of a drainage system (e.g. a French drain) to increase infiltration. Reinforcement of vegetation with various geosynthetic products reduced flow channelization and short-circuiting. Yu et al. (2001a) field tested grass swales in Virginia and Taiwan. Average pollutant removal efficiencies varied from 14 to 99% for total suspended solids (TSS), chemical oxygen demand (COD), total nitrogen (TN), and total phosphorus (TP). Water and sediment transport in grass swales and filter strips were modeled by Deletic (2001). The one-dimensional model simulated runoff generation and sediment transport. The modified Green - Ampt model was used for infiltration assessment, while a kinematic wave model was used for overland-flow simulation.

Limitations to vegetation establishment and abundance in biofiltration swales and other vegetated storm-water facilities that treat runoff were studied through field monitoring and greenhouse experimentation (Mazer and Ewing 2001). With adequate light, vegetation and organic litter biomass was strongly inversely related to the proportion of time that the bioswales are inundated above 2.5-cm depth during the driest time of year. For most bioswales, both flow velocity and hydraulic loading were too large for sedimentation of silt and clay particles, even with dense vegetation and abundant organic litter. A lack of correlation between vegetation abundance and pollutant removal was seen.

Ellis (1999) described the benefits and problems associated with directing roadway runoff to a roadside swale/infiltration

system. He summarized the range of pollutant removal efficiencies achieved by vegetative BMP and reviewed available design procedures for grass-lined swales and constructed wetlands for the United Kingdom. Gharabaghi et al. (1999) described how rolled erosion control products have proven to be successful in reinforcing vegetative channel lining systems and improving their performance in erosion and sediment control. Mendez et al. (1999) summarized the results from an 18-month field experiment that was conducted to evaluate the effectiveness of grass filter strips in removing sediment and various nitrogen species from runoff. They found that the grass filters reduced contaminant yields from 42 to 90% and concentrations from 20 to 83%, depending on length and nutrient species. Boubakari and Morgan (1999) tested the effectiveness of growing *Festuca ovina* and *Poa pratensis* on contour grass strips for erodible sandy loam soil on steep slopes. The *Poa pratensis* was less rigid and became flattened under submergence in the later part of the storms and was therefore not very effective in controlling erosion on the steepest slope tested (29%).

The effectiveness of grass strips in controlling highway-runoff contaminants was studied by Newberry and Yonge (1996). The largest portion of metals was found to be retained within the first 1 m of grass strip and 10 mm of depth, with 84% of the applied Zn, 93% of Pb, and >99% of Cd and Cu being retained by the grass strip. Pratt (1996) described recent research into design approaches for sizing of infiltration areas, illustrated the seasonal variability and difficulties in determining soil infiltration rates, and assessed the cost implications of alternative designs.

Bardin et al. (2002) reviewed the performance assessment using multiple indicators of stormwater infiltration devices. The purpose of these reviews was to evaluate the relevance and sustainability of several infiltration strategies.

Schaffner and Ostrowski (2002) describe the application of a combination of a surface collector flume that is connected to a subsurface infiltration trench. Application areas include impervious yards of single family or semi-detached houses, roof runoff, drainage of sidewalks and bicycle lanes, school yards and other public less polluted areas, pedestrian zones, and parking areas with low or medium traffic frequencies in domestic or small to medium size industrial areas. An infiltration system (permeable connection box, permeable underground pipe, permeable U-shaped and permeable pavement) has been installed in Japan for more than 20 years (Imbe et al., 2002). The paper presents the flood control results of the infiltration system based on observed data and runoff analysis using SHER (Similar Hydrological Element Response) Model.

Pitt et al. (2002a and, 2002b) reported on testing performed on the impact of compaction in urban soils on infiltration and bioretention designs. The results of these tests showed that infiltration rates are significantly affected by infiltration, even 20 years later. For sandy soils, infiltration rates were impacted by compaction and antecedent moisture conditions, whereas for clay soils, both infiltration and moisture condition were important in determining infiltration rates. The paper by Raimbault et al. (2002) addressed the temporal infiltration variability found in urban soils and on the evaluating the effect of soil drainage on infiltration capacity and consequently, on sizing retention structures. Akan (2002) proposed a design procedure for appropriately sizing stormwater infiltration structures based on the hydrological storage equation for an infiltration structure coupled with the Green and Ampt infiltration equation.

The paper by Dechesne et al. (2002) defines context indicators for assessing the present state of selected stormwater infiltration basins: a clogging indicator and a contamination indicator. An analysis of metals removal found that the metals were trapped in the top 30 cm of soil in the basin.

Ellis (2000b) addressed the potential conflict between the benefits of groundwater recharge of stormwater runoff versus the risks of long-term groundwater pollution in this paper. The long-term performance of a number of infiltration systems was reported in terms of their pollutant removal efficiencies, and the usefulness of an infiltration acceptability matrix approach was reviewed. Pitt et al. (2000a) presented a review of the literature available on the potential for groundwater contamination from the infiltration of stormwater runoff. The results on both the frequency and mobility of the potential contaminants was organized into a methodology that allowed evaluation of the potential contamination based on these two parameters. Part of this analysis included evaluation of the effects of infiltration on pollutant removal from the percolating water.

Nakazato (2000) presented a manual developed by the Japan Institute of Wastewater Engineering Technology on the technical issues faced by infiltration facilities. The objective of the manual was to clarify the definition of these facilities for stormwater management planning, and to promote the use of these facilities throughout Japan. The manual covers all phases of infiltration facilities through siting, design, installation and maintenance.

Morris and Stormont (2000) showed that near-surface processes such as precipitation, runoff, snowmelt and

evapotranspiration have a significant impact on moisture movement in soils, and that models must include these near-surface processes. Pitt and Lantrip (2000) examined the effects of urbanization on soil compaction and resulting infiltration capacity through a series of double-ring infiltrometer tests. They found that sand was mostly affected by compaction, with little change due to soil-water content levels. However, the clay sites were affected by a strong interaction of compaction and soil-water content. The fit of the data to the Horton equation was inconclusive, indicating that when modeling runoff from most urban soils, assuming relatively constant infiltration rates throughout an event, and using Monte Carlo procedures to describe the observed random variations about the predicted mean value may provide the best results. Pitt, et al. (2000b) argued that if the traditional design equations were going to be used to predict infiltration, local data must be obtained and used.

Reemtsma et al. (2000a), in their study on the infiltration of combined sewer overflows versus tertiary-treated municipal wastewater, found that, when looking dissolved organic compounds, the groundwater quality that results from infiltration of CSOs is comparable to or better than the quality after infiltration of tertiary-treated municipal wastewater. However, the nutrient quality of the CSO water was worse compared to the tertiary-treated municipal wastewater after infiltration of both. Desorption of both nutrients and organics previously adsorbed was seen to be a potential problem of long-term infiltration. They also investigated the metals content of infiltration water from these two sources and the retention of these metals in the soil profile (Reemtsma et al. 2000b). They found that the metals were effectively retained during passage through the soil; however, additional alkalinity was needed to buffer the acidity caused by bacterial nitrification and mineralization, since soil acidification likely would result in both a reduction in efficiency of metals removal and a potential release of previously-trapped metals. Singh et al. (2000) investigated the potential for metals release from dredged-sediment-derived surface soils in the Netherlands. The authors found that runoff rates and sediment yields were highest for a silt loam sediment. The metals content of both the runoff and percolating water was greater than the standards for groundwater quality and very high metal fluxes were observed for the recently-oxidized dredged sediment. Metals transport per unit surface area was found to be two to twenty times greater for the percolating water when compared to the runoff water.

Backstrom and Bergstrom (2000) investigated the impact that snowmelt and temporary freezing conditions would have on the infiltration capacity of porous asphalts. Their results showed that alternate freezing and thawing conditions (similar to times of snowmelt) would reduce the infiltration capacity of the asphalt by 90% to a level of approximately 1 - 5 mm/min. Westerstrom and Singh (2000) investigated the infiltration of snowmelt runoff in Lulea, Sweden, and found that unlike rainfall infiltration, the snowmelt infiltration resembled a flow hydrograph, i.e., there was a distinctive rise, peak and recession to the graph. Unlike the relationship for rainfall and infiltration which is decidedly non-linear, a strong linear relationship between the snowmelt runoff hydrograph peak and the amount of snowmelt was found.

The use of filtration media for stormwater runoff treatment was investigated by several groups of authors. Brown (2000) investigated the potential for using kudzu to remove heavy metals from dilute aqueous streams, such as stormwater runoff. Kudzu was found to be an effective adsorber for heavy metals, and while its capacity was lower than that of commercial-grade resins, it was also cheaper than the resins. The application of kudzu to stormwater runoff was found to be particularly attractive both because of the cost and because of the potential problem of premature fouling of an expensive resin. Clark et al. (2000) investigated the potential of using low-cost adsorbents, such as peat moss and municipal leaf compost, to treat dilute aqueous wastestreams of copper such as stormwater runoff. The capacity of these adsorbents was compared to the capacities of other well-known adsorbents, such as activated carbon, bone char and cation-exchange resins. The low-cost adsorbents had removal capacities of approximately 20 - 30 mg Cu/g media. While these capacities were less than those of the bone char and resin (approximately 90 mg Cu/g), their cost was significantly less, and they demonstrated a robustness for dealing with the intermittent flow and potential interferences of stormwater runoff.

The behavior of heavy metals (Cd, Cu, Zn, Cr, Pb), nutrients (organic C, P, and N parameters), and major ions were investigated during percolation of roof runoff water through an artificial infiltration site. The concentrations of various components were determined in rainwater, roof runoff, and infiltrating water at various depths in the soil (Mason et al., 1999). Permeable surfaces for roads and footpaths have been used as a means of disposal of stormwater in developed urban areas. Such surfaces provide an alternative to impermeable concrete or tarmacadam surfaces which would otherwise produce rapid stormwater runoff leading to possible flooding and degeneration of receiving water quality through the uncontrolled discharge of polluted urban waters. A further advantage may be obtained from such constructions by undersealing them so as to retain stormwater for reuse for non-potable uses (Pratt, 1999).

Given the characteristics of urban surfaces, and notably the amounts of the different pollutants that stormwater was likely to contain, an experiment was carried out in Valence (France) on two infiltration facilities, in order to assess the impact of intentional stormwater infiltration systems on the soil, and on groundwater. Stormwater from impervious urban areas can adversely impact water quality and quantity. The PET was a control device designed to moderate both the quality and quantity of urban runoff (Li et al., 1999). Urban stormwater often contains high levels of traffic-generated metal elements and particulates. These constituents were transported by stormwater runoff to surficial soils, drainage systems and receiving waters; Sansalone (1999) summarized the in-situ field-scale performance of a passive treatment system called a PET for source control of these constituents. Two infiltration trenches were constructed in a densely built-up area in central Copenhagen and equipped with on-line sensors measuring rain, runoff flow from the connected surfaces and water level in the trenches. Warnaars et al. (1999) described the field site, the measuring system and the results from an initial soil survey. There were numerous reasons, such the saturation of the existing downstream sewer system or its concentrate discharge impact on the receiving water, for using stormwater infiltration systems. However, their feasibility within an urban development project depends on physical soil characteristics and contamination risk, and also on socio-economic considerations (Alfakih et al., 1999).

Sediment transport was studied in non-submerged overland flow over grass in a laboratory. Artificial turf (astro-turf) was used to simulate natural grass and no infiltration was allowed at this stage of the investigation. Experiments were conducted for different grass densities, flow rates, sediment inflows, and sediment types (Delectic 1999).

Utilization of parking lots around Hattiesburg, Mississippi was examined to suggest mechanisms for reducing runoff into local streams (Albanese and Matlack, 1999). Suarman et al. (1999) reported a laboratory simulation study, supplemented with information from field installations, in which four paving sub-structures were subjected to sediment loads equivalent to those which could be expected below porous car park surfaces in stable, fully-developed residential neighborhoods in Adelaide, South Australia. Brough (1999) outlined the development philosophy behind the use of ground soakage (construction of soil adsorption basins), and discusses the procedures that have been used in the design of the basins at residential, industrial sites.

Peak flow reduction and aquifer recharge. Infiltration devices were installed in existing housing areas as a means of reducing the peak flow in a combined sewer system. The resulting economic benefits of the retrofit, especially as compared to the installation of a new sewer, were discussed by Simon and Terfuchte (1999). Watts et al. (1999) reported on the utilization of infiltration and groundwater recharge as part of an overall management strategy for Christchurch, New Zealand's waterways and wetlands. The infiltration devices used in the Upper Heathcote catchment included a separate infiltration system for roof drainage, grass swales for non-roof stormwater runoff, infiltration basins and storage of excess runoff for later infiltration. Flood control was also suggested as another benefit of planned infiltration. Yura et al. (1999) demonstrated the effects of a well-maintained infiltration facility on the volume of stormwater runoff from a large-scale housing site. In addition to flood control, the infiltration basin also had other positive effects: groundwater recharge, emergency water storage, and the control of pollutants in stormwater. Oka and Nakamura (1999) used a kinematic wave model in combination with GIS data to demonstrate basin scale effects of storm and infiltration on flood control. Rauch et al. (1999) evaluated an integrated drainage system and simple deterministic models for modeling this system in an Alpine area. The results revealed that the simple models worked well for simulating the system over a long period of time, and that infiltration was recommended, especially when compared to conventional detention ponds. Nawang et al. (1999) compared 1-D nonlinear PDE model results for water level profiles, outflow and stormwater profiles with laboratory investigations. The results were used to development infiltration design practices for tropical conditions, specifically for Malaysia.

Investigations by van der Werf et al. (1999) in Adelaide, South Australia, demonstrated that infiltration of roof runoff could occur through clay soils overlying a shallow sandstone bedrock even when the cumulative rainfall was significantly greater than the average annual rainfall. Barros et al. (1999) tested the same premise under laboratory conditions using laboratory columns with a shallow bedrock base, an intermediate soil layer (sandy loam and a silty clay loam) and a stone cover layer. The infiltration capacity of the soil layer was found to control the fraction of rainfall that becomes surface runoff. Pitt et al. (1999) investigated the effects of soil type, antecedent moisture content, and soil compaction on the infiltration rates of water. Compaction had the greatest effect on infiltration through sandy soils, while moisture content and compaction affected infiltration through clayey soils. Age since development tests showed that some infiltration capacity could be recovered over time even in severely compacted soils. King et al. (1999), using the Soil and Water Assessment Tool (SWAT) model, compared the Green-Ampt Mein-Larson (GAML) method with the SCS daily curve number (CN) for their abilities to predict runoff volume from the Goodwin Creek watershed. For this large watershed, the

curve number method generally underpredicted surface runoff volumes, while no pattern of over- or under prediction was seen with the GAML method. Yu's (1999) comparison of the Green-Ampt model and a spatially variable infiltration model showed that the Green-Ampt model consistently underestimated the infiltration rate when the rainfall intensity was high. The measured rainfall and runoff rates showed a positive relationship between intensity and infiltration rate, indicating a spatial variability in the infiltration capacity and making the spatially variable model a better predictor of infiltration rates.

Infiltration installations for pollutant removal. Pagotto et al. (1999) reviewed the information currently available regarding the ability of infiltration systems to remove pollutants from water, and including the various physical, chemical, biological and microbiological processes that occur in the unsaturated and saturated zones of the soil profile. Barraud et al. (1999) investigated the impacts on the soil and groundwater of two infiltration facilities, a new cylindrical soakaway and a thirty-year old rectangular chamber, used for treating urban stormwater runoff on the soil and groundwater in Valence, France. The study addressed the impacts of the pollutants contained in the runoff on the performance of these infiltration facilities as well as on the groundwater. A similar study on highway runoff was performed in Germany by Dierkes and Geiger (1999). They tested soil profiles and collected water samples at different soil depths for lead, zinc, copper, cadmium and PAH and found that the highest concentrations were found in the top 5 cm of soil and within two meters of the street.

Dupre et al. (1999) used ultrafiltration at different pHs to investigate the affinity of certain metal ions to form humate complexes in natural waters with a high dissolved organic carbon concentration. The log K constants for sorption to organic colloids (metal-humate complexes) were as follows: Al, Ga, Fe, Th, U, Y, Re (more than 7) >> Cr (5.5) >> Co (3) > Rb, Ba, Sr, Mn, Mg (approximately 2). The tendency of these metals to bind to organic colloids in water should be similar to their ability to bind to organic soils in the vadose zone during infiltration or to organic filtration media in a stormwater filter. Pitt et al. (1999) described adding compost to the natural soil in an infiltration system to improve both the flow and pollutant removal characteristics of the system. When compared to a natural soil infiltration area, the compost-amended soil system significantly increased the removal of both the quantity of surface runoff and the concentrations of many toxicants typically found in urban runoff. The drawback to the compost amendments was the increased nutrient loads in the system effluent. King and Balogh (1999) modeled the runoff losses of nitrates and pesticides from a golf course turfgrass using four irrigation schemes: normal and reduced water application using potable water and normal and reduced water application using reclaimed water. They showed that nitrate losses were significantly affected by the reduction in irrigation water volume, although the pesticides losses were not significant between irrigation strategies. Sansalone (1999) proposed using an oxide-coated sand in a PET to treat urban runoff. Sansalone and Hird (1999) investigated the one-year performance of the partial exfiltration reactor (PER) in removing heavy metals from highway runoff. The tested prototype was able to infiltrate 10 to 30% of the highway runoff while removing at least 75% of the heavy metal load from the stormwater. Hebrard and Delolme (1999) demonstrated that a biofilm of *Pseudomonas putida* on sand could significantly enhance zinc removal from runoff percolating through the vadose zone when the influent concentration ranged from 2 – 20 ppm.

The reservoir structure technique (used in streets and parking lots for infiltration) has been developed in Fr. and is used in Bordeaux to reduce flooding risks and to protect receiving water (Raimbault, 1998). The first function enables the construction of the structure to withstand various types of loads and the second temporarily retains rain, thereby reducing runoff and improving the quality of discharged water. The urban community of Lyons, Fr. uses infiltration facilities for urban drainage. Chocat et al. (1998) presented information on the rehabilitation of old infiltration pits and a study of an infiltration basin. 'Ruwenbos', a small housing estate in the western part of the city of Enschede in the eastern part of Neth., bounded by the German border, was the first project in Neth. where stormwater infiltration was applied on a large scale (Bruins, 1998). Stormwater of all the roofs and most of the streets is transported overland to wadis ('Wadi' is the Arabic word for dry riverbed) where it percolates through the soil. A case history described how stormwater management is carried out in Hillerød, Den. (Sulsbrück et al., 1998). The existing sewer system was enlarged with retention basins and detention ponds and urban storm infiltration has been expanded. The sizing and dimensions for the disconnection of sewer impervious areas to reduce the overflow frequency and hydraulic load of both combined and improved separate sewer systems was explained. The effect of a discharge drain at the bottom of a percolation trench was also investigated and it appeared that, compared to a facility without a drain, the required dimensions of a facility with a drain decrease significantly. (Leefflang et al., 1998).

Infiltrating stormwater locally into the ground instead of discharging to conventional sewers has been used increasingly as a means of controlling urban-stormwater runoff; however, much research is still required, including development of

methodologies for determining the design parameters based on local conditions, technologies for soil-clogging prevention, and a simplistic model for assessing the impact on soil and groundwater in local areas (Mikkelsen *et al.*, 1997).

Oka (1996) examined a gravel-storage infiltration method to control urban storm runoff. The gravel layer was inserted in the underground that had been covered with impervious faces, such as buildings and pavements. This method was shown to be more effective for decreasing flood discharges in the urbanized areas than the pipe infiltration method.

**Design and maintenance guidelines.** Hamacher and Haubmann (1999) compared infiltration as part of a decentral stormwater discharge program to the more traditional method of rapid removal of stormwater from an area through a planned drainage system. They provided information in the article about stormwater disposal through infiltration, including construction, maintenance and system costs. In Stockholm, infiltration was included as part of an overall stormwater drainage plan. Bennerstedt (1999) reported on the Stockholm plans, including the financing of the stormwater drainage system. Hasegawa *et al.* (1999) described the data collected during the installation of infiltration systems in Japan and that collected by seven governmental entities on the performance of existing infiltration systems. They also proposed a qualitative method for evaluating the applicability of infiltration for flood control and environmental protection. Argue (1999) described many of the misconceptions about stormwater infiltration systems and proposed design limits and practical advice for dealing with these concerns. Noki *et al.* (1999) outline some of the current research on infiltration and their application to establishing proper maintenance procedures.

Alfakih *et al.* (1999) described how siting of infiltration facilities was dependent on physical soil characteristics, groundwater contamination risk, and socio-economic considerations. Their paper provided an overview of feasibility and design criteria for infiltration systems, including a review of currently available models and approaches. Zimmer *et al.* (1999) argued for the use of physically based models to design infiltration systems, rather than the traditional approach of using a design storm to calculate the required storage volume. They developed diagrams which allowed the designer to read the necessary storage volume for the infiltration system once the soil's hydraulic conductivity was known. Gautier *et al.* (1999) reported on the progressive clogging of three infiltration facilities and used the results to develop a model for predicting the effect of clogging on the hydraulic behavior and pollutant removal ability of the basins. Todorovic *et al.* (1999) also evaluated the impact of clogging on the hydraulic performance of infiltration basins over time. They successfully tested their methodology for sizing an infiltration trench/soakaway for the Miljakovac catchment in Belgrade. Laboratory testing using a simulated colloidal suspension was performed by Raimbault *et al.* (1999) and showed that clogging began with the application of only a small amount of clay. The wetting-drying cycle typically seen in infiltration basins increased the amount of clay retained in the upper layers of a soil and decreased its hydraulic conductivity.

### **Porous Pavement**

Frentress (2006) reviewed a pervious Portland-cement pavement project that has been designed to accommodate long-term monitoring. Hou *et al.* (2006b) evaluated three porous pavement systems to determine their abilities to infiltration rainfall. The relationship between rainfall intensity, outflow, and outflow duration were analyzed.

Haselbach (2006) examined the vertical porosity distribution in pervious concrete pavement. The vertical variation in porosity impacted the strength distribution and permeability of the system. Haselbach *et al.* (2006) presented a method for predicting the permeability of sand-clogged Portland-cement pervious concrete systems. The experimental results correlated well with the model results for systems fully covered with sand. Montes and Haselbach (2006) described measuring hydraulic conductivity in pervious concrete. A quantitative relationship between porosity and hydraulic conductivity was established based on the Carman-Kozeny equation. Valavala *et al.* (2006) provided area-rated Rational coefficients for Portland cement pervious concrete pavement.

Permeable concrete blocks have been subject to clogging by street dust and dirt (James 2004). Testing determined the rates of permeable pavement clogging using synthetic urban runoff.

Abbott and Comino Mateos (2003) investigated the in-situ hydraulic performance and effectiveness of a permeable pavement system for managing parking lot stormwater runoff in the United Kingdom. The peak flows were reduced and the outflow duration from the system was increased compared to the rain events. Clogging was beginning to affect the permeability of the bricks and the gaps between bricks. Brattebo and Booth (2003) investigated the long-term quantity and quality of stormwater runoff in four permeable pavement systems after 6 years of daily parking usage. Virtually all rainwater infiltrated through the permeable pavements, with almost no surface runoff. The infiltrated water had

significantly lower levels of copper and zinc than the direct surface runoff from the asphalt area.

Brown (2003) reviewed the use of porous asphalt in Portland, OR as a method for managing stormwater. Porous asphalt was used to build a business driveway, and to date, the driveway has worked very well. James and Gerrits (2003) reviewed the required maintenance for interlocking concrete pavers with external drainage cells (EDC) that were designed to increase infiltration. Results indicated that the infiltration capacity decreased with increasing average daily traffic counts, and as the amount of organic matter and fine matter in the EDC material increased. Smith (2003) reviewed the current state of the art regarding permeable interlocking concrete pavers.

Knapton et al. (2002) reported on the design of permeable pavements surfaced with pavers as part of sustainable urban drainage systems (SUDs) planning. Hunt et al. (2002) tested two types of permeable pavements for runoff reduction. The block pavers (with an approximately 40% open space overlying a bedding layer of sand and washed marl) were found to provide runoff coefficients of 0.2 to 0.5. A 150-mm thick porous concrete installation was just beginning testing. A new cleaning device for permeable pavements is reported on by Dierkes et al. (2002). The results of the testing of the device showed that cleaning of the pavements to recover infiltration capacity is possible, especially if they are designed, constructed and maintained carefully.

James and James (2000) advocated the use of permeable pavement to reduce the impacts of the thermal pollution of receiving waters associated with urban stormwater runoff. They discuss the required design criteria for an acceptable permeable pavement, including long-term performance. Laboratory studies indicated that infiltrating pavements reduced both the flow and contaminant load of runoff to the greatest degree, although asphalt provided the least buffering capacity for acid rainwater and also the least contaminant removal.

Conventional asphalt and porous asphalt were investigated by Pagotto et al. (2000) for their impacts on both runoff quantity and quality. It was found that, compared to the conventional asphalt, porous asphalt attenuated peak flow and mitigated splashing. The porous pavement also retained particulate pollutants by acting as a filter.

According to Anderson et al. (1999), permeable pavements and similar stormwater control devices have not been exploited in the United Kingdom, in part because their adoption has been hindered by a lack of detailed knowledge of their hydrological performance. A range of simulated rainfalls, which varied in intensity and duration, was applied to the permeable model car park surfaces and monitored over an 18-month period. Results demonstrated that evaporation, drainage and retention in the structures were strongly influenced by the particle size distribution of the bedding material and by water retention in the surface blocks.

In order to develop design guidelines for using permeable pavements in parking lots, Andersen et al. (1999) investigated the pavement's hydrological/hydraulic behavior and its impact on evaporation and drainage during a range of simulated rain events and interevent periods. They determined that, for a one-hour, 15-mm simulated rainfall, an initially dry pavement could contain and infiltrate approximately 55% of the water, while an initially wet structure could retain approximately 30%. The ability to infiltrate significant quantities of runoff, especially as compared to asphalt, was confirmed by Booth and Leavitt (1999) in an experimental facility. Pratt (1999) reviewed existing information on water quantity and quality below porous pavement structures and suggested collecting the water that infiltrates through porous pavement structures for use in non-potable applications such as flushing toilets. The reuse of infiltration water below a porous pavement structure was applied at a Youth Hostel in the United Kingdom and details of the design were provided in the article.

Bond et al. (1999) reported on a 13-year study of permeable pavements in the United Kingdom. They found that microbial degradation of pollutants occurred in the pavement and that the addition of nutrients every three years was sufficient to support the microbial population. The retention ability of a 50-year old porous pavement structure and the soil below was investigated by Legret et al. (1999) and was modeled by LEACHM. Lead, copper, and zinc were not found in significant quantities in the soil below the pavement, i.e., surface retention of those metals, while cadmium was found to have migrated to a depth of 30 cm below the pavement.

Porous pavement was found to reduce storm-runoff-pollutant loadings significantly by Legret *et al.* (1996) at an experimental site that monitored about 30-rainfall events over four years. Influent-pollutant concentrations of SS were reduced by 64% and 79% for Pb.

## **Grass Swales**

Deletic and Fletcher (2006) examined grass filters for stormwater treatment using both field testing and models. The selected model, TRAVA, was able to reproduce within the desired range the removal of sediment in the grass filter. Nara and Pitt (2006) investigated sediment transport in grass swales. Depth of flow and swale length affected the transport of particles of different sizes. Equilibrium concentrations for different particle sizes appeared to be reached, below which no further removal will occur. Abida and Sabourin (2006) presented a combination grass-swale-and-perforated-pipe system for stormwater management. This design allows for curbless developments, encourages infiltration at rates consistent with the literature, and is smaller than conventional piped stormwater systems.

Backstrom (2003) investigated grassed swales for stormwater pollution control during rain and snowmelt in the Lulea region, Northern Sweden. The results showed that grassed swales even out the peaks in pollutant loads without producing consistent high removal rates. Possible design parameters for grassed swales included mean hydraulic detention time, surface loading rate or specific swale area.

Fletcher et al. (2002) reported on the results of controlled experiments on vegetated swales using in urban water design. Reductions in TSS concentration ranged from 73% to 94%, 44 to 57% reduction for TN and 58 to 72% for TP. Reductions in load ranged from 57 – 88% for TSS, 40 – 72% for TN and 12 – 67% for TP. Treatment performance decreased, especially for TSS, with an increased in flow rates. The k-C\* model has been developed to mimic the swale performance using a first-order decay equation. Backstrom (2002) measured particle trapping in nine different grassed swales using a standardized runoff event simulation procedure and found that the removal percentage for total suspended solids ranged between 79 and 98%. High infiltration rates improved particle trapping and longer swales led to increased capture of smaller particles. Mean swale residence time was suggested as a design parameter for grass swales.

De Souza et al. (2002) presented an experimental and numerical study of infiltration trenches for urban runoff control. The Bouwer model was used to represent the hydraulic functioning of the trenches. Management tools for specification of vegetative filter strips during site design is presented by Gharabaghi et al. (2002). These tools are based on site-specific soil, land use, land management and topography of the upland area. Performance of vegetative filter strips was also monitored under different flow conditions, pollutant loads and vegetation cover.

Hsieh and Davis (2002) investigated the use of engineered bioretention for urban stormwater runoff treatment. A variety of potential bioretention media were examined and the results showed that every media had excellent removal efficiencies (> 98%) for suspended solids, oil/grease, and lead. Total P removals ranged from 47 to 85%, increasing as the sand ratio in the media increased. Ammonia and nitrate removals ranged from 2 to 26% and 1 to 27%, respectively.

## ***Detention/Retention Ponds***

### **General**

Liaw et al. (2006a) assessed flood mitigation alternatives in Taipei, Taiwan. The results revealed that runoff detention facilities in the upper and middle parts of the watershed would be most effective in reducing downstream flooding. Liaw et al. (2006b) discussed the hydrology and storage capacity of detention facilities in Taiwan. The procedures developed can produce designs to maintain both pre-development flood peak and volume. Budhu and Bermudez (2006) reported on the concerns associated with the existing stormwater drainage system in Florida and the impact of the maintenance of this drainage system on land-locked ponds.

Goff and Gentry (2006) described the influence of watershed and development characteristics on the cumulative ability of stormwater detention ponds to control peak discharges. Watershed shape, age of development in the watershed and sequence of development had the greatest effect on the cumulative impacts of the ponds. Hong et al. (2006c) proposed simplified methods for evaluating detention storage volume in a small catchment. The results were then incorporated into a model for detention pond design. Sabadox (2006) reviewed the use of an underground detention facility at a big-box retailer to store and treat both parking lot runoff and runoff from the adjacent highway. Mourad et al. (2006) discussed the design of a retention tank using stormwater quality models with varying levels of complexity. Modeling results were highly sensitive to the input experimental data.

Kazemi-Yazdi and Scholz (2006) performed a design comparison of detention systems treating road runoff and included the evaluation of several additions to the pond design. The results showed that these additions – sand, gravel, Ecosoil, turf – provided no additional water quality benefits after sedimentation. Semadeni-Davies (2006) evaluated the winter



performance of a Swedish urban stormwater pond. A seasonal comparison of the removal efficiencies showed that removal of Cd and Cu was about the same for summer and winter-spring, but removal of Pb, Zn and TSS dropped from the summer to the winter.

Pyatt and Li (2006) monitored the performance of a constructed sediment pond in Ontario, Canada. The pond removed suspended solids to a large degree, but some events did have high concentrations leaving the sediment pond.

Sanders et al. (2006) investigated active and passive controls of diversion structures to an off-line reservoir for flood stage reduction. The lead time of flood forecasts appeared compatible with the lead time necessary to optimize diversions, and decision support systems should compensate for forecast uncertainties by early gate action. Xiao et al. (2006b) examined the interaction of micro- and macro-organics on the biogeochemical function of the sediment-water interface in stormwater infiltration basins. Invertebrate presence in the sediments affected the water quality results. Weiss et al. (2006) modeling heavy metal removal by plants and sediments in stormwater detention ponds. A first-order kinetic model adequately represented the removal of contaminants by plants. Strong stratification of metals in sediment was observed.

Hunt et al. (2006a) measured the occurrence and relative abundance of mosquitoes in stormwater retention facilities in North Carolina. A significant association between the presence of mosquito larvae or pupae and the absence of mosquitofish was found for innovative and wetland stormwater retention facilities but not for standard retention facilities.

Because of the presence of sinkholes and risk of sinkhole formation, the stormwater treatment ponds draining the interstate in a karst region of Maryland had special design criteria (Kutschke et al. 2005). The pond and drainage swales had to be lined with a geosynthetic membrane and a force main is required to discharge stormwater to the receiving water. The effectiveness of unrelated detention basins in a watershed to mitigate runoff peak flow rates was investigated by Emerson et al. (2005). The results showed that peak flow reduction on the watershed scale was minimal and that runoff-volume-based management was the most effective means of reducing peak flow rates at the watershed outlet. Long-term modeling of pollutant removal in stormwater retention basins was performed by Larsen et al. (2005). The authors applied this method to the simulation of pollutant discharges from CSOs with a connected retention basin.

Fortunato et al. (2005) compared dry and wet detention basins for their ability to remove sediments and nutrients. Dry detention basins were less effective than wet basins at reducing sediment and nutrient concentrations from their influent runoff. Mascarenhas et al. (2005) discussed the potential use of on-site stormwater detention tanks as a means of controlling flooding in ultra-urban areas. The modeling presented in this paper compared different hydraulic design criteria and different patterns of spatial arrangements of these tanks. With the right spacing and design criteria, these tanks may be effective in reducing the flooding risk in many areas. A regional stormwater wet pond/wetland was implemented in Berlin, New Jersey (Dauber and Balzano 2005). The regional approach was selected in order to preserve land in the development zone for development rather than for a stormwater treatment practice.

Hossain et al. (2005) investigated the TSS and metal removal efficiency of a wet detention pond treating highway runoff. The pond's flow regime was found to vary with its changing surface topography, which is due to sedimentation of suspended solids. Durand et al. (2005) characterized the complex organic matter present in the sediment of retention ponds draining urban and road areas. The authors separated and identified several fractions of the organic matter typically classified as lipids and humic-like substances. Scher and Thiery (2005) evaluated the impact of stormwater retention ponds receiving highway runoff on pollutant capture and biodiversity. Copper and zinc were elevated in the upper sediment layer and herbicides were found in the water column. Dragonfly richness was higher in ponds with a natural, rather than artificial, bottom, while amphibian richness was more sensitive to the surrounding landscape.

Sorge (2005) discussed how to design a smart pond. The techniques to constructing a well-designed pond include nutrient removal, mechanical raking, over-winter drawdown and biomanipulation. Storage volume for stormwater generated by hurricanes was discussed by Anonymous (2005g). The proposed system optimized a combination of holding pipes and tanks, and pipe-fed cell systems. Yurdusev et al. (2005) assessed retention basin volume and outlet capacity in urban stormwater drainage systems with respect to water quality. The study analyzed the effect of concentration time on surface water pollution. A linear S-curve was assumed for the flow hydrograph in the collection system. Starzec et al. (2005) studied detention ponds in Sweden that were treating highway runoff. The study showed that the pollutant retention capacity of many of the ponds was not optimal. Maintenance was shown to be crucial to the functioning of the pond. The use of a Precast box stormwater vault as an alternative to stormwater detention ponds was discussed by Hite and

Pirrello (2005). The addition of a sand media filter improved its treatment performance.

The performance of retention ponds based on data in the international Stormwater BMP database was presented by Barrett (2004). Some of the variability in performance observed for facilities of a specific type can be explained by differences in design and/or watershed characteristics; consequently, the expected performance for a given set of conditions can be predicted more accurately. Wang et al. (2004) modeled the flow and pollutant removal of a stormwater wet detention pond. The pollutant removal and flow routing models were tested with data obtained from an actual wet pond for treating highway runoff, with the model agreeing well with the observed data.

The spatial distribution of pollutant concentrations in a stormwater infiltration basin was investigated by Dechesne et al. (2004). Pollutant concentrations decrease rapidly with depth below the basin while pH, mineralization and grain size increase. Sustainable metal concentrations were reached at a 30-cm depth, even after 14 years of operation; hydrocarbon pollution was deeper. Durand et al. (2004) characterized the sludge from a retention pond and an infiltration pond in France. The main components in the organic fraction of the sludge were petroleum-derived products such as diesel fuel and motor oil. Graney and Eriksen (2004) analyzed the sediment collected from an urban stormwater retention pond in New York State for its metals concentration. Concentrations of Zn, Pb, Ni, Cu, Cr, Cd and As were elevated in the retention pond sediments when compared to sediment from rural retention ponds. Pb deposition within retention pond sediment temporally mimicked the rise and fall of leaded gasoline.

Ortell (2004) presented the upgrading of the Belhar (Cape Town, South Africa) stormwater system. The results of a modeling analysis prompted the selection of a dry pond as a pollution- and flood-mitigating measure.

England and Royal (2003) discussed the use of baffle boxes for stormwater treatment in Florida. Autosampler monitoring results for TSS, Total Phosphorus, COD, and BOD removal efficiencies were presented. In addition, the effectiveness of two baffle boxes in series was examined. Anonymous (2003d) reviewed the Highland, IN plans to install an underground water retention system (Storm Compressor™) of corrugated HDPE to handle flooding problems.

German (2003) investigated the performance of retention ponds and street sweeping as methods for reducing stormwater pollution. A correlation between pollutant concentrations in the water and in sediments was found, which indicated that pond sediments could be used for characterizing pollutant loads from urban catchments. The efficiency of street sweeping was also investigated by measuring the amount of removed sediment and heavy metals. German et al. (2003) modeled the performance of stormwater ponds under winter conditions. The most important effect of winter conditions was the changed hydrology due to snowpack and snowmelt interactions. Lower removal efficiencies were seen compared to non-winter conditions. For dissolved oxygen, wind is an important factor.

Wakelin et al. (2003) assessed the water quality in stormwater retention basins in Winnipeg, Canada. Results showed that increases in TSS and turbidity resulted from increased chlorophyll a concentrations associated with algal growth. TKN increases partly resulted in nitrogen incorporation into proteinaceous material in the algal cells. Ammonia concentrations showed a maximum attributed to chemoheterotrophic degradation of dead biomass. Orthophosphate made up 30% to 50% of the total phosphorus present. Temperature increased and then decreased over the summer months with no apparent thermal stratification.

To reduce flooding, the City of Austin, Texas initiated a watershed-based program to use regional stormwater detention facilities (Altman and Nuccitelli, 2001). The new program provided an alternative to using only on-site detention facilities. In addition, the City wanted to develop multi-objective facilities for recreation, water quality, flood-tolerant commercial uses, and/or other benefits. Dechesne et al. (2001) evaluated the long-term performance of infiltration basins by modeling their structural and environmental evolution through a LCA (Life Cycle Assessment) point of view. Sustainable infiltration basins were found to have good economic performance. Alternative configurations of detention ponds and land management plans have been generated using a genetic algorithm (GA)-based method to meet target pollutant removal levels at a relatively low cost (Harrell 2001). The GA-based method has been extended to incorporate reliability estimation into the evaluation of solutions in order to determine cost-effective pond configurations and land management plans to achieve a specified reliability level.

Barbosa and Hvitved-Jacobsen (2001) suggested a method for design and evaluation of the design of infiltration ponds for treating highway runoff in semiarid climates. The design was based on capture and infiltration of the most polluted runoff and accounted for the rainfall and soil hydraulic characteristics in the determination of the design volume. Seasonal

variations in rainfall and evaporation were considered. Soil characteristics (hydraulic conductivity, texture, pH, and cation exchange capacity), the infiltrated volume, and the infiltrated area were used to calculate the movement of the most mobile heavy metal, Zn, in the soil below the basin. In Dubai, United Arab Emirates, high groundwater levels restrict the amount of infiltration that is permissible and influence the design of the ponds (wet versus dry) (Darnell et al., 2001b). Design criteria specific to Dubai were established to maximize the efficiency of systems that incorporate the use of detention ponds. The criteria included minimum storage pond volumes, clear times, pond geometry, water depth, the use of linings, and alternative land uses. The first pond constructed using the design criteria is now in operation collecting runoff and excess groundwater flows.

For more than a decade, the Queen's University/National Water Research Institute Stormwater Quality Enhancement Group studied stormwater ponds with a fully instrumented on-line system in Kingston, Ontario, Canada as a representative field installation (Anderson et al., 2001). The Group concluded that a number of identifiable factors will significantly influence the success, failure and sustainability of these ponds. These factors included initial design, operation and maintenance, performance and adaptive design. Guo and Hughes (2001) presented a risk-based approach for designing infiltration basins with design parameters of basin storage volume, drain time, and overflow risk. The risk-based approach provided an algorithm to calculate the long-term runoff capture percentage for a basin size. The diminishing return on runoff capture percentage would serve as a basis to select the proper basin storage volume at the site.

Cosgrove and Bergstrom (2001) reviewed the new policies and proposed regulations in New Jersey that require that no increase in stormwater pollutant loads from proposed residential and commercial developments. The authors reviewed the use of a bioretention basin as an advanced BMP that can achieve very high levels of pollutant removal. The bioretention basin would manage and treat stormwater runoff using a conditioned planting soil bed and planting materials to filter runoff captured by a collection system and transmitted to the basin. Fennessey et al. (2001) used a continuous simulation stormwater management model (with 33 years of historical precipitation) to determine how the design criteria from five different stormwater management pond ordinances changed the runoff from a 7.77 ha watershed after hypothetical development. All five ordinances required that the postdevelopment runoff rates be less than or equal to the predevelopment runoff rates for each return period. None of the five ordinances limited the increase in runoff peak rates for the 1- and 2-year return periods. This indicated that the lower frequency runoff events should always be analyzed for a basin's design.

The objective of the study by Jacopin et al. (2001) was to develop new operational management practices for detention basins in order to limit flooding risk and to reduce pollutant discharges through optimizing the settling process. Current basin operation and "on/off" regulation studies were first carried out to quantify the freedom to act to change the control schemes. New operational rules were then elaborated and tested using a hydraulic model with their efficiency to protect against flooding and to reduce pollutant discharges being assessed.

A variety of pond-like stormwater treatment practices are used to treat urban runoff, including permanently-filled ponds (wet ponds or retention basins) and ponds that are allowed to go dry between storms (dry ponds or detention basins). Detention basins may be lined or unlined, with unlined ponds usually being vegetated. Bhattarai and Griffin (2000) studied the pollutant removal performance of a concrete-lined detention basin that receives runoff from a highway bridge in Louisiana. The basin primarily acted as a settling basin and was most effective in terms of TSS removal. For other constituents, the basin exhibited a somewhat erratic range of removal efficiencies, but it was still able to reduce their concentrations in most cases. Davies and Bavor (2000) compared the performances of a constructed wetland and a water pollution control pond in terms of their abilities to reduce stormwater bacterial loads to recreational waters. Bacterial removal was significantly less effective in the water pollution control pond than in the constructed wetland, likely because of the inability of the pond system to retain the fine clay particles (< 2  $\mu\text{m}$ ) to which the bacteria were predominantly adsorbed. The key to greater bacterial longevity in the pond sediments appeared to be the adsorption of bacteria to fine particles, which protected them from predators. Guo et al. (2000) experimented with modifications to the outlet structure of a dry detention basin to improve pollutant removal performance of the pond, and found no conclusive correlation between the pollutant removal efficiency and the detention time. Instead, pollutant removal efficiency in the field was strongly dependent on the inflow concentration.

Heitz et al. (2000) examined the precipitation and runoff patterns on Guam in order to: (1) characterize the hourly rainfall events for volume, frequency, duration, and time between storm events; (2) evaluate rainfall-runoff characteristics with respect to capture volume needed for water quality treatment; and (3) prepare criteria for sizing and designing of storm

water quality management facilities. The resulting design curves should lead to a reduction of non-point source pollution to Guam's receiving waters. Marsalek et al. (2000) examined the hydrodynamics of a frozen in-stream stormwater management pond located in Kingston, Ontario, Canada. Measurements of the velocity field under the ice cover agreed well with that simulated by a CFD model (PHOENICS(TM)). During a snowmelt event, the near-bottom velocities reached up to 0.05 m-s(-1), but were not sufficient to scour the bottom sediment. Van Buren et al. (2000b) studied the thermal balance of an on-stream stormwater pond in Kingston, Ontario, Canada. During dry-weather periods, pond temperature increased as a result of solar heating, and thermal energy input exceeded output. Conversely, during wet-weather periods, pond temperature decreased as a result of limited solar radiation and replacement of warm pond water by cool inflow water from the upstream catchment, and thermal energy output exceeded input.

Newman et al. (2000b) described the application of the Storage-Treatment (S-T) Block of the EPA Storm Water Management Model (SWMM) to design and/or analyze extended-detention ponds (EDPs). The importance of this refined method for EDP design was emphasized with examples of how the use of rules-of-thumb or BMP-manual guidelines could result in unexpectedly poor EDP performance. Proctor et al. (2000) reported on Kentucky's Sanitation District No. 1 working with a local elementary school to convert a badly eroding stormwater detention basin into an outdoor learning center for the school. The results were that the sewer district gained a corrected detention basin, the public gained an education in stormwater management, the students learned about water pollution, and the school gained an educational resource in the Outdoor Learning Center. Dewey et al. (2000) adapted a two-dimensional, vertically averaged hydrodynamic model to compute the circulation and sedimentation patterns in stormwater detention ponds or other water impoundment facilities. The Circulation and Water Quality Model (CWQM) identified areas in the pond where short-circuiting and dead zones occurred. Sedimentation, based on first-order decay, also could be predicted. Field testing verified that the predicted suspended solids (SS) concentration at the outlet and monitored outlet concentrations agreed.

The question has been raised as to whether stormwater ponds adequately protect downstream aquatic systems from the deleterious effects of stormwater runoff. Lieb and Carline (2000) examined the impact of runoff from a stormwater detention pond on the macroinvertebrate community in a small headwater stream downstream of the pond in central Pennsylvania, USA. Invertebrate communities 98 m and 351 m downstream of the pond were highly degraded, while a community 798 m downstream was markedly less degraded. Despite downstream improvement, all three sites were considered impaired relative to a reference community. These results were found to generally be in agreement with those of similar studies in other states and reinforced the need for land-use planning that considers the potential negative effects of urbanization on headwater streams. Based on an investigation into phytoplankton and periphyton algal communities of two recently constructed stormwater management ponds, Olding (2000) ponds suggested that stormwater impacts on biological communities are reduced during passage through the ponds, providing a degree of protection for biological communities in receiving waters by reducing harmful toxins and nutrients. The taxonomic composition of the two sites provided an indication of the incoming stormwater quality. The lack of blue-green algae suggested that stormwater facilities may be engineered to inhibit undesirable algal communities. Turtle (2000) studied the impacts of road runoff on spotted salamanders breeding in roadside and woodland vernal pools in southeastern New Hampshire and found that Salamander embryonic survival was lower in roadside pools that received road deicing salt runoff.

Current stormwater quality control pond design in Ontario, Canada typically includes the specification of a uniform detention time for extended detention ponds to ensure water quality control. In reality, the pollution-control performance of such facilities was governed by two opposing forces: improved pollutant removal efficiency over longer detention times and the decreased volume of runoff captured and treated by the facility for longer detention times (Papa et al., 1999).

Three seasonal surveys of suspended solids were carried out in an on-stream stormwater management pond, by means of a submersible laser particle size analyser. Size distributions were measured at up to 17 points in the pond, and water samples collected at the same locations were analysed for primary particles aggregated in flocs. Using a relationship defining the floc density as a function of floc size and Stokes' equation for settling, an empirical relationship expressing the free fall velocity as a function of floc size was produced (Krishnappan et al., 1999). Jacopin et al. (1999) examined the new operational management practices for detention tanks, with grassed banks and bottom installed on a separate stormwater network, during rainfall events in order to limit flooding risk and, at the same time, to reduce pollutant discharges by optimising the settling process.

Use of stormwater retention and detention basins has become a popular method for managing urban and suburban stormwater runoff. Infiltration of stormwater through these basins, however, may increase the risk to ground-water

quality, especially in areas like the Coastal Plain of southern New Jersey, where the soil was sandy and the water table shallow, and contaminants may not have a chance to degrade or sorb onto soil particles before reaching the saturated zone. Ground water from monitoring wells installed in basins in Camden and Gloucester Counties, New Jersey, was sampled and analyzed for volatile organic compounds (VOC), pesticides, nutrients, and major ions (Fischer, 1999). Crunkilton and Kron (1999) measured the toxicity of stormwater runoff before and after it had been allowed to flow through a pilot-scale wet-detention basin. Selected heavy metals and PAH compounds were measured in incoming and outgoing-settling basin water. *Daphnia magna* and *Pimephales promelas* (fathead minnow) were exposed to pre and post-settling basin treated stormwater runoff for three test periods of 14 days each in 1996 and 1997.

Stormwater reuse has been incorporated into the design of wet-detention systems constructed in Florida. Stormwater reuse reduces the volume of stormwater discharged downstream thereby decreasing the loss of potentially valuable freshwater resource. Additionally, by reusing the detained stormwater instead of discharging it, the treatment efficiency of the stormwater detention pond was increased thereby decreasing the pollutant load delivered downstream (Livingston, 1999). The suitability of treatment ponds for mitigation of chemical contaminant loads and toxicity was investigated under baseflow conditions in two systems serving urban and industrial catchments (Hickey, 1999).

Approximately  $40 \times 10^6$  L (10 MG) of stormwater were managed at a hazardous spill site for the release of ethyl acetate (Buckles and Sanborn, 1998). Five earthen dams were constructed in series along a stormwater drainage ditch to contain the contaminated stormwater and were removed after the completion of the project.

Vignoles and Herremans (1996) studied pollutant loads (SS, COD, TKN [total Kjeldahl nitrogen]) in runoff waters from a highway to determine capacity of a settling tank for collecting adequate volume of runoff to mitigate the spread of pollutants.

Solids-settling characteristics of urban storm runoff have been addressed by Pisano (1996), due to their importance in designing CSO and stormwater high-rate treatment facilities. Solids settling curves and median settling velocities for different waste types have been presented. Settling column methods and solids settling curves for various wastes were presented by Pisano and Brombach (1996) along with global estimates of median settling velocities and results of recent German research.

#### **Multiple drainage objectives and pond design conflicts.**

Wada et al. (1999) investigated the possibility of using a storage tank or pond, for both flood control and stormwater control. They found that the first flush could be directed into an initial storage area, while peak runoff flows could be directed to a secondary storage area. The suitable storage volume of the first pond would be 1-2 mm of runoff and the secondary pond volume would be 3-4 mm of runoff. Cabot et al. (1999) also described the dual use of ponds in Barcelona, Spain, where several detention facilities have been designed to simultaneously address both flooding and CSO. The design procedure has been validated with a detailed model, and a simplified rule has been developed stressing the use of the 10-year design storm. The 100-year design storm was then used to obtain the design capacity of the overflow structures of the facilities. Drainage objectives in Belgrade, Yugoslavia were to separate stormwater from wastewater in areas of existing combined systems and to limit peak discharges by means of detention ponds in the upstream part of the drainage areas for downstream flood prevention (Despotovic et al., 1999).

Henderson (1997), Sela and Chidananda (1997), Yeh and Labadie (1997), and Smith and Sila (1997) reported that stormwater-detention basins (ponds) in urbanized areas have been designed for many purposes, including flood and pollution control and recreation.

Gupta and Saul (1996) discussed use of storage tanks incorporated into the design of combined sewer systems at two sites in northwestern England for controlling discharges to receiving waters. The Regional Municipality of Hamilton-Wentworth operates a large combined-sewer system with 20 overflow structures that result in an average of 23 overflow events per year per outfall. Stirrup (1996) concluded that the only reasonable means of dealing with large volumes of CSO in Hamilton was to intercept it at the outfalls, detain it, and convey it to the wastewater treatment plant after the storm event ends. Target reductions of CSO to be achieved are 1 to 4 per year on the average.

Nix and Durrans (1996) analyzed offline-detention systems as a means of stormwater management and concluded that offline systems required considerably less storage than inline systems to achieve the same management goal.

**Pond sizing.**

Bertrand-Krajewski and Chebbo (2002) compared two types of stormwater treatment facilities – storage-settling tanks and on-line settlers) for event, annual and inter-annual time scales. Storage-settling tanks with specific volumes of 100 m<sup>3</sup>/active ha intercept approximately 80 % of the annual TSS pollutant load, and on-line settlers designed for 8L/s/active ha can intercept 82 to 85 % of this load. Differences exist between combined and separate systems but are usually less than 10-15 %.

Bertrand-Krajewski and Bardin (2002) evaluated how the uncertainties in urban hydrology contribution to calculating storage/settling tanks volumes and pollutant loads. The example presented was a calculation of the uncertainties in some quantities describing the behavior of the Venissieux (France) storage and settling tank during one rainfall event. The quantities were the flow rates and the volumes entering into the tank, the inflow and outflow mean concentrations and masses of TSS (Total Suspended Solids), and the TSS removal rate. The results led to the following relative uncertainties 8% for the total volume, 30% for the inflow concentration, 38% for the outflow concentration, 31% for the inflow mass, 39% for the outflow mass and 138% for the removal rate.

Guo (1999) described a simple method to size stormwater detention basins using a volume-based method such as provided by the Federal Aviation Administration that was applicable to small urban catchments. The average outflow from the detention basin (the most important aspect affecting reliability) was found to be related to the time of concentration of the catchment and the duration of the design storm. Guo and Adams (1999a) described how the flow-capture efficiency and average detention time (the performance measures commonly used in assessing the long-term pollutant removal effectiveness of stormwater detention ponds) can be statistically estimated. Guo and Adams (1999b) further described the analytical probabilistic approach that can be used for evaluating designs of detention facilities that was a computationally efficient alternative to continuous simulation. Papa et al. (1999) described how the pollution-prevention performance of detention facilities was governed by two opposing forces: improved pollutant-removal efficiency over longer detention times, and the decreased volume of runoff captured and treated by the facility for longer detention times. The combination of these effects produces a maximum attainable level of long-term pollution-control performance at an optimal detention time. Harston and Joliffe (1999) described the recent New South Wales (Australia) stormwater management manual which has identified three different classifications for sediment basins. Type F and Type D basins were designed for total containment of runoff and discharge after a predetermined time period to allow efficient containment and release after flocculation to settle the fine sediments.

Retention basins should be cost-effectively sized based on analysis of local-hydrological characteristics and their impact on stormwater-runoff capture. Urbonas *et al.* (1996) suggested that fine-tuning to site characteristics and local conditions can save significant costs over recommending oversized ponds. Guo and Urbonas (1996) presented a strategy for estimating stormwater-detention volume to achieve quality control based on the fraction of storm runoff volume captured and the number of storm runoff events predicted to occur in a given time period.

Kachalsky *et al.* (1996), discussed an approach to optimal sizing of a CSO-retention facility that was used for a planned CSO facility in Jamaica Bay, New York, NY, by the New York City Department of Environmental Protection. In this approach, an evaluation of the impact to water quality improvement versus construction cost of the CSO-retention facility was considered. Kluck (1996) investigated performance of CSO-settling tanks for certain selected designs as result of time-varying flowrates and dimensional effects as well. This research evaluated the effectiveness of baffles and diffusers and confirmed the importance of the shape of the tanks.

**Locating detention facilities in older areas.**

Rivard and Dupuis (1999) described how older drainage systems, especially combined sewers, that frequently experience hydraulic surcharges can sometimes be improved by restricting the inflows at the inlets, causing a limited retention of stormwater on the streets. Scott et al. (1999) examined both onsite detention and on-site retention for a set of hypothetical urban catchments ranging in size from 14 ha to 210 ha. The objective was to achieve the same peak flow rate reduction at least cost. The onsite retention facilities was shown to out-perform the detention in most of the medium to large catchments.

**Modeling pond performance.**

The paper by Guo (2002) presented a design method by which the overflow risk associated with a basin storage volume could be evaluated for various drain times. The risk-based approach developed in this study provided a quantifiable basis for making the decision on the operation of a stormwater quality control basin. Krishnappan and Marsalek (2002)

presented a new model to predict the transport characteristics of suspended sediment for an on-stream stormwater management pond. Simulated suspended concentrations vs. time and the size distribution of the flocculated sediment, produced with the calibrated model, agreed well with flume measurements.

Hollingsworth et al. (1999) also presented an analytical probabilistic model (MTOPOOND) that used probability distribution functions of rainfall characteristics in order to develop closed form expressions for the long term pollutant removal efficiency of stormwater ponds. Operational management practices for detention facilities to limit flooding risks simultaneously with reduced pollutant discharges was possible by optimizing the settling process, as described by Jacopin et al. (1999a). They found that proper descriptions of the particle sizes were critical and that the particle size distribution in the surface sediments were close to those of the suspended solids in the stormwater. Jacopin et al. (1999b) further described the optimization process where the detention facilities were empty most of the time, offering a large safety margin to protect against flooding. The detention facilities store all of the runoff from light and medium rainfall events, consuming about half of the detention capacity. The probability of exceeding the tank capacity was small, even for the larger storms. Adamsson et al. (1999) found that computational fluid dynamics (CFD) was a good tool for studying the hydraulic properties of detention basins in urban drainage systems.

According to Greb and Bannerman (1997), the influent particle-size distribution affected the efficiency of an urban residential area stormwater wet pond's performance on sediment and associated pollutant removal. Karounarenier and Sparling (1997) studied toxicity of stormwater-treatment-pond sediments. Guo (1997) measured the amount of heavy-metal content, organic content, and mass distribution of the bottom sediment in an 18-year-old-single-purpose-dry-stormwater-detention basin, assessed the effect of sedimentation on flood-control capacity, and determined values for predicting amounts of sediment and heavy-metal accumulation. Results of dye-tracing studies performed in a stormwater pond in Kingston Township, Ont., Can. demonstrated an increase in retention times with reduction in the velocity and volume of short-circuiting flow and a decrease in wind-generated-flow patterns due to the installation of retrofitted baffles (Matthews *et al.*, 1997).

Yeh and Labadie (1997) applied successive-reaching-dynamic programming (SRDP) and a multiobjective-genetic algorithm (MOGA) to the design of a stormwater-detention-system in the Pazam watershed located in southern Taiwan. This study indicated the computational efficiency of the SRDP algorithm and the MOGA's nondominated solutions for trade-off analysis. Lawrence *et al.* (1997) reported on the considerations involved in stormwater-hydrological and pollutant-mobilization processes and the selection of stormwater-detention and pollution control BMP. A summary of the major structural and nonstructural BMP commonly used including pollutant removal and flow attenuation capacities of each BMP was provided.

#### **Observed pond performance.**

Yang et al. (2002) reported on the use of aerated wet ponds at CVG airport (Cincinnati/Northern Kentucky) to treat glycol-contaminated streams in cold temperatures. The operation of the pond resulted in a nearly 50% BOD<sub>5</sub> removal and intermittent discharges that appear to have resulted in the reduction of nuisance growth in the once-polluted streams. Marsalek et al. (2002) reported on an assessment of the impacts of urban development on a small creek with an on-stream stormwater pond. The assessment included creek-pond system hydrology, water and sediment chemistry and toxicity, and benthic communities. The pond accumulated sediments and toxicants and thereby prevented further degradation of the creek condition downstream of the plaza drainage outfall.

German and Svensson (2002) explored the relationship between stormwater quality and sediment quality in stormwater ponds in Sweden. A correlation between the inflow EMCs and sediment concentrations of heavy metals was found. It was concluded that the pollutant load from a catchment could be characterized by analyzing the pond sediments. The pollutant removal efficiency of three wet detention ponds was investigated by Mallin et al. (2002). The results for solids removal were good for all ponds, but nutrient removal was variable. To achieve good reduction in a variety of pollutants, wet pond design should include maximizing the contact time of inflowing water with rooted vegetation and organic sediments. This could be achieved through a physical pond design that provides a high length to width ratio, and planting of native macrophyte species. Nehrke and Roesner (2002b) reviewed the influence of extended detention stormwater treatment practices and traditional flood controls on the flow frequency curve of urban runoff (pre- and post-development). Detention ponds with a variety of flow control orifices sized using traditional and innovative methods were examined singularly and in conjunction with extended detention ponds. Shammaa et al. (2002) investigated the effectiveness of dry ponds for removal of TSS from stormwater. Detention time was the most important factor affecting TSS removal. Two-stage facilities and multi-level outlet design were important means of enhancing TSS removal in dry ponds. Two dry

ponds within the city of Edmonton were selected to evaluate their TSS removal. Pettersson (2002) investigated the characteristics of suspended particles in a small stormwater pond. The results showed the particle volume in the stormwater (particle volume per stormwater volume) predominately consisted of very fine particles and that the smallest particles comprised most of the surface area. The stormwater pollutants exhibit strong correlation with particle characteristics. Scholz (2002) presented an overview of the pilot plant that will assist in developing design and management guidelines for operating stormwater pond systems. Sustainability analyses were also performed.

Konrad and Burges (2001) used a three-year rainfall record from a site in the Puget lowland, Washington in a mass-balance model to simulate outflow from single- and multiple- purpose detention systems, with the results compared to time series of measured runoff from Evans Creek. The discharge from a small on-site reservoir was sensitive to both the storage capacity and maximum controlled release rate for extreme high flows (those exceeded 1% of the time) and low flows (those exceeded 80% of the time). Using wetland filtration, the North Griffin Regional Detention Pond has proven to be an effective BMP for improving water quality to receiving waters and for reducing flooding (Feldner and Greuel 2001). The 30-year-old Expo Park regional stormwater detention facility in Aurora, Colorado needed renewal (Hamilton et al., 2001). Improvements to the multi-use 60-acre park facility were made to provide water quality, improve site drainage, increase flood control detention, improve recreational usefulness and aesthetics, and upgrade the facility to meet jurisdictional State dam safety requirements. Dam safety related improvements included new outlet works, spillway improvements, and acceptance by the Engineer's Office for using irrigated turf grass as overtopping erosion protection for the emergency spillway.

Karouna-Renier and Sparling (2001) investigated the accumulation of Cu, Zn, and Pb by macroinvertebrates collected in Maryland stormwater treatment ponds serving commercial, highway, residential and open-space watersheds to determine if watershed land-use classification influenced metal concentrations in macroinvertebrates, sediments, and water. Composite Zn concentrations in odonates from ponds with commercial development (mean = 113.82  $\mu\text{g g}^{-1}$ ) were significantly higher than concentrations in the other land-use categories. Similarly, Cu levels in odonates from commercial ponds (mean = 27.12  $\mu\text{g g}^{-1}$ ) were significantly higher than from highway (mean = 20.23  $\mu\text{g g}^{-1}$ ) and open space (mean = 17.79  $\mu\text{g g}^{-1}$ ) ponds. However, metal concentrations in sediments and water did not differ significantly among land-uses. The levels of Cu, Zn, and Pb in invertebrates from all ponds were less than dietary concentrations considered toxic to fish. Caltrans initiated a study in two Districts (Los Angeles and San Diego, California) to examine the benefits, technical feasibility, costs and operation and maintenance requirements of retrofitting extended detention facilities into existing highway and related infrastructure (Taylor et al., 2001). Monitored constituents will include suspended solids, metals, nutrients, and organics (e.g., gasoline). Detailed records will also be kept for maintenance and operations requirements. Sampling results showed average suspended solids removal was 73%, total metals removal varied between 61% and 75%, while dissolved metals removal varied between 16% and 44%. Removal was lowest for nutrients, especially nitrate, which was about 17%. Concrete lined basin showed generally lower removal rates. Major removal of sediment is estimated to be required every 10 years.

Petterson et al. (1999) studied the pollutant-removal efficiency of two stormwater ponds in Sweden. Observed outflow pollutant conditions were independent of the influent conditions for the two ponds. They also found that pollutant removal efficiency increased for increasing values of ratio of the pond surface area to the watershed impervious area, up to about 250  $\text{m}^2/\text{ha}$ , while the benefits of larger ponds were not as important. Bartone and Uchir (1999) compared the performance of two dry-stormwater-detention facilities, one having a concrete low-flow channel, and the other with a vegetated low-flow channel during four events. As they expected, the detention pond having the concrete channel was ineffective for stormwater quality control. However, the basin with the vegetated channel was also found essentially ineffective for water quality improvement, with flushing of previously captured pollutants being the most likely reason for the poor performance. The retention of heavy metals in a wet reed-bed wetland were compared to retention in a dry-detention pond near London, United Kingdom, by Hares and Ward (1999). A higher percentage removal occurred in the monitored wetland facility than in the dry pond. Shatwell and Corderly (1999) examined nutrient removals in a pond in Sydney's (Australia) Centennial Park that receives stormwater from a 120 ha catchment that was predominantly residential. They found significant amounts of phosphorus and sediment accumulating in the pond, especially during the small- to medium-sized rain events (approximately 60% phosphorous and 80% suspended sediment reductions).

Krishnappan et al. (1999) monitored in-pond particle sizes using a submersible laser particle size analyzer, reducing potential changes in particle characteristics that may occur during sampling. The suspended solids were mostly composed of flocs, and were about 30  $\mu\text{m}$  in size during winter surveys and about 210  $\mu\text{m}$  during the summer surveys. MacDonald et al. (1999) investigated the removal of heavy metals in a detention pond in Scotland. They found that the sediment in the



pond may reach unacceptable concentrations of heavy metals within twenty years. Petterson (1999) examined the partitioning of heavy metals in particulate-bound and dissolved phases in a stormwater pond in Goteborg, Sweden. The results showed a clear variation in lead partitioning affected by specific conductivity.

A monitoring study in Kingston, Ont., Can. (Shaw *et al.*, 1997) concluded that regardless of the magnitude of inflow, the length to width ratio (3:2) of the urban-stormwater-detention pond studied and inflow momentum promote short-circuiting of the flow and limit settling efficiency.

Maxted and Shaver (1966) studied the use of retention basins to mitigate stormwater impacts on aquatic life. Physical habitat and biological measurements were taken below eight stormwater ponds. Two of the sites were in commercial land use, while six were in residential areas. The results were compared to 38 sites with no stormwater treatment practices that had been sampled in 1993. The stormwater treatment practices did not prevent the almost complete loss of sensitive species. The stormwater treatment practices did not attenuate the impacts of urbanization once the watershed reached 20% impervious cover. This study showed that the data set size used here was too small for a conclusive evaluation of the effectiveness of stormwater controls to protect stream biota and habitat. It is also possible that the stormwater facilities studied were not used long enough to achieve improvements in habitat and to repopulate the species.

Papa and Adams (1996) analyzed the implications of required detention times for retention basins with respect to their actual pollution control performance. It was found that pollution-control performance is maximized with typically short-detention times and diminishes monotonically with additional detention time thereafter.

Van Buren *et al.* (1996) assessed the pollution-control performance of a retention pond in Kingston, ON, Canada, and provided results on removal rates for SS, nutrients, metals, organic contaminants, and selected dissolved constituents. Internal pond baffles were evaluated, and it was found that extended hydraulic-residence times and prevention of flow short-circuiting result in increased particulate settling and associated contaminant removal. Stanley (1996) quantified removal efficiencies achieved by a retention pond in Greenville, NC for SS, N, P, TOC (total organic carbon), and selected metals. The benefit of constructed reed beds in treating stormwater overflows was evaluated by Green and Martin (1996) in terms of reductions in discharges of BOD<sub>5</sub>, SS, NH<sub>4</sub><sup>+</sup>, and TON (total organic nitrogen).

### **Problems observed with stormwater ponds.**

The Queen's University/National Water Research Institute Stormwater Quality Enhancement Group has been actively researching stormwater ponds for the past decade, using a fully instrumented on-line system in Kingston, Ontario, Canada as a representative field installation of this group of stormwater best management practices (Anderson *et al.*, 2002). The factors that were found to be crucial to the success or failure of stormwater ponds could be grouped into the following categories: initial design, operation and maintenance, performance and adaptive design.

Beyerlin (1999) described the short-comings of relying on stormwater-detention facilities for complete mitigation of urban runoff problems. Increased winter flood flows, decreased summer low flows, and a general degradation of the stream systems has occurred with development. It was concluded that these problems persisted because of the attempt of replacing the complex interactions of the hydrologic cycle with a pond, which was not possible. Brown *et al.* (1999) described the degradation in quality in Sydney (Australia) Centennial Park's ponds over the past 150 years. Pond rehabilitation techniques have been developed and were being implemented, based on wetland principles.

## **Wetlands**

### **General**

Lee *et al.* (2006a) evaluated a constructed wetlands to treat concentrated stormwater runoff, and found that removals of metals, BOD and SS improved as the wetlands aged. Case-based reasoning methods were able to predicting outflow concentrations and can be used for design to achieve specific removal levels Lee *et al.* (2006b). Using a self-organizing map (SOM), Lee and Scholz (2006) showed that nickel was likely to leach under high conductivity conditions, while copper was not affected by salt increases during the winter season.

Bruland and Richardson (2006) assessed the phosphorus retention capacity of a Minnesota wetlands receiving urban and agricultural runoff. Organic phosphorus was the dominant form of phosphorus in the wetland. The soil properties that best predicted the phosphorus sorption index were soil organic matter, exchangeable calcium, and oxalate extractable iron. Yin *et al.* (2006) described the treatment of urban runoff by constructed wetlands in China. The wetland was effective in treating COD, TP, TN, and TSS. Liner (2006) described an engineered wetland system designed to treat benzene, toluene,

ethylbenzene and xylene. The system treated gasoline-contaminated groundwater and stormwater runoff. Heyvaert et al. (2006) investigated the ability of a constructed surface flow wetland to treat stormwater runoff in a subalpine, cold climate. Improvements were seen in dissolved phosphorus, nitrate and total suspended solids.

Stern (2006) presented the hydraulic changes to stormwater flow as it passes through two types of wetlands. Results indicated that there is a significant difference in the flow characteristics between scrub-shrub and emergent types of wetland. Differences were also found between leaf-on and leaf-off seasons. Conn and Fiedler (2006) proposed designing the bottom topography of constructed stormwater wetlands to increase hydraulic residence time and therefore increase pollutant removals.

Shutes et al. (2005) presented the results of an inventory of planted wetland systems in the United Kingdom that treat surface runoff. System performance will be assessed in terms of design criteria, runoff loadings, as well as vegetation and structure maintenance problems.

Traver and Woodruff presented the results of continuous monitoring of a stormwater wetland. Kay et al. (2005) investigated the effectiveness of a wetland created by a flood defense structure in reducing the flux of microbial indicator organisms from urban and agricultural land uses to marine recreational waters. Water draining to the wetland microbially resembled wastewater treatment plant effluents and the wetland was capable of removing 97% of that flux.

Scholz et al. (2005a) investigated the use of constructed wetlands and filters to treat gully pot (catch basin) liquor containing heavy metals. Filtration performance was similar among the media and nickel leaching from the filters was seen after road gritting and salting during the winter. Holland et al. (2005) performed high-frequency monitoring of suspended solids in a stormwater treatment wetland. They found that residence time distribution was able to explain the sedimentation rates better than steady-state, plug-flow-reactor models.

Rosseau et al. (2005) investigated the impact of operational maintenance on the asset life of storm reed beds in the United Kingdom. Operational maintenance was found to be critical to extending the life and function of these stormwater treatment devices. In addition, pretreatment of the influent flow was also critical in preventing process failure. Dittmer et al. (2005) modeled a subsurface vertical flow constructed wetland to treat CSOs. The simulation of laboratory experiments showed that the selected model could be applied to these wetlands. Licht and Isebrands (2005) linked the opportunity to install a phytoreactor to treat urban runoff with the later opportunity to harvest the biomass for fuel. Scholz and Kazemi-Yazdi (2005) showed how adding common goldfish to infiltration ponds can improve public acceptance of these ponds. They also control algal growth. Shastri Annambhotla and Bryant (2005) reported on the riparian wetland that served as a stormwater treatment practice in Greensboro, North Carolina. One feature of the project was an automatically-operated water level control gate.

Struck et al. (2004) compared, in mesocosms studies, retention ponds versus constructed wetlands for ability to remove pollutants from urban runoff. Preliminary data suggest constructed wetland mesocosms outperformed retention pond mesocosms for removal of TSS and TKN; however, ponds removed dissolved nitrates. Abteu et al. (2004) investigated the applicability of using constructed wetlands to remove phosphorus from stormwater runoff. The constructed wetland achieved a total phosphorus load reduction of 71% during the 4-yr period. Constructed wetlands were evaluated for their ability to remove chlorothalonil and chlorpyrifos (Sherrard et al. 2004). Constructed wetland mesocosms removed both pesticides from simulated stormwater runoff and decreased *P. promelas* and *C. dubia* mortality compared to untreated runoff.

Pontier et al. (2004) evaluated a wetland system in Berkshire, England, to control highway runoff. The results showed that over the long term, there were progressive changes in parts of the system for BOD and COD and for metal concentrations in the sediment fractions. Cold-climate, vertical-flow constructed wetlands were examined for their ability to treat gully pot effluent (Scholz 2004). Reductions of nickel, copper, biochemical oxygen demand and suspended solids were frequently insufficient to meet international secondary wastewater treatment standards. Revitt et al. (2004) evaluated the performances of a horizontal subsurface-flow constructed wetland and a vegetated balancing pond in treating metals, nitrates and sulfates in highway runoff. Median removal efficiencies ranged up to 85%.

Farrell and Scheckenberger (2003) reviewed the five-year monitoring of the Dartnall Road Interchange's wetland in Hamilton, Ontario. The authors investigated the quantitative and qualitative wetland water quality monitoring data (sediment, nutrients, metals) over the course of a total seven-year program. Richter et al. (2003) established the baseline

hydraulic performance of a constructed wetland treatment system at Heathrow Airport designed to treat de-icing and stormwater discharges.

Proakis (2003) investigated pathogen removal in wetlands constructed for stormwater treatment in Huntington Beach, CA. With mussel predation and based on laboratory experiments, enterococcus concentration was expected to be reduced by 90% (1-log removal) after 2 to 4 hours, and an average 97.2% reduction was seen after 24 hours. Scholz (2003b) investigated the effectiveness of small-scale wetlands and dry ponds to attenuate stormwater runoff at a residence. It was found that 50 L could be retained during dry weather and around 300 L after a heavy storm, with the absolute maximum capacity of the system being 2,500 L. Scholz (2003a) investigated the treatment efficiencies of vertical-flow wetland filters containing macrophytes and adsorption media. Nickel nitrate and copper nitrate were added to primary treated (screens of 0.25 mm diameter) gully pot effluent in order to simulate heavily polluted pre-treated stormwater runoff. No breakthrough was observed to date. Sherrard et al. (2003) examined the feasibility of constructed wetlands to remove chlorothalonil and chlorpyrifos from simulated stormwater runoff. Constructed wetland mesocosms decreased concentrations of chlorpyrifos and chlorothalonil in simulated stormwater runoff, and decreasing *P. promelas* and *C. dubia* mortality resulting from these exposures.

It has been hypothesized that smaller lot sizes in a development need not seriously decrease quality of life but instead, may result in increased use of local open space (Syme et al., 2001). This hypothesis was investigated with matched small and larger blocks in four areas in Perth, Western Australia. Households with smaller lots had increased visitation to the wetlands. Wetlands, while improving stormwater management, also fulfilled demands caused by higher urban densities. The City of Edmonton, Alberta issued "Draft Guidelines for Constructed Stormwater Wetlands" to assist developers who use constructed wetlands for stormwater management (Lilley and Labatiuk, 2001). Edmonton has accepted constructed wetlands as an alternative means of managing stormwater, while providing benefits of aesthetics, public enjoyment and wildlife habitat. The City's draft guidelines are intended to optimize the design of constructed wetlands for water quality improvements including suspended solids removal, drainage area, soil permeability, vegetation, water depth, wetland area, wetland volume, length to width ratio, forebays, inlets and outlets, grading, floatables and oil and grease, maintenance, monitoring, signage, secondary uses, land ownership, access, fencing, wildlife and mosquitoes. The research presented by Fassman and Yu (2001) examined the relative pollutant removal capability for specific wetland vegetation. Results of water quality analysis show various trends with respect to pollutant removal and time. In general, export of TP was shown in all vegetated cells. Maximum export for vegetated cells was observed usually during the first week of a treatment, especially for *Typha* spp. and *Phragmites* spp. By the end of most treatments, TP removal was observed in all cells. COD removal was seen in all cells for all weeks of each treatment (average removal ranged from 54-78%). TSS results were inconsistent. Export of Cu was noted for *Scirpus* spp. whereas all other plants showed positive removal. TOC was removed by all plants (average removal 24 – 69%), with the exception of the *Scirpus* spp. cell.

Data from 35 studies on 49 stormwater treatment wetland systems were examined for obvious trends that may aid future design efforts (Carleton et al., 2001). Despite the intermittent nature of hydrologic and pollutant inputs from stormwater runoff, steady-state first-order plug-flow models commonly used to analyze wastewater treatment wetlands could be adapted for use with stormwater wetlands. First-order removal rate constants for TP, NH<sub>3</sub>, and NO<sub>3</sub> for stormwater wetlands were similar to values reported in the literature for wastewater treatment wetlands. Constituent removals were demonstrated via regression analyses to be functions of the ratio of wetland area to watershed area. Goulet et al. (2001) tested a first-order removal model to predict metal retention in a young constructed wetland receiving agricultural and urban runoff. The wetland retained metals best during summer and fall. The first-order removal model predicted Fe and Mn retention in the spring and dissolved Zn retention from spring to fall in both years. However, first-order removal models failed to fit summer, fall and winter data for almost every metal under investigation (Fe, Mn, dissolved Cu, dissolved As) suggesting that HRTs (< 1-25 days) did not affect metal retention during these seasons. Therefore, the first-order removal model is inadequate to predict metal retention on a seasonal basis. Constructed wetlands design models for cold climates must consider seasonal changes that affect biological as well as hydrological variables. Wetland stormwater treatment practices have focused on smaller storms, encouraging long retention times and vegetative contact for pollutant removal, design elements not typically considered for detention basins (Traver 2001). It was hypothesized that traditional storage - indication routing may not be appropriate for stormwater wetlands, especially for smaller water quality storms. To test this hypothesis, a recently constructed wetland was monitored for rainfall and flow. Sediment behavior in a stormwater wetland in Adelaide, Australia was studied using models that were based on solving hydrodynamic and transport equations, with the results compared to field-observed deposition patterns (Walker 2001). The long-term residence time distribution was useful in predicting overall sediment removal rates. Comparisons between the model and field observations indicated generally good agreement. The importance of the transient nature of the flow events was

highlighted by the distribution of sediment throughout the wetland.

In the study by Kao and Wu (2001), a mountainous wetland located in McDowell County, North Carolina was selected to demonstrate the natural filtration and restoration system for maintaining surface water quality. Analytical results from the summer of 1997 indicated that this wetland removed a significant amount of NPS pollutants [more than 80% N removal, 91% total suspended solid removal, 59% total phosphorus removal, and 66% COD removal]. In Taiwan, research on constructed wetlands was conducted as part of a project supported by National Science Council (Yang 2001). Different waters, including contaminated river water, aquaculturing pond water, sewage, industrial wastewater, and storm water, were tested by using microcosm or macrocosm constructed wetland systems. The results of this project showed that the wetlands' effluents had a high potential for water reuse. Shutes (2001) illustrated the role of plants for treating water pollution in man-made wetlands in tropical and temperate climates. The design of the Putrajaya Lake and Wetland system in Malaysia was compared with an urban-runoff-treatment constructed wetland in a new residential development in the UK.

The ability of a wetland to mitigate highway-runoff pollutants, particularly metals, was investigated by Mitchell et al. (2001a). Fifty-seven rainfall-runoff events were monitored. Data collection included rainfall volume and frequency, conduit flow rate, and temperature, conductivity, pH and dissolved oxygen in the runoff. Metal concentrations were reduced via flow through the grassy median and then the wetland system. Average heavy metals removals were zinc (67%) and iron (67%), followed by lead (54%) and then nickel (45%). Metals were reduced some even during winter months and low temperatures. Wetland sediment analysis indicated a broad range of concentrations of metals. Rodgers et al. (2001) reported on the A-01 effluent outfall, which collected both normal daily process flow and stormwater runoff from a industrial park area and did not meet its South Carolina NPDES permit limits for metals, toxicity, and total residual chlorine at the outfall sampling point. Installation of a constructed wetland system including a basin to manage stormwater surges reduced the problematic constituent concentrations to below the NPDES permit limits before the sampling point. The constructed treatment wetland system proved its ability to treat industrial wastewaters containing metals with low O&M costs. With an anticipated life of over 50 years, the wetland system will be cost-effective.

The Greater Toronto Airports Authority (GTAA) constructed the first full-scale vertical-flow treatment wetland in Canada for reduction of ethylene glycol in stormwater (Flindall and Basran 2001). The two-cell treatment wetland was preceded by a sedimentation forebay. The wetland facility collected water discharged from terminal aprons, taxiways, and runways where aircraft receive de-icing compounds particularly glycol, are applied. The facility provided 24 to 48 h of retention to attenuate storm flows and remove suspended sediment. The selected vegetation was *Phragmites australis* reeds. This emergent hydrophyte should be able to withstand the periodic flooding conditions characteristic of a stormwater management system. The reeds will provide very little habitat benefit for gulls and waterfowl and will therefore not attract birds that may cause hazards for aircraft.

Constructed wetlands have been used to capture, detain, and treat stormwater runoff from urban areas because they have the potential to treat a variety of pollutants. Knight and Kadlec (2000) presented an overview of constructed wetlands used for water pollution control. Bachand and Horne (2000) examined the effect of vegetation type on nitrogen removal rate in wetlands used to treat wastewater, including urban runoff. Based on the study and a literature review, in organic carbon-limited free-surface wetlands, a mixture of labile (submergent, floating) and more recalcitrant (emergent, grasses) vegetation would be recommended for improving denitrification rates. Carleton et al. (2000) examined the pollutant removal performance of constructed wetlands treating stormwater runoff from a residential townhome complex in northern Virginia. Median load removals of all constituents were greater for a subset of storms that had inflow volumes less than the maximum volume of the marsh. Estimated removals were positive for most constituents and consistent with expectations based on the relative ratios of wetland area to drainage area at the two sites. Zhu and Ehrenfeld (2000) compared the ability of sediments from Atlantic cedar wetlands in suburban and undisturbed watersheds to remove added inorganic N in laboratory incubations. Results suggested that wetlands in suburban drainages may have limited ability to retain frequent, pulsed N inputs from runoff, and high intrinsic N mineralization in N-saturated sediments can become a cause of water quality degradation. Graham and Lei (2000) evaluated the effective long-term operation of stormwater management ponds/wetlands, including removal, methods of removal and disposal of removed sediments.

Davies and Bavor (2000) compared the performances of a constructed wetland and a water pollution control pond in terms of their abilities to reduce stormwater bacterial loads to recreational waters. Bacterial removal was significantly less effective in the water pollution control pond than in the constructed wetland. Quintero-Betancourt and Rose (2000) assessed the microbial quality of stormwater and/or reclaimed water in terms of bacterial indicators, coliphages,

Cryptosporidium and Giardia in order to determine its suitability for use in recharging stressed wetlands overlying a public water supply wellfield. Preliminary data demonstrated that the level of bacterial indicators such as fecal coliforms and total coliforms in three of the lakes sampled were above the water quality standard established by the Florida Department of Environmental Protection for ambient waters, and other pathogens and indicators were detected.

Wetlands have been chosen for retrofitting existing developments or stormwater detention facilities to improve the treatment of stormwater pollutants. Kerr-Upal et al. (2000) presented a conceptual plan to retrofit a wetland component within the a stormwater management facility in Toronto, Canada, using three wetland design options. Traver (2000) converted an existing stormwater detention pond to an extended detention wetland at a site near Philadelphia, Pennsylvania. The project maintained the original storm water controls and provided proper hydrologic growth and non-point source pollution control. The City of Elkhart, Indiana has constructed an artificial wetland at a CSO outfall to capture and treat overflows prior to discharge into the Elkhart River. The treatment process consisted of (1) a bar screen/sedimentation basin to remove grit and floatables, (2) nearly 30 different species of native aquatic and transitional vegetation, and (3) a downflow drainage and collection system to enhance biological removal of dissolved organics and inorganics, dissolved metals, and suspended particulates (Umble et al. 2000). Davis et al. (2000) reported laboratory and field results of a study of bioretention for treating urban runoff. Kim et al. (2000) evaluated the capacity of bioretention to remove nitrate from urban runoff using a design modification to incorporate a continuously submerged anoxic zone with an overdrain. Work so far has focused on selecting an electron donor/carbon source that promotes significant denitrification and is stable for an extended time in the subsurface. Further studies will use the electron donor (newspapers, wood chips, small sulfur particles/limestone) with the best nitrate removal efficiency and effluent quality.

Since surface flow constructed wetlands (SFCW) are now often designed with low aspect ratios to circumvent surfacing problems, plug flow is not ensured; therefore, alternative models which more accurately describe the flow must be considered. However, to solve the alternative models, a value for dispersion is required. The fundamental variables affecting dispersion are the interstitial velocity (dependent on flow rate, porosity, and cross-sectional area) and the pore geometry (dependent on media characteristics such as average grain diameter and permeability). The dispersion number also will fluctuate with a series of uncontrollable variables specific to a particular SFCW situation. Cothren and Daly (2000) reported the results of their research to extend the results of an empirical relationship between the interstitial velocity as a function of flow rate and aspect ratio and the dispersion number developed using a bench-scale model to the field scale application. Larm (2000) presented a methodology for quantifying yearly and monthly material transport into and out of stormwater treatment facilities (STFs) and discussed problems related to monitoring and estimation of reduction efficiency. Standard values of runoff coefficients and pollutant concentrations together with precipitation data and estimated areas of different land uses within sub-watersheds were used to predict loadings to a multiple pond-wetland STF. A comparison of standard concentrations with measurements shows good correlation for nitrogen, but variable correlations for other pollutants. Tucker and Acreman (2000) described a user-friendly, physically-based model for the estimation of ditch water levels in wet grassland drainage ditches and thus assess the impacts of different water level management strategies on ecological communities and agricultural practices in wet grassland areas. Simulated rain events and runoff were found to produce a more realistic influent to a stormwater treatment wetland than do averaged inlet flow and concentration. Network flow models provided a more realistic prediction of a treatment wetland's internal flows than did plug flow or complete mixing estimation (Werner and Kadlec 2000). Moustafa (2000) extended empirical mixed-reactor models governing phosphorus (P) retention and nutrient assimilation in lakes and reservoirs to include free surface water wetland treatment systems. It was found that sedimentation rates, loading rates, and settling velocity in these wetlands, and their typology were comparable to their lake counterparts. Stormwater treatment areas (STAs) are extremely large-scale (several square miles) wetland stormwater treatment practices being constructed on former agricultural areas of south Florida to provide total effective treatment of stormwater before discharge to the water conservation areas and Everglades National Park. Hyder and Hilton (2000) reported on the hydraulic design model that provides a technical basis for management of STAs. Neumeister et al. (2000) presented a modeling approach to evaluate design alternatives for STAs. The flexibility of their model allowed impacts from alternative design scenarios to be evaluated and incorporated.

Because vegetation is crucial in many wetland treatment processes, the establishment of vegetation in newly constructed wetlands is important. Fassman et al. (2000) examined strategies for planting constructed wetlands to enhance development and survival of constructed wetland systems used for stormwater management and mitigation credit. Galatowitsch et al. (2000) used wetland biomonitoring approaches to determine when changes in response to stressors were occurring and to predict the consequences of proposed land-use changes for 40 wet meadows in Minnesota. Site impacts (stormwater, cultivation) and landscape disturbance (agriculture and urbanization, combined), coincided with a

reduction in native graminoid and herbaceous perennial abundance.

One often cited advantage of wetlands for stormwater treatment is the associated development of wildlife habitats. A study by Bishop et al. (2000a) of 15 stormwater pond wetlands and one natural wetland varying in age from 3 to 22 years in the Guelph and the Greater Toronto Area (GTA) in Ontario, Canada, showed that wildlife made use of the ponds, but species richness at almost all sites was low to moderate, indicating that the ponds did not provide high quality habitat for wildlife. Due to concerns that wildlife would be attracted to stormwater detention ponds and be exposed to contaminants accumulating in these ponds, contaminant levels in ponds, sediments, and wildlife were also investigated (Bishop et al. 2000b). A variety of impacts detected in wildlife species including fish, songbirds, and amphibians led the authors to conclude that stormwater ponds did not offer clean ecosystems for wildlife and the monitoring of contamination and its effects within stormwater ponds was necessary. The Lake County Sanitation District has developed a program to recycle treated wastewater in Lake County, California. The plan included constructed wetlands to improve water quality, enhance wildlife habitat, offer evapotranspiration of excess water, and provide public benefits by creating settings for passive recreation and wildlife study. Kimmelshue et al. (2000) presented a paper which included results from a wetlands screening study, a preliminary design effort and the design and construction of an initial wetland.

According to Koob et al. (1999), the successful design of constructed wetlands required a continuous supply of water or vegetation that can withstand drought conditions. Detention structure designs should be based on times between events as well as on hydrologic return periods, since between events was when most evaporation and infiltration losses were likely to occur. Serrano et al. (1999) investigated phosphorus (P) concentrations in Donana seasonal wetlands in southwestern Spain as the wetlands started to fill following storm events after a drought. NPS N from riverine origin was a major water quality problem throughout the world. Hunt et al. (1999) reported that total annual N removal for the in stream wetland was approximately 3 kg/ha per day, which was about 37% of the inflow N. Removal of both  $\text{NO}_3\text{-N}$  and total N ( $\text{NO}_3\text{-N} + \text{TKN}$ ) were positively correlated to temperature with r-values of 0.77 and 0.62, respectively. According to Zhu and Ehrenfeld (1999), the presence of urban and suburban lands adjacent to wetlands may cause changes in nutrient-cycling processes, due to changes in the quality of the ground and surface waters that drain from the developed uplands into the wetlands. The alternations in hydrology and the input of mineral-rich sediments, in addition to excess N from the septic drainage and road runoff, can apparently cause increases in N mineralization within the wetland sediments, thus exacerbating the direct deleterious effects of roads and housing on water quality. Quantitative estimates of denitrification were needed in designing artificial wetlands to optimize nitrate ( $\text{NO}_3^-$ ) removal. Acetylene blockage and N-15-tracer methods were employed to quantify denitrification in constructed wetlands receiving agricultural tile drainage, using plastic tubes to enclose in situ mesocosms. Because water infiltration carries  $\text{NO}_3^-$  through the anaerobic sediment/water interface for denitrification, a subsurface-flow wetland may denitrify more  $\text{NO}_3^-$  than a surface-flow wetland (Xue et al., 1999).

According to Guardo, (1999) the Everglades Nutrient Removal (ENR) Project, a 1544-ha wetland, was designed and constructed as a pilot project to gain experience on design, construction, and operation of the stormwater treatment areas. For the 732 days analyzed (19 August 1994 through 19 August 1996), the average water inputs into the project were as follows: 86.2% from the inflow pumps, 11.2% from rainfall, and 2.6% as emerging measured and estimated seepage from an adjacent area with higher stages; the average water outputs from the project consisted of 85.1% from the outflow pumps, 8.9% as evapotranspiration, and 6.0% as a net seepage and groundwater component. The ENR Project's purpose was the removing of nutrients (especially phosphorus) from agricultural drainage and stormwater runoff before entering the Everglades. The hydrology and water quality of an urban wetland receiving stormwater runoff from a municipal maintenance garage were measured during the summer of 1993 to evaluate the wetland's water quality enhancement function. According to Thurston (1999), hydrologic and analytical data together suggest that sedimentation was the primary mechanism actively reducing water column concentrations of lead and petroleum hydrocarbons introduced to the wetland via stormwater runoff.

It was evident that existing designs for the control of highway discharges were primarily if not exclusively intended to control runoff volumes rather than as any complementary pollution treatment function. However, regulatory pressures on highway authorities and agencies were increasingly requiring that drainage controls should include reference to water quality treatment and the clear inadequacy of conventional drainage systems has stimulated interest in the design, implementation and operation of alternative vegetative systems, such as swales and wetlands (Ellis, 1999a and 1999b).

To address the unknowns and design concerns of a stormwater wetland system, a bench-scale vegetative-treatment-cell study has been conducted for the purpose of examining nutrient and metal dynamics and removal efficiencies of three

individual plant species under various stormwater-pollutant loadings and detention times. The plant species being evaluated are: cattails (*Typha latifolia*), reeds (*Phragmites sp.*), and bulrushes (*Scirpus sp.*) (O'Shea et al., 1999). The design and pollutant removal performance of seven wetland mitigation sites and two detention basins with emergent vegetation in Virginia were examined over a three-year period to assess the effectiveness of mitigated wetlands for the control of NPS pollution and the influence of design on wetland performance as a stormwater treatment practice, in a study sponsored by the Federal Highway Administration and the Virginia Department of Conservation and Recreation (Shaw et al., 1999). The Tollgate District Sewer Separation Project involved the separation of a combined sewer system, and the creation of a wetland detention basin. In addition to its stormwater detention uses, the wetland serves as a wildlife refuge, learning center, and a local point of public outreach to bring the community together (Lindemann, 1999).

The Virginia Stormwater Wetland Simulation Model (VASWETS) was developed on the basis of a double-layer (water column and substratum) box approach to model the fate of pollutant transport in bucket wetlands (Liao et al., 1998a and 1998c) and has the ability to predict and optimize performance and to compare design criteria of stormwater-wetland systems. The Harris County Flood Control District implemented a wetland mitigation bank project northeast of Houston, Tex. that included highway runoff. The project includes 89 ha (220 acres) of stormwater-polishing wetlands as part of the overall 607 ha (1 500 acres) Greens Bayou Wetland Mitigation Bank (Knight and Koros, 1998). The Tollgate Drain project of Ingham County, Miss. created a wetland to act as a natural filtration system for stormwater runoff from a 95 ha (234 acre) developed watershed. At \$6.4 million, the system cost was about half of the other options (Lindemann, 1998). Denison and Tilton (1998) provided a summary of the Rouge Project wetland demonstration including wetland design, construction, and monitoring and assessed the practicality of using wetlands for stormwater treatment. Case studies of the Wetland Conservation Area located in New Albany, Ohio, the Streetsboro Wetland Park in Streetsboro, Ohio, and the Oakland Ravine Wetland Treatment System of the Borough of Queens, N.Y. illustrated that skillfully designed wetland projects represent a tool for communities to show compliance with the upcoming Phase II NPDES regulations (Evans, 1998). The wetlands serve as CSO reduction, stormwater treatment, park enhancement and educational uses. Scholes et al. (1998) presented monitoring and performance results from constructed-wetland treatment systems at two selected sites in southeastern U.K., both of which receive large volumes of urban runoff. The results show widely varied influent pollutant concentrations and removal efficiencies, and indicate that the tissues of reeds in the wetlands accumulate metals. A study of nutrient absorption capacity of different species of Lemnaceae (duckweed) in a stormwater detention pond concluded that monoculture *Lemna minor* consistently removed the largest amount of  $\text{NH}_3$  from stormwater and had the largest biomass density while a polyculture of *Lemna minor* and *Spirodela polyrrhiza* was the most stable nutrient sink and removed the largest amount of P from stormwater in eight weeks (Pernial et al., 1998).

Environmental agency effluent quality data were given for 39 sites where reed beds either treated stormwater and secondary effluent together or have been installed as remedial treatment for works struggling to meet secondary treatment standards (Green et al., 1998). Brdjanovic et al. (1998) attributed deterioration of biological P removal (BPR) efficiency observed after heavy rainfall and weekends to excessive aeration. The lull in BPR performance was originally thought to be low plant loading that took place during such events. A quarry in Du Page County, Ill. currently used for temporary flood control storage was evaluated for treatment of stormwater and dry-weather flow in order to improve water quality to Salt Creek (Lampe et al., 1998).

As wetland ecosystems degrade due to human actions, restoration efforts have become more pronounced. Mass-balance models could provide valuable information about ecosystems with respect to input sources and the relative importance of each pollutant load, based on a study of P and SS loadings to Cootes Paradise Marsh in Hamilton Harbour, Lake Ontario, Can. (Prescott and Tسانis, 1997). Shutes *et al.* (1997a and 1997b) reported on the results of two case studies of the pollution-removal performance of constructed wetlands for urban-stormwater-runoff treatment. The design of constructed wetlands included primary-treatment components, substrate composition, and flowrate regulation. Two subsurface-flow-constructed wetlands were tested for pollutant-removal performance in conjunction with an online-stormwater-detention pond. The wetlands were able to maintain removal of SS (46%), dissolved metals (Cu 50%), and organic C (10%) (Rochfort *et al.*, 1997). Stormwater-control basins can be easily and inexpensively modified to act as stormwater-treatment wetlands. Preliminary results indicated removal of 93% SS, a total P removal of up to 83%, and a minimal amount (22%) of total N removal (White *et al.*, 1997).

Somes and Wong (1996) modeled a series of hypothetical wetland systems to determine the influence of different outlet types on their hydrologic regimes. It was concluded that the design of constructed wetlands for stormwater-pollution control involves consideration of the inherent variability of storm events and intervening dry periods to size the wetland storage volume and outlet characteristics. The outlet of a wetland must retain the stormwater in the wetland as long as

possible but also provide adequate wetland storage capacity for the next storm event. This study concentrated on three outlet configurations for draining wetlands: an orifice, riser, and siphon. Each outlet type was evaluated for its ability to maintain the hydraulic effectiveness and hydrologic regime of the wetland.

Existing wetlands located in the future Rocky Ridge subdivision of Calgary, AB, Canada will be retained and incorporated into an integrated-stormwater-management system for the subdivision. Van Duin *et al.* (1996) discussed measures taken to protect the integrity of these wetlands during and after construction of the subdivision including a multiyear-monitoring program. Werner and Kadlec (1996) evaluated the performance of constructed wetlands in terms of effluent concentrations resulting from impulse-tracer inputs to the systems.

#### **Design guidelines.**

Nirupama and Venema (2002) demonstrated how multi-criteria evaluation (MCE) decision-making tools which incorporate GIS can be used to manage wetlands. Remotely-sensed satellite data and GIS have excellent capabilities to study and analyze spatial issues regarding wetlands management.

Koop *et al.* (1999) stress that the successful design of constructed wetlands requires a continuous supply of water for vegetation to withstand drought conditions. They acknowledge that there were drought tolerant species of vegetation that can be used in constructed wetlands, however, it can take several days to re-establish the attached bacteria communities that were necessary for optimum pollutant removal. Lawrence and Breen (1999) described new design guidelines for constructed wetlands. They also highlighted some areas where further information was required to facilitate a more rigorous analysis of wetlands to optimize their selection, design, and assessment. Lawrence (1999) described a generic pond and wetland model that can provide water quality assessments for a range of geographic areas and information needs.

Persson *et al.* (1999) examined the hydraulic efficiency of constructed wetlands. They found that proper control of the hydrologic regime of the wetland and optimal flow hydrodynamics within the wetland were necessary for their sustainable operation. They concluded that many of the problems encountered in constructed wetlands can be minimized, or avoided, by good engineering design principles, including optimizing their shape and layout. Rash and Liehr (1999) also looked at the flow patterns within a constructed wetland near Wilmington, North Carolina, using lithium chloride tracers. Short-circuiting was common in subsurface-flow wetlands, while vegetated free water surface wetlands were well-mixed and not as subject to short-circuiting.

#### **Wetlands for CSO control.**

Liebig, *et al.* (1999) described the stochastic behavior of hydraulic and pollutant loadings of constructed wetlands for CSO and stormwater treatment. A comprehensive three-year monitoring program of a constructed CSO wetland in Kamen-Methler, Northrhine-Westfalia, Germany, was undertaken to monitor the pond's effectiveness and to establish planning, design and operation guidelines. Wong *et al.* (1999) reported on the performance of the Braunebach research wetland in Germany and described the suitability of a two-parameter first-order-decay model for predicting the performance of the constructed wetlands for the treatment of CSO. A total of 30 CSO events were monitored and the results demonstrated the suitability and reliability of this model for SS, BOD<sub>5</sub>, total phosphorus and soluble reactive phosphorus. The Fulda Fellenweg wetland system, also in Germany, was built in 1992, and consists of a 550 m<sup>2</sup> soil filter planted with reeds, and a basin with a detention volume of 786 m<sup>3</sup>. Born (1999) described the performance of this system in treating CSO. The efficiency of the system was about 90% for COD, NH<sub>4</sub>-N, SS and PO<sub>4</sub>-P and the removal efficiencies were independent on the resident times in the system. The permeability did not decrease during the five-year monitoring period. The main design parameter for the system was the surface loading rate (usually about 0.011 L/m<sup>2</sup>-s). Faster rates (up to 0.027 L/m<sup>2</sup>-s) showed only a negligible decrease in performance.

#### **Observed wetland performance.**

The advances in Australian practice on the use of constructed wetlands for stormwater treatment were discussed by Wong and Breen (2002). The Australian design practices of constructed stormwater wetlands include the compartmentalization of constructed stormwater wetlands, testing of particle size distribution on suspended sediments conveyed by urban stormwater and the use of hydrologic effectiveness curves for selection of appropriate extended detention storage volume of constructed wetlands. The implementation of stormwater management practices, the Integrated Weed Management Program and the Blue-Green Algae Management strategy in the Botany wetlands resulted in reversing the decline of the wetland's ecological aesthetic and recreational values (Sim, 2002). The analysis suggested the need of a comprehensive monitoring program to substantiate the success or failure of restoration projects.



Dennett and Spurkland (2002) investigated the performance of a constructed wetland along Steamboat Creek, a tributary to the Truckee River. Monitoring of the wetland for one year showed that total nitrogen was reduced by an average of 42 percent, and the inorganic forms of nitrogen were removed more efficiently. The stormwater management system, including wetlands, at Intel's Ronler Acres Campus in Hillsboro, Oregon was described by Whitaker et al. (2002). The project uses extended dry detention basins, spreader bars at the outlets, and pervious, vegetated spillways to maximize stormwater infiltration. Also, bio-retention planting strips are incorporated in the parking lot landscaping to encourage infiltration of stormwater flows and reduce the use of irrigation water. Integration of the stormwater facilities with the mitigated wetland benefits local wildlife by creating a larger habitat block. Nietch et al. (2002) compared ponds and constructed wetlands for stormwater treatment. Compared to wet ponds, wetlands tended to have higher constituent concentrations in an effluent, inefficient nitrogen removal and preferential retention of phosphorus. The reuse of stormwater collected in retention ponds by nurseries was investigated by Norman et al. (2002) because of the potential for concentrating plant pathogens. *Erwinia* soft-rot bacterial accumulation on plants watered with water from nursery retention showed that without treatment of the runoff prior to use, there was a potential for introducing concentrated *Erwinia* onto the plants.

The paper by Higgins and Maclean (2002) reviewed the feasibility study for a sub-surface flow constructed wetland to treat runoff water from the Edmonton International Airport. A comparison between the Edmonton facility and a similar facility at Heathrow Airport was also presented. Subsurface transport and commensurate water quality transformations in a combined wetland/recharge basin was studied using bromide and rhodamine dye (Fox et al., 2002). Vertical infiltration rates varied across the basin; however, the variation in infiltration rates did not affect water quality transformations since an excess of carbon has accumulated in the wetlands sediments.

Guardo (1999) examined the nutrient removal ability and the hydrologic balance of a wetland located in South Florida over a period of two years. A 1540 ha wetland was constructed as a pilot project as part of a major study investigating methods to reduce nutrient discharges into the Everglades. Hunt et al. (1999) studied nitrate removals in a wetland located in North Carolina. The average concentrations were reduced from 6.6 to 2.0 mg/L. Nitrate mass removals were highly correlated to inflow concentrations in the warmer months when biological processes were more active, while the ammonia mass removals were highly correlated to inflow ammonia concentrations during the cooler months. Moustafa (1999) described monitoring results from Boney Marsh, Florida. Water-loading rate, water depth, phosphorus-loading rate, and water-retention time were examined for their influence on phosphorus removals. A simple quantitative diagram was developed that related these factors to phosphorus removal. White (1999) described the performance of a small wetland, located near Mobile, Alabama, for reducing suspended solids and nutrients in stormwater. The wetland system was constructed in January 1996 and monitoring results have shown that suspended solids and total phosphorus removals were significant (up to 90%), but that nitrogen removals were much less (about 20%).

Bacteria removal rates in a marshland upwelling system were reported by Rusch et al. (1999). Fecal coliform (FC) bacteria analyses indicated reductions from an average influent value of about 1500 FC/100 mL to an average of 2 FC/100 mL in 5-foot deep monitoring wells. A filtration model predicted that the  $k$  value for the first order removal reaction was 0.40 – 0.56/d and that the predicted content of FC in the wetland surface was near zero.

Scholes et al. (1999) described the performance of two wetlands located near London, United Kingdom. Removal efficiencies were greater than 65% for Zn, Cd, Pb, and Cu, at one site, while they were only about one-half of these rates at the other site. They also investigated the role of microorganisms in removing the heavy metals and two metal tolerant strains were found to accumulate Pb and Zn. It was believed that this ability may prove to be an important year-round pollutant removal process. Lead and petroleum hydrocarbons (originating from a municipal public works yard) were monitored in an urban wetland by Thurston (1999). Levels of these compounds in the sediments were higher near the inlet than elsewhere. It was concluded that sedimentation was the primary mechanism responsible for reducing the concentrations. Dombeck et al. (1999) examined the assimilation of trace metals in wetland sediments at the Sacramento (California) Regional County Sanitation District's Constructed Wetland Demonstration Project. Six metals (silver, cadmium, copper, mercury, lead and zinc) consistently exceed mass removal rates of 60%. Chromium and nickel were observed in concentrations approaching or exceeding the freshwater sediment Probable Effect Levels (PEL). It was expected that the nickel enters the wetland in a predominantly dissolved and strongly organic-complexed form.

### **Problems in wetlands.**

An overview of natural and constructed wetlands in Canada was presented by Kennedy and Mayer (2002). They found

that natural wetlands remain threatened by anthropogenic activities. They also found that the use of constructed wetlands is not as widespread as in the U.S. and that more research is needed before the technology will gain widespread acceptance (cold weather performance, more monitoring, design adaptation, and effects of constructed wetlands on wildlife).

Traver (2002) compared routing techniques in a stormwater-wetlands and found that the traditional storage-indication routing likely is not appropriate for stormwater wetlands, especially for smaller, water-quality storms. This concern was tested using a retrofitted detention pond and the results showed that the concern was valid and more research was needed.

The aquatic plant community was found to dramatically degrade in an urbanizing wetland study area located in Portland, Oregon, during studies by Magee et al. (1999). They were concerned that current wetland management practices were replacing natural marshes and wet meadow systems with ponds, further resulting in changes in the composition of the plant species assemblages. Revitt et al. (1999) studied the pollutant removal at two constructed wetlands. The behavior of suspended solids was the greatest concern, as higher outlet concentrations were consistently discharged compared to inlet conditions, presumably due to re-suspension.

Russell (1999) was very concerned about artificial wetlands providing suitable habitats for mosquitoes in Australia. The Ross River virus, spread by mosquitoes, was of special concern as it was responsible for thousands of cases annually of a disease that was severely debilitating. It was suggested that mosquito control should not rely solely on chemical and biological agents, but that the design parameters of wetlands can also be important. Shallow water and dense vegetation promote mosquito production, while deeper habitats with cleaner steeper margins, and more open water, produce fewer mosquitoes. Aeration and fountains can reduce larval densities and vegetation thinning can assist mosquito predators.

### ***Critical Source Area Controls***

Roseen et al. (2005) reviewed a procedure for normalized technology verification of structural and non-structural stormwater treatment practices, including manufactured treatment devices. The purpose was to evaluate the ability of these stormwater treatment practices and to characterize performance trends.

Chen and Adams (2005) examined the use of storage facilities for urban stormwater quantity control to mitigate the negative impacts of high stormwater discharges on receiving waters. The authors promoted the use of numerical modeling to determine the efficient size of these storage facilities to prevent either under-design or over-design. Phelps (2005) outlined the use of ASCE's Water-Quality Capture Volume methodology for sizing a Stormvault™ Mitigation System to meet the goal of stormwater treatment to the maximum extent practical. Anonymous (2005e) reported on the Development Concrete Washout System, a watertight roll-off bin, which can be used to collect concrete washout material and runoff. Mazza (2005) reviewed the use of a StormGate and StormFilter device at a scrap metal recycler in New Jersey to meet its discharge permit. The combination device was shown to be in compliance with the New Jersey stormwater management regulations. Kalli et al. (2005) described a steel composite pipe that could be used for stormwater drainage and an application where it was installed. Sobelman et al. (2005) reviewed the work of the California Department of Transportation to develop, test and finalize designs of trash-screening devices that can be installed in the existing storm drainage system. Gibbs (2005) reported on the use of CDS systems to improve the quality of stormwater runoff in the Poplar Creek watershed.

Catch basin inserts were evaluated using simulated rainfall by Morgan et al. (2005) for their ability to remove TSS and TPH. Results indicated that the inserts were capable of some removal of TSS and TPH. Kim et al. (2005d) examined the use of a metal membrane for filtering rainwater for reuse. The filterability was found to depend on the rainwater source, nominal filter size, filtration conditions and operation mode. The major fouling mechanism was pore blockage. Martin et al. (2005) investigated the potential of nonwoven geotextiles to treat polluted runoff water. The interior of the geotextile would contain a biomass that would aid in the degradation of the organic pollutants.

Jang et al. (2005) investigated the potential of using mulch to remove heavy metals from urban runoff. Of the three mulches investigated, the hardwood bark mulch had the best physicochemical properties for adsorption of metal ions. Liu et al. (2005a) investigated the adsorption kinetics for urban runoff metals on composite-oxide coated polymeric media. Metal ions with the highest adsorption affinity also were shown to have the highest rate constants. Observed porosity and the good model fit indicated a complex adsorption mechanism. Rangsvik and Jekel (2005) investigated the use of zero-valent iron to remove dissolved metals from stormwater runoff treatment. Zero-valent iron was found to be comparable in terms of removal ability and kinetics to commercial adsorbents such as ferric hydroxides. The concern for use with this

media would be the surface formation of iron oxides. Sansalone and Teng (2005) studied the transient nature of rainfall-runoff loadings delivered to a partial exfiltration reactor. A numerical model was used to simulate the effluent hydrograph of water flowing through the reactor. The use of calcium carbonate to bind phosphate in ion exchange filtration was explored by Yanamadala (2005) for urban runoff in Los Angeles (California). Denitrification was also encouraged since ammonia interfered with the phosphate binding. The purpose of these activities was to reduce the eutrophication of Madrona Marsh.

Pinto et al. (2005) studied a cement-based solidification/stabilization process for stormwater runoff solids residuals. Non-conventional differential thermal analysis was used to investigate the early hydration stages of a Portland cement containing the raw residual, two fractions of the residual and two additives. The studied concern was that the residuals were still reactive and that the reactivity would interfere with the stabilization and future use of residual-modified cement.

Bennett and Curtis (2001) tested a soil and vegetative contact treatment system (modified Howland Swale) for stormwater runoff from a fuel cell manufacturing facility. It was designed to remove copper and zinc (and thus overall effluent toxicity) to the point where the toxicity guidelines for the daphnid, *Daphnia pulex*, were met. The paper detailed the design and construction of the treatment system. To better understand the cost, maintenance requirements, and pollutant removal ability of sand filters, the California Department of Transportation retrofitted five Austin-style and one Delaware-style sand filters in the Los Angeles and San Diego metropolitan areas (Barrett and Borroum 2001) at their maintenance yards and park-and-ride facilities. Contributing areas averaged less than 0.7 ha. They had a relatively high cost of implementation, about \$350,000/ha treated. Pollutant removal was comparable to the performance observed in various City of Austin studies. Average suspended solids removal was 85%, total metals removal varied between 51% and 85%, while dissolved metals removal varied between 19% and 77%. Poor removal occurred for nutrients, especially nitrate, which was generally negative. No major maintenance has been required, although evidence of clogging is beginning to appear.

Hird et al. (2001) tested a passive treatment system, called a sorptive buoyant media clarifier (SBMC), for highway-runoff treatment. Pollutant removal efficiencies approached 95% on a mass basis total suspended solids (TSS), turbidity and particulate-bound chemical oxygen demand (COD), with the efficiencies not being affected by highly variable influents or extended periods of non-operation between storms. Prototype treatment capacity, at breakthrough, was 1000 pore-volumes treated. Liu et al. (2001a) investigated the potential of manganese oxide coated polymeric media (MOPM) for urban stormwater runoff treatment. The adsorption onto the MOPM was shown to be very sensitive to the pH, with the order of adsorption affinity on MOPM for the four divalent heavy metals studied being  $Pb(II) > Cu(II) > Cd(II) > Zn(II)$ . MOPM was seen to be a viable alternative adsorption medium for heavy metal removal in upflow filters, such as a SBMC. Further investigations of the surface of the MOPM (with a specific gravity of less than 1) showed that the surface area increased from 0.05 m<sup>2</sup>/g (uncoated media) to 27 m<sup>2</sup>/g for the same media after oxide coating (Liu et al., 2001b). The multiple-layer coatings enhanced filtration and adsorption of heavy metals. Investigation of materials (Liu et al., 2001c) with specific gravities greater than 1 demonstrated that cementitious materials could be coated effectively for use in stormwater treatment devices. The increase in surface area resulting from coating sand was not as significant as it was for the coating of the cementitious materials.

Pitt et al. (2001) reported on the results of laboratory-scale investigations into of upflow filtration as a means of increasing the run times of traditional stormwater filters (which tend to clog rapidly due to the small size of particles in urban runoff). Using laboratory-scale columns (4.8-cm inner diameter (ID)), a power equation to model downflow filtration was demonstrated. However, the coefficients for the laboratory sand filter were significantly different from those of the Lakewood, CO sand filters reported by Urbonas. Testing with a larger diameter column has been performed. Comparison of the two clogging tests indicated that a significant scale-up effect exists. Clark et al. (2001b) investigated the ability of filter media to retain previously-trapped pollutants under aerobic conditions, as would be expected if the filters were operated in an upflow mode. Permanent retention of heavy metals occurred even in an anaerobic environment. However, retention of nutrients did not occur. These results showed that aerobic conditions must be maintained in the media if nutrient removal and retention is important. The permanent retention of the heavy metals indicated that upflow filtration may be feasible where the primary stormwater pollutants are metals.

The use of jute and mulch as filtration media for stormwater runoff treatment was investigated by Wojtenko et al. (2001b). The effectiveness depended on the physical characteristics of the media. Both the sand content and the particle size of the filter media affected stormwater flowrates and the media's pollutant removal capacities. Removals as high as 100 % of copper (Cu) were observed for both mulch or jute. The removal of benzo(a)pyrene (B(a)P) depended on the

media-to-sand ratios and ranged from 68 to 94%. Brown et al. (2001) assessed the use of kudzu (*Pueraria lobata ohwi*) as a medium for of copper, cadmium, and zinc removal from low concentration waters. Kudzu was an effective adsorbent for heavy metals. Although its capacity for metals removal is less than commercial-grade ion-exchange resins, kudzu could be used at much lower cost, and may be useful in treating dilute mixed-matrix metal wastestreams, such as urban runoff, where the application of resins is not practical. Davis et al. (2001b) investigated laboratory-scale bioretention facilities to treat urban runoff. The roles of the soil, mulch, and plants for the removal of heavy metals and nutrients were evaluated. Reductions of specific metal removals ranged from 15 to 145 mg/m<sup>3</sup> per event. Moderate reductions of TKN, ammonium, and phosphorus levels were found (60 to 80%). Little nitrate was removed, with nitrate production noted in several cases. The mulch later in metal removal was found to be important.

Five sets of field test results of the Storm and Groundwater Enhancement System (SAGES) device were presented by Koustas and VanEgmond (2001). The SAGES device, a three-stage filtering system designed to be retrofitted to existing catchbasins/stormwater inlets, consisted of three separate filtering sacks consisting of gravel on top, sand in the middle, and granulated activated carbon on the bottom. The testing showed that the highest removal efficiencies occurred in conjunction with elevated influent suspended solids concentrations. Washout from the modified catchbasin appeared to contribute to increased effluent suspended solids concentrations that clogged the SAGES filter sacks.

In their paper, Cairo and Pujol (2000) advocated the use of membranes and biofilters for urban wastewater treatment. They demonstrated that the membrane and bio-filters produce a high quality effluent during both dry- and wet-weather flows. Lau et al. (2000) demonstrated that biofilters, even with a biofilm as young as three days, is capable of providing good removal efficiencies for both dissolved and sediment-adsorbed metals. During the nine-week operating of a laboratory-scale biofilter, 90% of the total Cu and Zn were removed. Field-testing of a submerged, aerobic biofilter for the treatment of stormwater runoff was reported by Mothersill et al. (2000). They found that the biofilter removed 97% of the suspended solids in the runoff; however, the suspended solids accumulation interfered with the nutrient removal through bacterial assimilation. Removal efficiencies of 64% for ammonia nitrogen were seen throughout the life of the filter. Backwashing to remove sediment was found not to be sufficient to maintain optimal biological filtration conditions.

Stormwater runoff contains a greater variety of pollutants than sanitary wastewater including such priority pollutants as benzene, PAH, pesticides and toxic heavy metals (Fan et al., 1998). These pollutants are usually associated with particles < 50  $\mu$ m which are difficult to remove using standard WWF sedimentation technologies, however, advanced sedimentation systems have shown effectiveness for removing such particles. Biological leaching was proposed as a method to treat urban stormwater sediments contaminated with trace metals. An iron oxidizing bacteria indigenous to the sediment removed soluble Cu (64% solubilization) and Zn (98% solubilization) in laboratory and pilot-scale experiments (Anderson et al., 1998). Lainé et al. (1998) provide a treatment system for urban stormwater designed to meet treated water standards suitable for bathing.

### **Filtration/sorption**

Compost is now accepted by the EPA as a technique for partially meeting the six minimum measures for best management of stormwater, during and after construction (Anonymous 2006a). Hatt et al. (2006b) evaluated biofilters for stormwater treatment and recycling with a focus on the hydraulic properties of flow as they affect pollutant removal. This paper presents preliminary findings on the effect of clogging on pollutant removal efficiency in conventional stormwater filter media.

Coarse monomedia filtration for preliminarily-treated wastewater during wet-weather flows was examined by Bentivogli and Davey (2006). These filters were able to reduce total suspended solids and biochemical oxygen demand at high loading rates for this wastewater stream to provide treatment during high-flow events. Shane (2006) reviewed the use of the Smart Sponge™ Plus in Long Island Sound watershed. The filtration system encapsulated and transformed hydrocarbon pollutants into a stable solid for easy recycling through waste-to-energy facilities.

Hong et al. (2006a) investigated the ability of bioretention media, including the mulch layer, to remove oil and grease from stormwater runoff. The mulch layer was very effective in removing these pollutants from the passing runoff. Huang et al. (2006b) discussed sorption of PAHs in urban runoff by altered aspen wood fibers. This study demonstrated that aspen wood fibers are a potential sorbent for PAHs and that chemical modifications of the wood matrix can effectively increase its sorption efficiency. Huang et al. (2006c) measured and modeled herbicide removal by mulch in laboratory batch and column experiments. A reactive transport model provided a good fit for the experimental breakthrough data for isoxaben; adjusting the exchange rate coefficients allowed breakthrough curves for oryzalin and diuron to be predicted

effectively using no adjustable parameters.

Ray et al. (2006) examined the removal of selected pollutants from simulated stormwater runoff by hardwood mulch. The hardwood mulch sorbed all the selected pollutants from a spiked stormwater mixture, including copper ( $\text{Cu}^{2+}$ ), cadmium ( $\text{Cd}^{2+}$ ), chromium ( $\text{Cr}^{6+}$ ), lead ( $\text{Pb}^{2+}$ ), zinc ( $\text{Zn}^{2+}$ ), 1,3 dichlorobenzene (DCB), naphthalene (NP), fluoranthene (FA), butylbenzylphthalate (BBP), and benzo(a)pyrene (B[a]P). Bertling et al. (2006) performed laboratory investigations in the fate of corrosion-induced copper runoff in soil columns. The results were correlated to the model Hydrus-1D™ using the Langmuir-Freundlich constants, and the model showed longer breakthroughs with increasing pH and organic content.

Eberhardt et al. (2006) investigated phosphate removal from stormwater runoff using refined aspen wood fiber treated with carboxymethyl cellulose and ferrous chloride. The modified media were shown to be better at phosphorus removal than the unmodified media. Seelsaen et al. (2006) investigated the effectiveness of several filtration media to treat stormwater runoff. The sorption efficiency of the different Enviro-media mixes showed that a combination of traditional (sand) and alternative materials can be used as an effective medium for the treatment of dissolved metal contaminants commonly found in stormwater. The application of using recycled organic materials and other waste materials (such as recycled glass) also added value to the products' life cycle.

Boving and Zhang (2004) investigated the use of aspen wood fibers to remove PAHs from stormwater runoff. Batch and column studies demonstrated that aspen wood has the potential to become an effective remedial agent for PAH in stormwater runoff or other PAH contaminated waters. Min et al. (2004) researched the removal of cadmium from solution using a base-treated juniper fiber. Compared to untreated juniper fiber, the base-treated fiber showed substantial improvement in removal ability.

Clark et al. (2004a and 2004b) reviewed the WERF-funded project that investigated the use of media filtration to remove heavy metals from stormwater runoff. The metals of interest for the research were zinc, iron, copper and a small amount of particulate-bound lead. Effluent concentrations below 10 – 15  $\mu\text{g/L}$  for all metals were not achievable. A TCLP evaluation of the used media indicated that in most urban runoff applications, media disposal would not be as a hazardous waste. The complete report, which also contains information on the use of swales for stormwater treatment, was published by WERF in 2004 (Johnson et al. 2004). Incorporation of these results with particle association research was presented by Pitt et al. (2004e and 2004f). Part of the earlier research focused on upflow filtration. This work was further developed and presented in Pratap et al. (2004). This project showed that upflow filters appeared to have a longer life at an acceptable TSS removal efficiency than conventional downflow filters due to the postponing of filter clogging.

Delolme et al. (2004) investigated the fate of heavy metals in stormwater sand filters when introduced in the presence of low complexing organic compounds such as acetate. Compared to a no-acetate experiment, zinc retardation was increased and the maximum outlet concentration decreased with increasing pH and acetate concentration. Marx et al. (2004) reported on the testing of catch-basin inserts and cartridge filters to treat stormwater runoff at the Port of Seattle's Seattle-Tacoma International Airport. The paper reviewed the monitoring scheme and the preliminary monitoring results. Tobiason (2004) investigated the potential of Downspout Stormfilter units to treat the dissolved zinc from rooftop runoff at the Port of Seattle's Sea-Tac airport. Peat and leaf compost media were capable of removing 81% and 76% of the dissolved zinc, respectively.

Liu et al. (2004) reviewed the laboratory testing of oxide coated buoyant media for its removal to remove heavy metals from stormwater runoff. The results showed that a thin coating of manganese oxide improved the adsorption capacity of the media. This media was then used in an in situ partial exfiltration reactor (PER). Sansalone and Teng (2004) demonstrated that the PER was effective at treating highway runoff. The results showed that the PER could reduce the quantity of runoff as well as at improving the quality of the runoff water. In addition, Teng and Sansalone (2004a and 2004b) demonstrated that the PER was capable of removing 71 to 96% of the solids, measured as a mass-based concentration, and 92 – 99%, measured as a number-based concentration.

Woodhouse and Duff (2004) investigated the use of an aerobic trickling filter to treat stormwater runoff from a log yard. Twenty-four-hour treatment at lower temperatures, 24 and 5° C, reduced BOD concentrations by 97 and 76%, COD by 91 and 64%, and tannins & lignins by 95 and 67%, respectively.

Aldheimer and Bennerstedt (2003) reviewed the methods used by the Stockholm Water Company to treat stormwater runoff from various land uses. The City of Stockholm in 2000 arranged a competition for improved stormwater treatment

technologies.

Alper (2003) investigated the removals of oils and organics from wastewaters, including stormwater, using MYCELX HRM (Hydrocarbon Removal Matrix). MYCELX HRM filters physiochemically captured and immobilized oils and organic compounds rapidly with negligible  $\Delta P$  and minimal contact time (typically less than one second). Abdel-Fattah et al. (2003) investigated the use of activated carbon, molecular sieves and naturally-occurring zeolites to remove lead from stormwater runoff from small arms ranges at Barksdale AFB, LA. The relative rate for lead adsorption was: molecular sieve 13X > chabazite > clinoptilolite > molecular sieve 5A > activated carbon.

Barrett (2003) investigated the performance of five Austin-style sand filters constructed by the California Department of Transportation (CALTRANS). Linear-regression analysis indicated that for sediment and almost all particle-associated constituents, effluent concentration was independent of influent concentration. Rejuvenation of the filter bed was required at three sites after 3 years of operation when the solids loading to the system was between 5 and 7.5 kg/m<sup>2</sup> of filter area. Johnson et al. (2003) investigated the potential of filter media and grass swales to remove heavy metals from typical urban runoff. The filters proved effective at removing influent concentrations down to a level of approximately 10 – 15  $\mu\text{g/L}$ . Removals to concentrations lower than that were not possible on a consistent basis.

Anonymous (2003d) reported on the use of the DownSpout StormFilter system to treat galvanized roof runoff at a plating company in Portland, OR. Kimura et al. (2003) presented a porous polypropylene (PPL) media for use in highway stormwater treatment filters. Using artificial highway runoff with constant flow and SS concentration, results of 70% or more of SS removal with 5 mm/hr and 50% or more with 10 mm/hr were obtained. COD removal efficiency was about 90% of SS removal efficiency. Landers (2003c) reviewed Western Kentucky University's installation of a stormwater treatment system to filter floodwater prior to diverting it to a cave system beneath the university. Vortechs filtration units were selected as the filtration setup. de Ridder et al. (2003) investigated the influence of flow rate and media gradation on the cost-effective design of stormwater filtration stormwater treatment practices containing perlite to remove TSS. The results indicated that media gradation and filtration rate acted synergistically to affect removal performance.

Anonymous (2003e) reviewed the incorporation of a stormwater treatment train into the expansion of airport facilities at Newark Liberty International Airport. The result is that water discharged from the units into the perimeter ditch is free of most of the solids and debris carried in stormwater, and the oil is reduced to 10 parts per million. Anonymous (2003f) presented the Moore Creek Stormwater Facility, a combination of detention ponds and a large underground storage tank that were designed to treat airport runoff. This treatment facility was installed at the new developments owned Greater Toronto Airports Authority.

Buchholz (2003) presented the living roof at Ford's Rouge River complex. The living roof is composed of a sedum grass-like blanket that reduces storm-water runoff, doubles the roof's lifespan, and insulates the final assembly area, generating an estimated 5 percent savings in energy costs.

Ray et al. (2002) evaluated the treatment of stormwater by filtering the runoff through natural organic materials. The results demonstrated that the fluxes through pure media were higher than those through a traditional sand bed, and that mixtures of the media with sand had fluxes that decreased as the sand quantity increased. Clark et al. (2002a) performed an initial evaluation on the effectiveness of upflow filtration to treat stormwater runoff. The results demonstrated that upflow filtration likely would provide longer filter run times. A concurrent study by Clark et al. (2002b) evaluated the effect on pollutant retention if stormwater filters of peat moss, activated carbon, sand, or a municipal leaf compost go anaerobic. Permanent retention of heavy metals, but not nutrients, was found during the studies.

Ellard et al. (2002) evaluated the potential of using direct filtration for wet-weather flows at sewage treatment plants or for SSO and CSO treatment. The filters were able to achieve near secondary effluent quality on suspended solids, CBOD and other contaminants and an innovative rapid backwashing technique was developed to clean the filters in order to handle the peak flows. Kang et al. (2002) presented a unique design for a municipal wastewater treatment plant equipped to deal with wet-weather flows (and operating data for 2000) where sand filters were used to filter an enhanced primary effluent and an activated carbon adsorber was used to polish the filter effluent prior to chlorination.

Treatment of runoff containing copper from roads and roofs by a special adsorber made from granulate iron-hydroxide and calcium carbonate was proposed by Boller and Steiner (2002). The results of testing of this adsorption trench showed average copper reductions of 96 – 99%. Tramonte et al. (2002) studied the transport and treatability of entrained

particulate matter from elevated transportation infrastructure by rainfall-runoff. The passive treatment device of interest was adopted from in-situ adsorptive-filtration systems that had been installed to treat storm water from an elevated section of Interstate 10 in Baton Rouge, Louisiana. Results indicate pollutant removal efficiencies of greater than 90% could be realized for total suspended solids (TSS), turbidity and total chemical oxygen demand (COD). Removal efficiencies were not affected by a highly variable influent composition or extended periods of non-operation between storms.

Approximately 1000 pore-volumes were treated and breakthrough of TSS and COD mass in the clarifier effluent nor excessive head loss across the adsorptive-filter media clarifier was observed, indicating treatment capacity has not been exceeded.

Davison et al. (2002) reported on the ongoing ETV verification of a hydrocarbon control stormwater treatment practice, the Hydro-Kleen™ Filtration System, which was designed for use with storm water catch basins and area drains to trap hydrocarbons, metals, sediments, and other storm water and surface runoff constituents. Testing consists of challenging the device with wastewater spiked with constituents the device claims to treat, as well as constituents that could have an effect on the devices treatment capabilities. By completing this ETV testing, NSF anticipates verifying the efficacy of the device will also validate the use of laboratory testing procedures as a method of obtaining reliable data with 'real world' implications and uses.

Sansalone and Hird (2000) reported the results of a prototype partial exfiltration reactor (PER) to remove metals such as lead, cadmium, copper, nickel, zinc and chromium from stormwater runoff. The PER proved effective at removing these metals from the runoff influent. Clark (2000) conducted a pilot-scale study on the ability of several potential filtration media for treating pre-settled urban stormwater runoff. The results of the study showed that modeling pollutant removal in traditional pre-settled stormwater runoff will be difficult because the low concentrations of many pollutants are near the removal limit of many of the filters. Clark also investigated modeling equations for the removal of solids by filtration from stormwater runoff. The model equations that fit the data were similar to the power loading equation proposed for the sand filters in Lakewood, Colorado. This project also investigated the effects of anaerobic conditions on pollutant removal by four of the media: activated carbon, sand, compost and peat moss. The results were that most of the previously-sorbed metals would not be released if the water in the filter turned anaerobic; however, many of the nutrients would be released and washed off the filter during the next storm event.

Sala and Hensch (2000) tested the ability of silica micro encapsulation (SME) for the treatment metals-contaminated wastewater. They found that the technology has potential and they proposed that it could be used to treat stormwater runoff such as by injecting it into a runoff flow stream. The end result was that the metals were permanently stabilized and the SME material could be disposed of properly once its capacity was exhausted. Wigginton and Lenhart (2000) reported the results of using an iron-infused resin for the removal of phosphorus from stormwater runoff. Testing of the iron-infused resin in the Stormfilter™ cartridge showed 38.6% removal of dissolved phosphorus, 44.9% for total phosphorus and 78.6% for total suspended solids. Increased removals were observed between test cycles, indicating that increased oxidation of the iron occurred which provided additional sites for phosphorus adsorption.

Sansalone (1999) conducted detailed tests of a partial exfiltration trench (PET) for passively treating highway runoff at a test site in Cincinnati, Ohio. Runoff treatment in the PET occurred primarily by sorption and filtration. Media in the PET was expected to last more than 10 years. The mass pollutant removal efficiency generally exceeded 80% during the one year of tests. Exfiltration from the PET to clayey glacial till soils also exceeded 30% for some runoff events. Stephenson et al. (1999) also described a pilot-scale stormwater runoff treatment system for highway runoff that used peat, sand, and rock to remove contaminants by sedimentation, filtration, and adsorption. Field-testing sites were located in Knoxville, Tennessee, and Frederick, Maryland. The primary goal of this investigation was the development and evaluation of practical remedial measures for treating highway runoff draining into sinkholes, where very rapid movement of surface runoff to the groundwater can occur. Urbonas (1999) presented a detailed description of the design approaches needed for effective sand filtration of stormwater. The approach uses the unit processes known to exist in urban stormwater runoff and within filter devices. The suggested design was based on hydraulic capacity of the filter media, which, in turn, was a function of the total suspended solids removed by the filter. Shibata (1999) reported on the performance characteristics of pipe installations with replaceable filters. The data collected included information on the quantity of sand and gravel trapped in the filter section, as well as the ability of the filter to concentrate pollutants from stormwater runoff.

A system that included settling tanks, sand and carbon filters, and an ion exchange unit treated stormwater runoff from an airport prior to infiltration (Vivona et al., 1998). A laboratory and parking lot investigation showed that porous pavements significantly reduced the volume of stormwater runoff, as well as the concentrations of undesirable constituents in

stormwater. Asphalt pavement had increased petroleum products (e.g, phenols) possibly due to the interaction of acid rain with the asphalt pavement (James and Shahin,1998). Laboratory experiments conducted over the past three years showed that activated carbon, peat moss, zeolite, and compost were efficient at removing toxicants such as organics and metals from the stormwater runoff and retaining them during subsequent flushings with distilled water (Clark et al., 1998a). Sand was found to effectively remove toxicants from runoff, but then released them in subsequent flushings. Field experiments evaluated several filtration media for stormwater infiltration and treatment potential (Clark et al., 1998b). An activated carbon and sand mixture showed the best overall removal, though a recommendation for settling of runoff prior to filtration is given. A two dimensional model was developed to assist in the design of infiltration systems for stormwater management (Guo, 1998). The model revised the Federal Aviation Administration method to predict the detention storage volume by maximizing the volume difference between the design storm runoff and the basin infiltration rate.

A filter with humic media was discussed for the treatment for stormwater runoff (Kratch, 1997b). The media, which contains a processed leaf compost, removes 90% of SS, 85% of oils and grease, and 98% of metals.

### **Treatment train systems**

Devices that combine or enhance unit processes are gaining in popularity to treat stormwater runoff. Dierkes et al. (2006) investigated a combination hydrodynamic separator-multistage filter for the treatment of stormwater runoff from metal roofs and traffic areas. The multi-stage filter was made of porous concrete. Eldridge (2006) described an oil-water separator designed to perform properly in a 10-year storm. Fassman (2006) examined the effectiveness of a manufactured treatment device compared to traditional stormwater control practices for removal of total suspended solids from urban runoff. Lee et al. (2006e) evaluated a hydrodynamic filter separator to treat urban stormwater runoff. Removals were improved compared to conventional hydrodynamic separators. Stidger (2006c) reviewed reported performances of manufactured treatment devices that might be suitable to treat urban runoff.

Annadurai et al. (2002) presented the factorial design analysis for turbidity and humic acid removal from stormwater using polyaluminum chloride (PACl) as a coagulant. The response surface method along with the Box-Behnken design of experiments was adopted to investigate the effects of pH, turbidity, and alkalinity of the suspension, the PACl dosage, and the dosed amount of humic acid. The PACl dosage was the most significant variable for turbidity removal, while that for humic acid removal was the suspension pH. A compromise will be needed to produce both large and loose flocs.

Greenway et al. (2002) monitored the spatial and temporal changes in stormwater quality through a series of treatment trains. The case study evaluated the performance of several devices in a 'treatment train,' including a sediment basin, constructed wetland, pond, CDS unit, ECOSOL unit, natural riparian wetland and a 600 m length of natural stream channel. The study showed that during a storm event there was little reduction in the concentration of total suspended solids throughout the treatment train due to limited detention time, however there was a decrease in soluble nutrients. The sediment basin, wetland, pond and riparian vegetation were all effective in removing these nutrients. The existing 600 m natural stream, lagoons and associated vegetation were effective at removing sediment and nutrients to achieve Water Quality Objectives of 15 mg/L TSS, 0.65 mg/L TN and 0.07 mg/L TP, at the end of the treatment train.

Pitt (1996) discussed the utility of the SLAMM stormwater quality model in designing watershed-scale pollution reductions and evaluated technologies for control of stormwater, such as catchbasin retrofit devices, a multichambered treatment train (MCTT) for critical source areas, and different filtration media. The Multi-Chambered Treatment Train (MCTT) was developed for removal of stormwater toxicants from critical source controls (Pitt et al.,1999). The MCTT was an underground device that has three main chambers: an initial grit chamber for trapping of the largest sediment and release of most volatile compounds; a main settling chamber (providing initial aeration and sorbent pillows) for the trapping of fine sediment and associated toxicants and floating hydrocarbons; and a sand and peat mixed media "filter" (sorption-ion exchange) unit for the reduction of filterable toxicants. A typical MCTT requires between 0.5 and 1.5% of the paved drainage area, which was about one-third of the area required for a well-designed wet detention pond. The research report described extensive development of the MCTT, including much stormwater treatability information that can be used by others who want to enhance performance of conventional stormwater control devices. A pilot-scale unit was tested in Birmingham, Alabama, at a large parking lot. During monitoring of 13 storms, the MCTT was found to have the following overall median reduction rates: 96% for total toxicity, 98% for filtered toxicity, 83% for SS, 60% for COD, 40% for turbidity, 100% for lead, 91% for zinc, 100% for n-Nitro-di-n-propylamine, 100% for pyrene, and 99% for bis (2-ethyl hexyl) phthalate (Pitt et al., 1998b). Corsi et al. (1999) reported the results of a full-scale test of the MCTT at a public works yard in Mileaukeee, WI, conducted by the USGS and the WDNR. Monitoring of 68 common and toxic constituents was conducted during 15 storms having rain depths ranging from 0.17 to 1.4 inches in depth, over a five-



month period. Very high reductions were found for all particulate-associated pollutants (reductions of 98% for SS, 88% for total phosphorus, and 91% for total ZN, for example), and somewhat less reductions for dissolved pollutant fractions (13% TDS, 78% dissolved phosphorus, and 68% for dissolved ZN, for example). The WI DNR also conducted a full-scale test of an MCTT at a 4-acre municipal parking lot at Minocqua, in northern Wisconsin, with similar high level removals noted.

### ***Airport Deicer Control***

Greenhough (2006) described the Airfloat Modular Pontoon System installed in an airport's runoff treatment lagoons to solve the buoyancy problems caused by polystyrene.

Buckles and Slone (2004) reviewed the management system implemented by the Bluegrass Airport in Lexington (Kentucky) to capture glycol-contaminated runoff during icing season. This runoff has a high BOD and requires treatment prior to discharge.

Walls et al. (2003) reviewed DFW Airport's recent deicing and water quality history. Specific examples of structural improvements, stormwater treatment practices, and other wastewater and stormwater initiatives at DFW were given. Aerators were incorporated to maintain water quality during an entire deicing season. Stover et al. (2003) presented a more detailed view of the deicing fluids stormwater treatment used at DFW Airport. The primary control were the nine Designated Source Isolation Deicing Pads.

Worrall and Revitt (2003) investigated the biodegradabilities of airport de-icing fluids (ADF), which can result in high BOD loadings in receiving waters, at low temperatures. Zitomer and Tonuk (2003) investigated propylene glycol deicer biodegradation kinetics. The study determined and compared the rates of ADF chemical oxygen demand (COD) removal in anaerobic complete-mix stirred tank reactors (CMSTRs), anaerobic filters (AFs), and anaerobic fluidized bed reactors (FBRs) treating acidified and nonacidified propylene glycol ADF at temperatures between 35 and 11°C. The most significant increase in overall COD removal rates (mg COD/L-day) were a result of biomass immobilization and increased biomass concentration in AFs and FBRs. Final COD concentration in the CMSTR were chronically high (circa 700 mg/L), and did not decline after five additional days of batch reaction time, whereas no chronically high final COD concentrations were observed in AFs and FBRs.

Revitt et al. (2002) investigated the biodegradability of glycol- and acetate-based aircraft de-icing fluids on airport surfaces at three temperatures below 8°C, because the high solubilities of these substances results in high BOD loadings in runoff and pose a serious toxicity problem in receiving waters. The reductions that could be expected in ethylene/diethylene glycol-, propylene glycol- and potassium acetate-based deicing fluids by bacteria, actinomycetes and fungi on airport surfaces would be 33.6, 30.6 and 15.2%, respectively. Rusten et al. (2002) investigated the potential co-treatment of spent airport deicing chemicals and municipal wastewater in Oslo. The deicing runoff was mixed with primary-treated municipal wastewater and treated using a moving bed biofilm reactor, coagulated and then treated by DAF separation. With that treatment, the mixed wastewater was suitable for discharge to the biological treatment stage at the municipal wastewater treatment plant. Results were better when treatment temperatures remained high.

The paper by Switzenbaum et al. (2001) provided a theoretical assessment of the potential environmental impact of airport stormwater runoff. It also described in detail current information on alternative deicing fluid application methods and materials, collection and treatment practices.

Periello et al. (1999) described a biological treatment system for treating stormwater runoff that was contaminated with de-icing fluid at the Syracuse (New York) airport. During winter deicing operations, spent deicing fluid, combined with storm runoff, was collected and held in large treatment lagoons. When warmer weather arrives and deicing operations cease, the collected deicing fluid and combined stormwater runoff (deicing runoff) were treated in aerobic lagoons to reduce the BOD in the deicing runoff to levels suitable for discharge to the local receiving waters. Safferman et al. (1999) studied the treatment of stormwater contaminated with ethylene glycol originating from airport deicing operations using a bench-scale subsurface microbiological contactor. Zitomoer et al. (1999) discussed the use of anaerobic co-digestion of aircraft deicing runoff and municipal wastewater sludge. The high COD runoff can lend organics for increased methane production and the oxygen demanding constituents in propylene glycol deicing fluid were found to be readily converted to methane, with neither effluent BOD<sub>5</sub> nor TKN concentrations higher in co-digestion systems as compared to a conventional digester. They concluded that existing municipal digesters could be employed to convert the seasonally-generated deicing fluid organics to methane that could be used to run equipment or generate electricity.

## ***Combined Sewer Overflow/Sanitary Sewer Overflow Control***

### **General**

Several large-scale CSO/SSO abatement projects were discussed this year in the literature. Clarke (2006b) reviewed Niagara's partnership approach to sewer inspection and the use of the Sewer Scanning and Evaluation Technology to inspect the piping system. Landers (2006d) presented the decision issued by the US EPA and the state of New York to guide the remediation of Onondaga Lake. Parnell (2006) discussed the Jacksonville, Florida, project that addresses reducing sanitary sewer overflows (SSOs) caused by fats, oils, and grease (FOG) in the collection system. Wright et al. (2006) proposed a screening and prioritization tool for providing costs estimates for sewer rehabilitation and replacement.

Bachand and Gilbert (2005) reviewed the Baton Rouge (Louisiana) Sanitary Sewer Overflow Corrective Action Plan, which includes increasing capacity, storage and ballasted flocculation units to reduce the frequency of SSOs. Szabo et al. (2005) described the performance of a wet-weather treatment facility to control combined sewer overflows in Cincinnati (Ohio). Treatment included off-line sedimentation tanks and fine screening. Given the high pollutant loadings in the first part of the hydrograph, first-flush capture was the most effective at reducing pollutant loadings. Strauch and Wetzel (2005) reviewed how a small community tackled an I/I problem. The paper discussed the tasks performed by the municipality, the lessons learned and the interim results of the program.

Bach et al. (2005) reviewed the new sewer tunnels under construction in Vienna, Austria. These tunnels have sufficient storage capacity and drain to the treatment plant so that CSOs will be prevented. Maeda and Kushiyama (2005) described the "compact shield-tunneling method" designed for use in replacing and rehabilitating aging sewers as a means of preventing overflows. Reina (2005) documented the construction of a stormwater diversion tunnel that sends flood water to a holding tank until water levels receded. The construction of an underground CSO control tunnel in the Puget Sound (Washington) was described by DeMuth (2005). The tunnel has been designed to reduce the number of CSOs occurring in the area from 20 to less than 5. A procedure to size replacement interceptor sewer pipes using flow monitoring data was proposed by Lee (2005b).

Faure et al. (2005) reported on the multi-year use of a radar-based alert system to operate a sewer network. The alert system was based on the identification of intense rain cells in radar images. Lee (2005a) reviewed the use of storm flow data as a means of identifying the type of inflow and infiltration into the sewer system. Mitchell and Stevens (2005) reviewed the uses of detailed flow monitoring data in sewer systems and how to maximize the information extracted from the monitoring data set. Good flow monitoring allows for better characterization of I/I.

Weldon (2005) described the Moonlight Beach urban runoff treatment facility in California. The treatment facility has reduced the bacteria loads entering the Pacific Ocean at the beach. Case (2005) reported on the development of an ozone treatment facility to treat urban runoff entering Santa Monica Bay, California. Screening devices are planned as a pretreatment for the runoff. A Hydro-Brake Flow Control and stormwater storage facility is being used by the Seven Trent Water Company to alleviate flooding in Leicestershire village. The other benefit is that it operates under a fluctuating head and has no moving parts and needs no power (Anonymous 2005f). Mackie (2005) reviewed the installation of Storm Monsters™ - overflow screens – that are designed to remove particulate pollutants from CSOs. Wood et al. (2005) examined the use of high-rate stormwater clarification with polymeric flocculant addition. The use of the polymer did not increase the acute toxicity of the treated effluent. The clarifier sludge was severely polluted by several heavy metals and will require special disposal.

Vasconcelos and Wright (2005b) experimentally investigated surges in a stormwater storage tunnel. Generally, surge intensity was greatest when a hydraulic bore propagating towards the surge riser just filled the pipe cross section. The effects of air phase pressurization should be included in numerical simulations if ventilation is limited. Zhang (2005) introduced a basic regression approach with autoregressive errors to support statistical inferences with respect to the level of rainfall-derived inflow and infiltration. Improving prediction of I/I will improve the sewer system's ability to control SSOs.

Luyckx et al. (2005) developed dimensionless efficiency curves for several prototype CSO structures. These efficiency curves are mainly influenced by the settling velocity distribution of the sewer sediments. Loncar et al. (2005) described the hydraulic properties of U-shaped stormwater overflow facilities. Buyer et al. (2005) examined the use of a side weir to regulate the discharge of CSOs. The hydraulic behavior shows that the side weir provides a discontinuous evolution of water depth, resulting in a hydraulic jump. Pilot-scale testing of underflow baffles for the control of floatables in CSOs

was performed by Cigana and Couture (2005). Permanent capture decreased with an increase in the horizontal flow velocity, regardless of the baffle depth. The use of a flexible, floating dam to collect and store rainwater, stormwater and desalinated seawater was presented by Anonymous (2005c). The dam would create a floating reservoir for additional water supply.

Pleau et al. (2005) reviewed the global optimal control system implemented in Quebec's sewer network to manage flows and water levels in order to reduce the frequency and volume of CSOs. In addition, the cost-effectiveness of the system was reviewed. Maeda et al. (2005) outlined the development of a real-time control (RTC) system for the Tokyo sewer system. The RTC measures the rainfall volume and the water level in the pipe as part of its control program. The vulnerability of water quality due to accidents, failure and contaminated runoff events was shown to be elevated in intensively urbanized watersheds (Beck 2005). The author proposed that real time control be combined with integrated urban water management to improve sustainability of water resources.

Farmer et al (2004) described the design and integration of the new supervisory control and data acquisition (SCADA) system for the Milwaukee, WI, Metropolitan Sewerage District collection system. The new SCADA system uses ultra high frequency radio signals between 285 remote facilities and the central control station. The remote facilities include flow measuring stations, flow control structures, weather stations, pumping stations and the inline storage system (deep tunnel).

Rowe et al (2004) reported that utilities often find that the basic data and information needed to support good decisions is incomplete or has varying degrees of reliability. Therefore, whenever possible, the utility embarks upon a condition assessment program to improve their information and knowledge about the conveyance system.

Andoh (2004) concluded that combined sewers, which have served the UK and other developed countries for hundreds of years, have been responsible for major improvements in public health by reducing contact between humans and contaminated wastewater. An overview of the US EPA's continuing efforts to improve the management of municipal sewer collection systems, specifically to reduce sewer overflows, was presented by DeBell (2004).

Heath et al (2004a and 2004b) described how Nashua, NH, decided to reassess its CSO control approach that stressed sewer separation. The total cost to separate the city's 110 miles of combined sewers would be about \$250 million. The sewer separation work was disruptive to neighborhoods and businesses, and increased the volume of contaminated urban stormwater discharged to receiving waters. A hydraulic model and watershed-based planning approach was used to develop an alternative CSO control plan that maximized the use of in-line storage and minimized the total discharges to the receiving waters.

The US EPA's report to congress (Moore et al 2004) summarized the extent of human health and environmental impacts caused by CSOs and SSOs, which can have significant impacts which are mostly apparent at the local watershed level. They concluded that greater funding is needed to improve the US's wastewater infrastructure.

Portland, OR, used a hybrid contracting scheme, combining the scheduling advantages of design/build with the control of a construction manager arrangement, to address its CSO problems (Boyce et al 2004). The method enabled contractors and engineers to work together to find alternative methods of construction that saved both time and money.

Combined sewer overflows (CSOs) and sanitary sewer overflows (SSOs) continue to be an important source of water pollution throughout the world. The analysis of CSO abatement alternatives often proceeds in an evolving manner. Landside models are generally used to determine which outfalls need CSO abatement, sometimes in conjunction with receiving water quality models. Once CSO outfalls needing abatement are identified, an optimal level of abatement needed to achieve water quality standards can be determined. With the required abatement level determined, various methods of achieving that level can be explored. Many small-to-medium-sized communities with combined sewer systems are faced with regulatory mandates to prepare long-term CSO control plans.

Dwyer (2002) reviewed the 2001 Combined Sewer Overflow Report to Congress. The report benchmarked the status of CSO permitting and enforcement activities and the implementation of CSO controls in accordance with EPA's 1994 CSO Control Policy. It also identified key program challenges and next steps to be taken by EPA. The paper addressed the activities that EPA has taken and plans to take in response to the Consolidated Appropriations Act for 2001, and in meeting a requirement to prepare the second Report to Congress that is due in December 2003.

The paper by Siddique (2002) described the District of Columbia Water and Sewer Authority's proposed approach for incorporating wet-weather provisions and CSOs into the water quality standards. The Large Diameter Sewer Assessment Program (LDSAP) of Sanitation District No. 1 in Kentucky and the James Avenue Pilot Project was reviewed by Cantrell and FitzGerald (2002). The program was developed to prioritize the District's collection system using a customized criticality analysis procedure and then to set priorities for detailed structural inspection and grading. Walker et al. (2002) presented an overview of the Massachusetts Water Resources Authority Long-Term Control Plan (LTCP) for CSO control. The plan used a watershed approach to assess CSO impacts in the context of other pollution sources in the watershed and resulted in the decision to eliminate CSOs in critical use areas and cost-effectively minimize them in non-critical use areas. Adoption of the plan was contingent on changing existing water quality standards in areas where CSO would remain, which was accepted provided that certain specific conditions were met. Doshi et al. (2002) provided an overview of the key elements of the regional SSO control program contained in the City of Detroit's long-term wastewater master plan. Examples were also provided of how the seven key elements have been applied in the service area and the corresponding results. The paper by Bouchard (2002) focused on the how the planning components of infrastructure management were used in long-term infrastructure management in Champaign/Urbana (Illinois). The process exposed the need for expansion of one treatment plant and rehabilitation at both plants.

Godsey (2002) presented the engineering toolkit used by the Central Contra Costa Sanitary District to effectively determine the most effective method/technology for improving the performance of the sewer system. The paper by Marcotte et al. (2002) described the selection of Washington, D.C.'s CSO Draft Long-Term Control Plan, and the difficulties encountered in balancing costs, water quality benefits and public expectations. Hassey et al. (2002) presented an overview of Sacramento's CMOM project for SSO control, which contained an extensive audit of the system and identified necessary improvements. Short-term and long-term improvements were identified in three key areas: (1) SSO reduction; (2) asset management; and (3) improvement of information management. Smith et al. (2002) reviewed the second phase of the long-term control plan for CSO abatement in Augusta, Maine. The program focused on the West Side Consolidation Conduit and the design challenges it faced: narrow project corridor, active railroad, steep and unstable banks, and coordination with a rails-to-rail project. Walker and Donahue (2002) reviewed the CSO long-term control plan for Alewife Brook in the Boston, MA suburbs and the problems that arose when the investigation showed that the brook's dry-weather bacteria levels did not meet standards and that elimination of CSOs by sewer separation would increase flooding in the Brook. These problems are currently being addressed in the plan development.

Geiger and Schuster (2002) reviewed the City of Concord's (NC) CMOM program and its sanitary sewer evaluation study. The city has replaced 20,000 feet of pipe a year since 1994 to reduce SSOs. Ablin and Kinshella (2002) provided an overview of Phoenix's Lower Buckeye sewer emergency repair, rehabilitation, and replacement project. The project included sewer investigations, pipeline collapse, installation of 790 feet of 84-in diameter sewer in an area with utility conflicts; and bypass pumping of 150 MGD. Allen and Yee (2002) reviewed the collaborative service lateral rehabilitation program in Sacramento County. The program is a joint effort of the following two work groups in the District: the Design and Rehabilitation Engineering section and the Special Projects section. Fee and Ramirez (2002) reviewed an emergency project that included the cured-in-place lining of approximately 1,200 linear feet of 30- and 36-inch interceptor sewer and the implementation of a 30-MGD bypass pumping system. Davis et al. (2002) reviewed Onondaga County's (Syracuse, New York) CSO program and the technologies that are incorporated into it: Vortex treatment, storage, sewer separation, netbags, floatables boom, screening and disinfection. Giguere et al. (2002) presented the City of San Diego's five-year program to inspect and assess the condition of 1,000 miles of its 3,000-mile sewer system. The paper discussed the key challenges and benefits achieved through the development and implementation of GIS-based computer software system to store and evaluate the data and video collected in the inspection program.

The paper by Brombach (2002) provided an overview of the European history of urban stormwater practice, specifically focusing on Germany and discussed the latest trends in technical equipment to reduce the impacts of CSOs. Fujita (2002) studied the improvements in the combined sewer and flood control systems in Japan, including the recent changes in technology. Chan et al. (2002) presented the City of Edmonton's Interconnection Control Strategy, which has been designed to eliminate or minimize the discharge of sanitary and combined sewerage to the storm sewer system and the North Saskatchewan River. The focus of the Strategy has been on monitoring the sanitary sewer to storm sewer interconnection activity and fixing dry-weather interconnections.

Oldenburg et al. (2002) reviewed the separation of wastewater streams in Luebeck Flintebreite. The analysis showed that the separation of wastewater into blackwater, graywater, and stormwater was more cost effective than other systems.

O'Neill (2002) discussed the Topeka, Kansas best management practices for reducing CSOs. The recommendations from a workshop were sewer separation and diversion of stormwater into a construction wetlands system. Frehmann et al. (2002a) investigated stormwater management in an urban catchment through simulation of the system. It was shown that the management measures, especially source control measures, could significantly reduce the CSO volume and pollutant discharge load, resulting in a positive impact on receiving water quality. Pond et al. (2002) presented the use of stormwater micromanagement systems (temporarily storing stormwater in many varied locations on the surface and, as needed below the land surface, near to where it falls as a method of preventing persistent basement flooding. The goal is not to prevent the volume from entering the system but to delay the entry of the runoff to the hydraulic capacity of the sewer system.

Hollenbeck (2002) reviewed 100 projects performed by RJN Group, Inc., throughout the U.S. in the last 25 years, for lessons learned in terms of investigating sewer systems and determining rehabilitation needs. The key variables in these programs included: inflow source distribution/flow meter spacing; rainfall/inflow design storms; private/public sector source distribution; system rehabilitation procedures; and rehabilitation costs. Olthof et al. (2002) reviewed the ongoing initiatives of the City of San Diego in reducing SSO occurrences. These initiatives include an accelerated cleaning program for all 3,000 miles of pipe, a CCTV inspection program and a capital program, which are coordinated with a GIS implementation. Rietsch et al. (2002) presented a new concept for evaluating all relevant processes occurring in stormwater structures, including combined sewers, and especially focusing on sedimentation processes. The possibility of enhanced retention of pollutants by using lamella separators was also discussed.

Agbodo et al. (2002b) introduced the use of gage-adjusted radar data to estimate precipitation volumes for wastewater and water resources planning studies for either sanitary or combined sewer systems; the methods to estimate the optimum number of rain gages for precipitation-volume measurement; the advantages and disadvantages of alternative measurement approaches; and the use of radar precipitation data for enhancing collection systems planning, development, and operations and maintenance. The paper reviewed the data collected in South Florida and contained a cost comparison of gage-adjusted radar and rain gage methods for precipitation measurement. Boccardo et al. (2002) reviewed the methodology used in the Stony Brook Illegal Connection Investigation in Boston, Massachusetts, to identify wastewater discharges in Boston's storm drainage system. Water-quality investigations during dry weather flow for pH, conductivity, temperature, ammonia and surfactants was followed by placing sandbag barriers in the pipe to confirm no dry-weather flow and the use of dye testing where dry-weather flow was found.

Keefer and Gilbert (2002) reviewed the North Central Sewer Separation project in the Columbus, Ohio downtown area. The paper included a discussion of the problems that were encountered by working in a historical area and the solutions that were developed with federal, state and local concerns in mind.

Brilhante et al. (2000) described the use of USEPA's Storm Water Management Model (SWMM) in CSO analysis. As a project proceeds through planning and design of CSO abatement, the model would be refined to test alternatives and set the detailed specifications. Lyon (2000) advocated a systematic approach to CSO control systems. The first step would be to examine wastewater treatment plant flows during dry and wet weather periods to determine the effectiveness of the CSO control system in capturing base sanitary flows. Second, all available data should be examined to determine how the system is affected by wet weather events and the probable relative magnitudes of CSO loadings to area receiving streams. This approach was successfully used in Charleston, West Virginia, to identify a low-cost solution to minimize CSO loadings to the Kanawha River. The City of Niagara Falls, New York, also used a step-wise approach in dealing with levels of infiltration and inflow in its collection system, which are creating service problems for residents and impacting the City's ability to redevelop its eastern portion. The City sought the cooperation of state officials when addressing the problem which seemed to keep from imposing undue financial hardships on the ratepayers and residents (Roll and Benson 2000).

Gomis et al. (2000) analyzed the factors involved in the response of an urbanized drainage basin with a combined sewer system to a rainfall event. In the case of moderate and heavy rainfall, the coefficient of flow was independent of the rain characteristics and was close to the imperviousness coefficient. For lighter rainfall, flow was determined by the initial surface state of the drainage basin. Lindholm and Nordeide (2000) evaluated the relevance of different methods and criteria for choosing the best system to solve a CSO problem in Oslo, Norway. A simple EIA analysis with a pragmatic choice of criteria was found most suitable for choosing between conventional or nature-based solution. Marsalek and Giulianelli (2000) presented a comparative analysis of urban drainage challenges in Italy and Canada. Canada offered stormwater management practices and satellite CSO treatment; Italian contributions included effective layouts of

distributed CSO storage and operation of such systems in real time. The City of Livonia, Michigan used Geographic Information Systems (GIS) technology to enhance the implementation of its illicit discharge elimination program. As a result, record keeping was improved, problem areas identified earlier, and joint efforts with surrounding communities and agencies in Livonia simplified (Rohrer and Beckley 2000). Smith et al. (2000d) presented observations and determined causes of increased odor production and release in recently separated collection systems. The authors also presented the corrective actions which have been shown to reduce these odor effects. Hydraulic/hydrologic modeling was conducted using the EPA SWMM model in support of the design of a CSO consolidation/relocation project in South Boston. The SWMM model was used for design, facilities planning, The model was refined and recalibrated as needed to provide greater confidence in the design flows. A 50-year storm that occurred during the flow monitoring period provided confidence that the recalibrated flows were appropriate for use as design criteria for the CSO consolidation/relocation conduit (Walker et al. 2000b). A detailed hydraulic model was used to simulate alternative flows scenarios to and through the treatment plant as part of a city-wide CSO Strategy in Edmonton, Alberta, Canada (Ward et al. 2000).

Buchholz et al. (2000) used a computer model to evaluate the performance of a CSO retention treatment facility in Michigan. To comply with the requirements of the Federal Clean Water Act, improvements to the system were accomplished by additional storage of CSO, removal of storm water inputs to the treatment facility, and maximization of the use of the existing interceptor system. The regulatory impetus for this work was Michigan's CSO Policy, which states that CSOs must be eliminated or controlled to protect designated uses at times of discharge. The level of control may be determined either by a water-quality based demonstration or by accepting a presumptive level of treatment described in terms of a retention/treatment structure (Cowles 2000). Six years after the EPA's 1994 CSO Policy was issued, only two of the 30 States with CSO municipalities have taken actions to implement the water quality provision of the federal CSO policy. Conditions in urban areas and other point and non-point sources of pollution may make current water quality standards in some urban waters no longer appropriate or unable to be met, regardless of CSO controls that are implemented. Dwyer and Huang (2000) have advocated a review and revision of existing water quality standards in order to save unnecessary expenditures, ensure that proper water uses are maintained, and significantly improve the implementation of the water quality-based provisions. The expectation of the CSO Control Policy was that long-term control plans (LTCPs) would be developed to meet water quality standards (WQS) and, where appropriate, states would revise their WQS to reflect the difficulty in achieving compliance with current bacterial standards in urban areas during wet weather events. Slack and Nemura (2000) discussed the difficulties CSO communities face in obtaining revisions to WQS as part of developing LTCPs that are cost-effective and protective of water quality and human health.

Rowe (2000) presented an overview of SSO control strategies to management and engineering staff who represent a National Pollution Discharge Elimination System (NPDES) permittee. The U.S. EPA's Environmental Technology Verification (ETV) Program was established to overcome the numerous impediments to commercialization of innovative environmental technologies, particularly the lack of credible performance data. Stevens and Frederick (2000) described the ETV approach and two recently initiated pilot programs for verification testing of source water protection technologies and wet-weather flow technologies. USEPA is currently completing the issuing of a SSO Rule that will add control of SSO to the NPDES permit requirements. Lai et al. (2000) provided a preview of the rule and described the advantages of employing a collection system modeling approach for capacity analysis and development of the SSO mitigation plan. Historically, EPA and the States have allowed municipal facilities to bypass peak wet weather flows around the secondary treatment process, to disinfect the rerouted flows, and then blend the peak flow with the other, more highly treated, effluent. A reinterpretation of the federal "bypass" rule by some regulators includes the position that if rerouting causes any of the waste stream to skip a treatment process, bypassing is illegal (Hall et al. 2000).

Many large-scale SSO, CSO and WWF control programs are underway worldwide. The city of Evanston, Illinois, successfully undertook a large-scale project to control basement flooding from combined sewer backups by limiting the entry of wastewater to the sewer system to exactly the quantity that matches the conveyance capacity. Figurelli et al. (2000) evaluated the performance of the program against the following criteria: technical hydraulic performance (basement backup and street ponding performance), citizen perception of performance, maintenance concerns and costs, capital costs, level of construction disruption, and public acceptance. The City of Saginaw, Michigan completed the second phase of a comprehensive CSO control project that was required to meet NPDES Permit requirements. Hubbell and Phillips (2000) have provided information on the historical background of the existing Saginaw sewer system, NPDES permit issues, project planning requirements, design considerations, construction, operations, and performance. A multifaceted project including highway improvements, development of waterfront parks, and water quality improvements resulting from CSO abatement was begun in New York, New York. According to Kloman et al. (2000), the New York City project has served as an example of inter-agency cooperation to benefit the community and environment.

Kok et al. (2000) reviewed the work of Canada's Great Lakes 2000 Cleanup Fund, which is administered by Environment Canada, in supporting the development and implementation of cleanup technologies to control municipal pollution sources, to clean up contaminated sediments, and to rehabilitate fish and wildlife habitats. The Urban Drainage Program has been instrumental in advancing the state of the art in CSO and stormwater management in Ontario (Kok et al. 2000). The Philadelphia Water Department's (PWD's) CSO program goal is to improve and preserve the water environment in the Philadelphia area and to fulfill PWD's obligations by implementing technically viable, cost-effective improvements. The PWD's strategy to attain these goals has three primary phases (currently being implemented): (1) continued implementation of a Nine Minimum Controls comprehensive program; (2) planning, design, and construction of 17 capital projects to reduce CSO volume and frequency; and (3) a commitment to complete comprehensive watershed-based planning and analyses to identify the actions needed to further improve water quality and quantity dynamics in local water bodies (Marengo 2000). In 1998 the City of Rockland, Maine, began a major capital improvement program of its wastewater collection and treatment system and included provisions for high-rate treatment of CSO flows (Freedman et al. 2000). Clifford (2000) reviewed efforts by the English and Welsh water industry to solve urban CSO pollution problems and to develop guidance for integrated stormwater management. The Northeast Ohio Regional Sewer District has undertaken the lead role in CSO management in the metropolitan Cleveland area and has recommended a CSO control plan. This plan includes several technologies that will maximize use of the existing system, as well as new facilities for CSO control (Matthews et al. 2000). Various public utilities in Broward County, Florida have implemented sanitary sewer rehabilitation programs which are expected to include a minimum of at least 7,796 repairs (Larsen and Garcia-Marquez 2000). Seigle et al. (2000) reported on the negotiated long-term CSO control plan for Manchester, NH. An inventory and structural evaluation of CSOs in towns (greater than 30,000 inhabitants) in Slovakia was carried out during a three-year joint research project of the Water Research Institute and the Department of Sanitary Engineering of the Slovak Technical University in Bratislava (Sztruhar et al. 2000).

Riverine litter occupies a spatial and temporal position in any systematic analysis of river systems and was a problem that was increasing in scale. Quantifiable source factors of litter in the river Taff, South Wales, United Kingdom, system were found to be mainly two - sewage inputs through CSO and fly tipping. Whilst sewage-derived material constituted approximately 23% of all items on the river Taff, large quantities of waste, especially plastic sheeting, originated from fly tipping sites (Williams and Simmons, 1999). If the storage in the rain water tanks can be used to flatten the rain water runoff, rain water tanks can have an additional benefit. The effect of rain water tanks on the CSO emissions was therefore investigated with a reservoir model. Compared with storage in the combined sewer system or at the overflow, storage in rain water tanks will be more efficient in reducing the overflow emissions (Vaes and Berlamont, 1999). Milina et al. (1999) described the results of an integrated model development and its application to the Hovringen wastewater system in Trondheim, Norway. Major model development needs concern the integration of sewage production, transport and treatment simulation, the interface with existing databases and the possibility of simulating processes that were controlled in real time. The developed integrated model has been used to design the treatment process as well as static and dynamic measures in both the catchment and the sewer system.

The use of sand and other media filters was gaining acceptance in the field of urban stormwater structural best management practice. Much work has been done to develop local design guidance, such as in the State of Delaware and in Austin, Texas. The suggested design of the media filters for stormwater runoff treatment was based on hydraulic capacity of the filter media, which, in turn, was a function of the total suspended solids removed by the filter (Urbanas, 1999). Welsh et al. (1999) provided a discussion of the use of on-street storage as an effective means to control stormwater runoff. It focuses on the success achieved by using street storage in two communities in Illinois and includes a description and evaluation of how this technology eliminated surcharging and basement flooding, complied with regulations and proved to be a cost-effective solution which earned public support.

As a demonstration project, the Auckland Regional Council had designed and constructed a filter device to treat stormwater from a 3000 m<sup>2</sup> carpark. Eight sand filters were installed in 1993 to provide stormwater treatment at a new Alaska Marine Lines, Inc. barge loading terminal along the Duwamish River in Seattle, Washington (U.S.A.). Constructed according to the "Delaware" design, each consists of a settling chamber where relatively large solids can settle before the flow passes over the weir onto the sand for filtering. A performance study monitored the flow rate through two sand filters and the water quality of inflow and outflow (Horner and Horner, 1999). Because the Urban Community of Bordeaux had been hit by important floods in 1982, it was decided to set an efficient management system to control stormwater flows. Studies have showed the significant impact of discharged effluents on the environment, especially with regard to the contribution from CSO. Therefore, it was of importance to improve the management of the

sewer system during rain weather and to foresee the design of new storage structures and new treatment plants to integrate the environmental protection target (Briat et al., 1999).

Overviews of WWF controls were provided by two papers. Buriean et al. (1999) summarized a comprehensive historical literature review, highlighting the development of WWF management from ancient times to the present. The relationship between past developments, the current state, and the future of WWF management were addressed by identifying several lessons learned. Barner (1999) discussed the problems associated with stormwater management in a karst terrain in Springfield, Missouri. The lack of recognition of sinkholes as integral parts of dynamic hydrologic systems may result in problems with on-site/off-site drainage.

CSO control planning. Bontus et al. (1999) described Edmonton's proactive long-term CSO control plan, which brought the opinions of stakeholders, including Alberta Environmental Protection, river user interest groups, the local health authority and a representative of the University of Alberta, to the technical process, and ensured that their input was considered in developing the plan. Newhouse et al. (1999a) described the development of a long-term CSO abatement plan by the City of Richmond, Virginia. The protection of recreational uses of the James River was a priority for the city. City officials at Richmond, Virginia, agreed to a joint venture with the Richmond Riverfront Development Corporation that would eliminate CSO and restore the Haxall/Kanawha canal system. Engineers not only had to ensure that each project's requirements and objectives were met, but also address technical and environmental issues without compromising the area's recreational and commercial needs or diminishing its aesthetic appeal or historic character (Newhouse et al. 1999b). Based on interviews conducted during 1998, Slack and Freedman (1999) compared and contrasted current state-to-state and community-to-community differences in efforts to control SSO. The variability in abatement efforts were tied into the proposed language for EPA's forthcoming Federal Register notice that will clarify NPDES requirements for municipal sanitary sewer collection systems and SSO.

Other authors addressed the steps taken to achieve CSO and SSO control. In the early 1990s, the City of Auburn, New York, was faced with the challenge of achieving CSO abatement and sanitary and interceptor sewer overflow (SSO) elimination in its extensive, aged sewer system and achieved their overflow abatement goals by: (1) quantifying and characterizing sewer overflows to provide a basis of design for abatement-related system improvements; (2) selecting a principal approach of conveyance of excess WWF to a centralized high-rate treatment facility for a majority of the sewer system; and (3) re-evaluating and applying alternative technologies to select portions of the sewer system to minimize project costs. Li and Banting (1999) presented a case study using a GIS planning tool for stormwater quality management in urbanized areas. The planning tool comprised five steps: (1) definition of stormwater retrofit goals and objectives; (2) identification of appropriate retrofit stormwater management practices; (3) formulation of stormwater retrofit strategies; (4) evaluation of Strategies with respect to retrofit goals and objectives; and (5) selection of stormwater retrofit strategies.

Markowitz et al. (1999) described the conceptual ideas, cost analysis and other issues that effect implementation of watershed controls within the scope of a CSO control plan. Osaka City's (Japan) major measures for improving CSO include: (1) leading as great a volume of pollutants as possible to WWTP in dry weather to avoid the pollutant accumulation in sewers; (2) storing first flush, which contains a large volume of pollutants, for treatment at WWTP after rainfall; and (3) treating WWF directly. Shiomi (1999) discussed the methods used to achieve these measures and reports the conclusions drawn from the cost-benefit analyses. A 5-year cooperative study of the Cumberland River at Nashville (Tennessee) allowed Nashville to alter its CSO control plan, eliminate two major detention tanks, and save \$106,000,000. The study showed that neither DO depletion nor toxic material discharges were a problem, and that a fecal coliform bacteria problem would not be solved by planned detention tanks, or even by eliminating all CSO (Thackston and Murr, 1999). Today conventional planning and reconstruction of both the drainage network and the treatment plant for the same urban catchment was usually subdivided into two nearly independent parts. Walther and Rohlring (1999) demonstrated optimal design of a combined sewer system and sewage treatment plant for a German city with 500,000 inhabitants by simulating the operation of both systems simultaneously, and costing each system based on a variety of possible configurations of the other.

Additional published accounts of the experiences of various municipalities in controlling CSO and SSO provide guidance for those beginning a WWF control program. The City of Auburn's (New York) sewer overflow abatement program summarized by Gorthey et al. (1999) can serve as a guide and source of information for other municipalities faced with achieving sewer overflow abatement. Igwe et al. (1999) focused on design and operational issues encountered during the evaluation of the Rouge River National Wet Weather Demonstration Program, which includes the construction of nine CSO detention basins of varying sizes and design. The City of Akron (Ohio) has successfully implemented the



demonstration approach to CSO control and has supported controls that will result in measurable improvement of recreational use, aquatic life use and aesthetics of the receiving streams, including concepts other than traditional collection system alternatives. These include riparian setbacks in undeveloped areas, stream restoration, linear parks or greenways and artificial riffles for stream aeration. Merritt and Wilkinson (1999) presented studies on wastewater collection systems, including: collection system design and construction; wet weather control; infiltration and inflow; SSO; innovations in sewers and collection systems; infrastructure modeling; sewer pipe maintenance and rehabilitation; sediment transport, deposition and erosion in collection systems; and sustainable development. Protopapas (1999) reported the methodology used by New York City to abate pollution from CSO in the receiving harbor waters based on a case study for the East River facility planning. The approach integrates water quality studies, facility planning, environmental assessment and public participation. Wong et al. (1999) presented a case study that covers the planning, design and operation aspects of implementing a pumping drainage system into the existing drainage system at the Pasir Baru residential area in Kuala Lumpur (Malaysia) city. Zettler et al. (1999) discussed how the City of Fort Wayne, (Indiana) has successfully applied a consistent set of GIS-based information management tools to support both their CSO planning efforts and preliminary design process.

Both typical and non-traditional areas must be considered in order to eliminate SSO and prevent future, potential overflows from occurring. Community and wastewater leaders must change the influences which allowed SSO in the first place — insufficient funding, short term thinking, inadequate maintenance, insufficient inspection, lack of widespread understanding of the issues and other such factors (Jurgens, 1998). The town of Smithville, Tex. (Myers, 1998) demonstrated how a small city with a population under 5 000 can address and implement sound water-quality practices as an integral part of handling stormwater runoff and implementation of an overall drainage plan. A case study in the Great Lakes region of Can. illustrated the planning process for development of stormwater retrofit strategies for existing urbanized areas using downspout disconnection, oil/grit separators, exfiltration systems, and stormwater ponds (Li et al, 1998). Through a \$1 billion wastewater improvement program the Miami-Dade Water and Sewer Department (Fla.) achieved a 56% reduction in the occurrence of SSO over a three year period and a 66% reduction in the total volume of SSO (Cardozo et al., 1998). The department also met 800 other milestones, some of which carried stipulated penalties of up to \$10 000 per day for noncompliance.

To meet a 2001 deadline to eliminate SSO, Fort Worth, Tex. commenced a tunneling project to redesign its sewer system in 1995 (Sahu et al., 1998). The tunnel would result in a shorter, more direct route for the sewer and offered a potential savings of \$4.5 million over feasible open-cut routes. Richmond Va., which was required to control two CSO points by retention storage for one month design storms by the Va. Water Control Board, chose to install tunnels because of the minimal disruption during construction and their low environmental impact (Harksen et al., 1998). The 3 960 m long and 3.35 m diameter North Dorchester Bay consolidation conduit will provide complete capture and relocation of discharges from seven CSO outfalls tributary to Dorchester Bay and the bathing beaches of South Boston, Mass. (Heath et al., 1998b and 1998c). Columbus, Ohio implemented the minimum control of maximizing collection system storage as part of the CSO Operation Plan (El-Hosseiny et al., 1998b). Investigations of the Chestnut St. Regulator indicated that a system separation may not reduce the number and duration of overflows from the combined system and that separation may have a negative impact on the receiving stream.

The MWRA's recent CSO facilities plan provided that floatables control technologies be applied to 48 CSO outflows (Walker et al., 1998). After testing several floatable control mechanisms, the authority found baffles most cost effective, though little data was available about baffle performance or maintenance. The Boston Water and Sewer Commission undertook a study of alternatives to the MWRA's proposal of a screening and disinfection facility to deal with CSO and recommended all of the combined sewers along the Stony Brook Conduit be separated (Keohan, 1998). The MWRA accepted this alternative and revised its CSO plan. A cooperative project with the U.S. EPA and the Association of Metropolitan Sewerage Agencies to track improvements and benefits associated with CSO control involving "stakeholders" interested in CSO control identified the use and benefits of performance measures and recommended a process for selecting among 24 practical and useful performance measures (Sullivan et al., 1998). Turner and Reindel (1998) proposed the establishment of a national database on CSO outfalls.

The U.S. EPA and Tex. Natural Resource Conservation Commission mandated that Houston, Tex. control wet-weather overflows caused by excessive I/I during rainfall events by December 1997. A long-term simulation model was used for the construction of wet-weather facilities as part of the SSO control strategy for three service area collection systems (Maa et al., 1998a). Relief of Houston's collection system bottle necks for the short duration, high intensity thunder storms of the Gulf Coast Region was found to be a more cost-effective alternative than rehabilitation (Maa et al., 1998b).

Based on 91 sewersheds worldwide the average reported I/I reductions were 49% of peak I/I rate with a standard deviation of 25%. Twelve projects reported reductions greater than 75% (Keefe, 1998). Racine, Wis. (Marman et al., 1998) constructed diversion facilities with storage and partial treatment. The facilities prevented a cumulative SSO discharge volume of 3 million m<sup>3</sup> (783 MG) between 1993 and 1998 and actual SSO discharge was limited to 0.05 million m<sup>3</sup> (14 MG). A study to set up a long-term wet-weather control plan by the NORSD in the Westerly District of Cleveland, Ohio discovered problems with manhole invert plates, system blockages, and located sources of dry-weather flow (Bingham et al., 1998).

A five-year study confirmed the benefits of the original automation of the Lima, Ohio combined sewerage system by maximizing their CSO system storage and minimizing the impact of storm overflows on receiving waters. An upgrade provided additional benefits including decentralized communication, data accessibility, and additional control capabilities (Nye et al., 1998). Applications in the U.S., Can., and Fr. of Global Predictive Real Time Control (GPRTC) which can optimize and aid design of more efficient CSO control were described by Villeneuve and Pleau (1998). Perdek et al. (1998) discussed both international and national state-of-the-art technologies related to storage and sedimentation treatment for CSO. Harold et al. (1998) provided guidelines for accurate data from SSO and CSO monitoring based on the experience of major SSO and CSO monitoring projects conducted.

Gaffoglio et al. (1998b) used NYC's Inner Harbor CSO Facility Planning Project to demonstrate the cost effectiveness of maximizing WWF to the WPCP. This strategy has led from 74 to 88% capture of CSO. The East Bay Municipal Utility District and local communities eliminated sewer overflows to San Francisco Bay, Calif. by increasing capacity to its treatment plant, installing seven miles of large-diameter sewer interceptors, and increasing storage among other techniques (Housen and McCormick, 1998). The city and county of San Francisco, Calif. has, since the completion of the combined sewer system control structures, achieved a reduction in the number of overflows to the shoreline, and an associated reduction in the elevated bacteria counts and days of beach postings for public health concerns (Foree and McGregor, 1998). The WPCP of combined sewer systems are designed to operate satisfactorily for the design case and consequently all plants maintain reserve capacities for most of the time, even during high stormwater inflows. Müller and Krauth (1998) reported of the development of an automatic control strategy to manage the wastewater flow to a WPCP according to its actual treatment capacity. Winnipeg, Can. initiated a CSO management study in 1994 to establish a cost-effective prioritized implementation plan for remedial works (Rempel et al., 1998). The study indicated that the use of inline storage in 43 individual combined sewer districts covering roughly 10 000 ha is the most effective first step in the wet-weather pollution control plan. The database MED-MEASURE was used for in-sewer and CSO online monitoring in the city of Paris (Fr.) where more than 100 points were monitored simultaneously for COD, BOD, and SS (Tremblay et al., 1998).

Schaefer (1997) discussed that the challenge of stormwater management will be an environmental challenge in the 21<sup>st</sup> Century. New partnerships between environmental engineers and other professional groups have to be established to minimize diffuse long-term deposition of hazardous substances (Boller 1997). In Wayne County, Mich., animation was used effectively as a public information/presentation tool on the Rouge River Watershed National Wet Weather Demonstration Project to illustrate CSO and water-quality impacts (Shaw and Murray 1997).

A fast-track approach was taken in the construction of a 60-ft high surge well around an existing 108 in. outfall downstream of the effluent pump station in response to Tropical Storm Gordon in the City of Miami, Fla. (Chorlog *et al.*, 1997). Guderian *et al.* (1997) showed that rigid flow management for a sewer and treatment plant did not always fulfill the total emissions reduction goals for CSS. Sanders (1997) reviewed results of a detailed study of six WWTP facilities in Missouri that were impacted by the Great Flood of 1993 and concluded design engineers could probably have prevented many of the negative impacts.

The cities of St. Paul, South St. Paul, and Minneapolis, MN recently completed their 10-year, \$331-million sewer-separation program for CSO control (*Water Environ. & Technol.*, 1996b). Included in this program were the installation of 189 mi of storm sewers, 11.9 mi of sanitary sewers, paving of 168 mi of oiled streets, and disconnection of roof leaders at 21,900 residential properties.

#### **Innovative CSO controls - source controls.**

McCann (2006b) described Europe's sewer rehabilitation tool, CARE-S (Computer Aided Rehabilitation of Sewers and Stormwater Networks).

Andoh (2004) described the monitoring results of satellite CSO treatment facilities at Columbus, GA, which have undergone more than 5 years of monitoring. He concludes that satellite treatment systems within the collection systems (away from the end of the pipe) provides significant benefits from both a process and public health standpoint compared with the conventional approach of increased treatment plant capacity.

Todd Pacific Shipyards in Seattle, WA, was required to treat contaminated stormwater. Jackson et al (2004) described the work that concluded that the discharge of this water to the Harbor Island sanitary sewer for treatment at the King County treatment plant was the preferred option, allowing Todd to consistently meet the final effluent limits required by their NPDES permit.

Carrier et al (2004) described how Charlotte-Mecklenburg, NC, Utilities is expanding wastewater flow equalization in their collection system. By storing peak flows upstream, downstream capacity is still available for existing downstream peak flows. Welsh and Esposito (2004) described street storage systems to prevent combined sewer surcharging and to mitigate basement flooding, including two case studies. Street storage allows the full volume of stormwater runoff into the sewer system, but greatly reduces the peak rate of entry of stormwater into the system.

Tuttle et al. (2003) reviewed the emergency response planning for SSOs in Baltimore, MD. Kelly (2003) reported on managing sewers in creek based on the experience in Austin, TX. Meeting the objectives of the CSO abatement program was complicated by the following: a) the short timeframe; b) the location of many pipes in stream channels; c) the fact that stream channels with drainage areas over 64 acres are protected by a Critical Water Quality Zone (CWQZ); and d) the prohibition of development (including new construction or major rehabilitation of existing wastewater lines) in the CWQZ.

Moore (2003) reviewed the use of asset management to ensure cost-effective usage of resources and capital investments over the assets' life cycle. The goals and benefits overlapped with accounting practices for government agencies concerned with the Governmental Accounting Standards Board Statement No. 34 (GASB 34) requirements, and could also be well-aligned with the objectives of municipal CMOM programs. Smith et al. (2003) detailed the implementation of the second-phase of Augusta's Long-Term Control Plan to abate its CSO discharges. Numerous challenges were encountered during the design including: narrow project corridor; active railroad; steep and unstable banks; and coordination with a rails-to-trail project. Brown and Hill (2003) presented a generic process that can be used to develop a basement flooding remediation strategy. The process was divided into five main steps, and was designed to be developed in conjunction with a stormwater management model (SWMM) such as EPA SWMM, or the many commercially-developed graphical user interfaces that have been built around it (PCSWMM, XP-SWMM, MIKE SWMM, etc).

The methodologies used by several sewerage agencies to control combined sewer overflows (CSOs) and sanitary sewer overflows (SSOs) were presented/reviewed during 2001. Jewell (2001) outlined the methodology used by the Boston Water and Sewer Commission to identify and correct illicit connections to the storm drain system, as detailed in the Massachusetts Water Resources Authority's Combined Sewer Overflow Facilities Plan. The Plan proposed improvements to the system infrastructure to reduce the frequency and duration of CSOs. The CSO control plan proposed by the City of Springfield, Massachusetts to meet EPA and Massachusetts DEP requirements was reviewed by Heath and Donahue (2001). The cost for the various alternatives ranged from \$144 million (reduce discharges to 12 per year) to \$525 million (complete sewer separation to eliminate CSOs). Economic analyses were coupled with a regional water quality model to evaluate the benefits of various proposed alternatives for CSO control. Lai et al. (2001) reviewed the SSO Control Plan developed for Henrico County, Virginia. The paper discussed the following components: (1) dry-weather wastewater flow projections using GIS, water consumption records, and flow monitoring; (2) rainfall-dependent infiltration/inflow predictions; (3) capacity analysis (present and future conditions) using the SWMM EXTRAN model; (4) hydraulic and process capacity analysis of the wastewater treatment facility, including expansion requirements; and (5) implementation of a capital improvement program for additional facilities (sewers, storage tanks, pump stations, force mains, and wastewater treatment plant expansion or process retrofitting). O'Rourke et al. (2001) presented the Northeast Ohio Regional Sewer District's long-term control plan (LTCP) for bringing the District into compliance with EPA's CSO control policy. This approach included traditional and non-traditional cost issues, including non-cost issues that were deemed important by the public. The paper presented by Stupar and Dierksheide (2001) reviewed the new integrated maintenance, inventory and purchasing system implemented by the Ocean County Utilities Authority. The goal of integrating the system was to not only ensure that high quality WWTP effluent is discharged but also to reduce the probability of sanitary sewer overflows. Scott et al. (2001) reported on the Emergency Response Plan implemented by the City of Baltimore, Maryland as a response to the EPA's guidelines for developing a CMOM program. In this Plan, critical

facilities (pumping stations, pipelines, valves, and other components with a high risk of failure) were identified and their impact on public health and the environment was ranked. This Plan is guiding the implementation of recommended mitigation measures.

The use of analyzing utility data relative to sanitary sewer overflows was presented by Nelson et al. (2001). The purpose was to establish protocols for identifying SSOs through data already collected by utilities. Turner et al. (2001b) reported on Columbus, Georgia's development of plans for managing CSOs and SSOs. The strategy was based on the "further-reasonable-progress" approach to attaining water quality standards. The keys to success have been the demonstration of sustainable watershed solutions and the results from continued receiving water monitoring. The EPA BASINS model, with field-data calibration, was used to digitally represent the watershed and evaluate potential improvements. According to McConico et al. (2001a), in 2000, the City of Richmond, Virginia conducted a bacteriological monitoring. The purpose of this data collection was to monitor the effectiveness of the City's long-term CSO control program through comparing the new data to data collected in the 1980s and 1990s. The data was also used in the combined sewer system and James River tidal models that predicted for the effectiveness of long-range CSO planning. Carr (2001) reviewed the concept of micromanagement of stormwater flows to reduce SSOs and CSOs. Micromanagement of stormwater advocates temporarily storing stormwater in many and varied locations on the surface (off-street and on-street) and, as needed, below the land surface, near to the source. The paper reviewed the application of stormwater micromanagement in Skokie, Illinois and the lessons learned from the implementation.

CSOs often have been treated at the overflow point. Overall, the operating experience of the nine CSO control facilities on the Rouge River (Detroit, Michigan) has provided valuable information for designing future phases of CSO control on the river and for communities engaged in CSO control in other watersheds (Johnson et al. 2000). Andoh and Saul (2000) outlined recent developments in CSO technologies, particularly screening devices, and described the characteristics of the ideal intermittent wet-weather screening system. The authors then describe the development and evaluation of a novel self-cleansing CSO device - The Hydro-Jet Screen™. Averill and Gall (2000) examined the implications of intermittent loadings on operation of treatment systems and outlined a strategy for the planning and design of CSO, SSO or stormwater treatment systems. In the City of Niagara Falls, New York, options other than storage for CSO control were evaluated because of the high cost of constructing a storage facility. High rate treatment by means of vortex separators was considered an attractive option after preliminary settling column tests showed that the settling characteristics of the CSO were amenable to this treatment (Cheung et al. 2000). Underflow baffles have become popular for intercepting floatables in CSOs, but largely have been untested. Cigana et al. (2000) reported the results of a study of floatables capture by 17-meter-long basins at various flowrates. Their data suggested that capture efficiency of existing underflow baffles in an overflow chamber will be very low whenever the horizontal velocity is greater than 0.30 m/s or 1ft/s. Inappropriate operation of a partly-lowered gate in a new overflow structure caused the interruption of a 100-year old brick interceptor sewer in the Sea Cliff area of San Francisco during an intense, but not extraordinary, rainstorm (Medley 2000).

Clegg et al. (2000) presented projects for removal of rainwater inflow sources on private property from combined and sanitary sewer systems in Lansing and Port Huron, Michigan. Keys to success for these projects included property owner understanding, city identification of inflow sources, free advice and site visits, tracking and follow-up, flexibility on removal method, and ordinances to help enforce inflow removal on all private properties. Detroit, Michigan planned the Conner Creek Pilot CSO Control Facility to provide skimming, settling, and disinfection to meet the daily and monthly fecal coliform limits of 400 and 200 colony forming units (cfu) per 100 milliliters (ml), respectively (Fujita et al. 2000a). If this 30-million gallon "pilot facility" can meet the fecal coliform limits, it likely would provide significant cost savings in CSO treatment (Fujita et al. 2000b). The CDS method performs a liquid/solid separation and consists of a stainless steel perforated and deformed separation plate placed in a hydraulically balanced separation chamber. Louisville and Jefferson County MSD (Kentucky) have been a demonstration site for one of the first CSO applications of CDS technology (Gratzer 2000). The Detroit (Michigan) Water and Sewerage Department, in developing the Long Term CSO Control Plan, has recommended an innovative screening and disinfection approach to reduce CSO impacts on the Detroit River. Underground structures were designed for two pilot facilities to convey the flows through 4mm raked bar screens, and then direct the solids to the wastewater treatment plant through a side stream, thus eliminating the need for residuals to be collected and transported from remote facilities (Rabbaig and Neibert 2000). Zaccagnino et al. (2000) reported on several end-of-pipe CSO controls implemented by the New York City Department of Environmental Protection to reduce CSO impacts on Flushing Bay.

A case study of the development, implementation, and evaluation of a capital-works program aimed at reducing the contribution of rainfall-induced-extraneous flow from an existing sanitary-sewer-collection system by nonstructural

means was presented by Rowe *et al.* (1997). In Lower Paxton Township, Pa., > 60% of the I/I was identified as coming from private sources (Elliot *et al.*, 1997 ). Besides rehabilitation of public sewers, where necessary, the town developed an ongoing plan to seek out and correct I/I from private sources. The Miami-Dade Water and Sewer Department of Florida developed a very comprehensive Infiltration/Exfiltration/Inflow-reduction program that is one of the largest and most successful in the country (Aguilar, 1997).

Sanitary-sewer flows and wastewater-treatment-cost effectiveness were compared five years before a downspout-diversion program and 15 months after the program. The diversion program yielded a 25% reduction in mean-flow volumes and a significant reduction in wastewater-treatment costs (Kaufman and Wurtz, 1997).

Innovative WWF control strategies include using rainwater and runoff for potable uses and controlling gaseous emissions from combined sewer systems. Herrmann *et al.* (1999) reported on a four-story apartment building which was renovated using an innovative water concept. Roof runoff used stored for use in flushing toilet, and excess runoff was infiltrated, allowing the building to be completely unconnected from the stormwater sewer. The authors showed that independent from the soil and the available space it was possible to restore the natural water balance again by combination of rainwater use and subsurface infiltration. Lausten *et al.* (1999) described the use of a biofilter to capture and control hydrocarbon odors including VOCs from a combined sewer and an interceptor sewer in Philadelphia, Pennsylvania. The biofilter has proven to be a successful process application for treating VOC compounds from the air stream. Lim and Lim (1999) described a unique scheme to implement urban stormwater pond collection systems for potable water use in Singapore. Close monitoring and control of pollution through the adoption of stringent anti-pollution measures and enforcement actions have resulted in the collection of generally good quality raw water from these urbanized catchments with very low levels of heavy metals and low coliform counts as compared to raw water from largely forested catchments.

Source control of WWF aims to reduce overflows by reducing inputs to the system. Schmitt *et al.* (1999b) described the correct procedures for inclusion of source control measures in urban stormwater management into the German design procedure A 128. Results obtained by long term pollution load simulations emphasized the need to review existing guidelines. Williams *et al.* (1999) reviewed a partnership between the Louisville and Jefferson County Metropolitan Sewer District (MSD), the Louisville Education and Employment Partnership (LEEP), and the Jefferson County Public Schools (JCPS) designed to provide an opportunity for students and teachers to work in a paid summer internship with consulting engineering firms that contract with MSD, and assist MSD in collecting information regarding wet weather issues such as misconnected downspouts, sump pumps, and leaky sanitary sewers. The program, which has been successful for five years, provides a quick and cost effective investigation that identifies inflow source reduction opportunities for mitigation of property damage and SSO.

Walesh *et al.* (1999) provided a discussion of the use of on-street storage as an effective means to control stormwater runoff and CSO in two communities in Illinois. This technology eliminated surcharging and basement flooding, complied with regulations, and proved to be a cost-effective solution which earned public support. Lachmayr and Schofield (1999) focused on the fieldwork techniques used to identify specific inflow sources from large buildings in the area served by the Boston Water and Sewer Commission, Massachusetts. Vaes and Berlamont (1999) examined the effect of rainwater tanks on CSO with a reservoir model. Compared with storage in the combined sewer system or at the overflow, storage in rainwater tanks will be more efficient in reducing the CSO discharges (Vaes and Berlamont, 1999).

### **Sewerage repairs and Inflow/Infiltration (I&I) control**

Kwietniewski and Lesniewski (2006) performed a reliability assessment of a typical structure decay of a stormwater collection system. The unfitness of the system was related to a reduced area of the drainage basin. Zhao *et al.* (2006) experimentally examined surcharged flow at combined sewer junctions. The study confirmed the existence of three flow regimes in sewer junctions with a steep outgoing pipe.

Iyer and Sinha (2006) discussed segmenting pipe images to detect cracks in buried sewers. The evaluation of 225 pipes showed that the methodology performed well. Energy losses in storm drain access holes was reviewed by Kerenyi and Jones (2006). The technology presented by the authors allowed much smaller scale models while maintaining the accuracy of the results. Landers (2006e) presented a guidance for sewer rehabilitation program implementation – the Pipeline Assessment and Certification Program.

Dent *et al.* (2004) described the Vallejo, CA, pilot rehabilitation program to comprehensively evaluate the effectiveness of collection system rehabilitation. The methods applied to this project included selecting representative test basins,

monitoring the wet weather flows, rehabilitating both sewer mains and laterals, and then measuring the reduction in both peak flow and volume. Several rehabilitation techniques, including conventional dig and replace, cured in place pipe, pipe bursting, and other trenchless technologies, were examined. Salem, OR, has had an active rehabilitation/ replacement program for their sanitary sewer system for several decades (Roley et al 2000 and Craven and Lunch 2004). Salem has gone through several changes in philosophy over the years in terms of how successful the removal of infiltration/ inflow (I/I) will be and the contribution or component of I/I that originates from private property. Salem spends approximately \$4.0 million each year on the sewer R/R program. Morgan et al (2004) described how King County, WA, has embarked on an extensive program to assess I/I in their service area. A preliminary assessment in 1995 indicated that an expenditure of \$100 million in sewer rehabilitation could eliminate the need for \$300 million in conveyance facility improvements. Over 775 flow monitors and radar imaging combined with 72 rain gauges were used throughout the 420-square-mile service area for continuous modeling of I/I using MOUSE.

A closed-circuit TV survey was incorporated in the sewer asset database and InfoWorks modeling software, that is being developed by UK's Severn Trent Water (*Water 21* 2004). Downey (2004) described the integration of a sewer sealing system (Sanipor) to reduce I/I. The system can seal an entire local sewer network, including the main pipe, laterals and manholes in one operation. Rowe and Kathula (2004) and Rowe et al (2004) described how a utility wanted to revitalize its closed-circuit television inspection program, but were not satisfied with the current defect scoring and ranking systems. To address these and other important needs, the Sewer Condition Risk Evaluation Algorithm Model (SCREAM) was developed.

Dutt and Hemphill (2004) described a toolbox approach used in Portland, OR, for optimizing recommended alternatives targeted at eliminating basement flooding. Gonwa (2004) described how Milwaukee has been investigating control of private I/I sources for over five decades. The first step occurred in 1954 when the plumbing code changed to not allow new connections of foundation drains or sump pumps to the sanitary sewer system.

Ablin and Kinshella (2003) reviewed the problems in Phoenix with accelerated corrosion rates due to flat slopes and warm temperatures. Due to the rapid deterioration that is being experienced, the City accelerated their rehabilitation program to include lining of all unlined concrete pipes. Bickerstaff et al. (2003) reviewed the Charleston experience with using an Environmental Management System (EMS) to launch CMOM. Wilmut and Carroll (2003) reviewed the sanitary sewer overflow elimination program in the City of Lafayette, LA. The program began in the early 1990's as a typical I/I analysis, Sewer System Evaluation Survey (SSES), and Collection System Rehabilitation Project, but evolved into a comprehensive systems approach which included wet weather flow holding basins and wastewater treatment plant improvements as well.

Dent et al. (2003b) presented an optimization model to support a system-wide capital improvement program (CIP) for an SSO Elimination Program for the Vallejo Sanitation and Flood Control District in California. Dungan (2003) reviewed the CSO long-term control in Muncie, Indiana. The CSO reduction project characterized Muncie's combined sewer system, evaluated CSO reduction alternatives, recommended a 20- year plan to achieve the state's 85% volume reduction goal. Lukas et al. (2003) evaluated where and how much flow enters the Minneapolis sewer system, the hydraulic conditions contributing to the overflows, and modifications to the sewer system or inflow removal projects that could further reduce overflows. Myers et al. (2003) reviewed the lessons learned in implementing a comprehensive sewer inspection program in Sacramento, CA. Using the Predicted Pipe Condition model, pipes with the highest (worst) scores were identified for the initial inspection work under the condition assessment program. St. Germain et al. (2003) provided sewer system rehabilitation guidelines based on the experience of the Sewerage and Water Board of New Orleans, LA.

Wright and TenBroek (2003) presented the investigation done by Ann Arbor, MI to identify the circumstances controlling the flooding and to evaluate alternatives for mitigating it. It was observed that system flows increased rapidly after the commencement of rainfall, leading to the conclusion that contributions from footing drains in older residences were a major contribution to the increased system inflows. Stonehouse et al. (2003) summarized the impact of residential footing drain flows on SSOs and wet-weather I/I. Findings indicated that wet weather flows from areas with footing drains connected to sanitary sewers are 3-4 times higher than in areas without connected footing drains, in some cases accounting for up to 90 percent of the total wet weather infiltration and inflow. Lukas and Lipinski (2003) reviewed the impact of a foundation drain disconnection program on I/I in Duluth, MN. The removal project consisted of redirecting residential footing drains into a new sump pump pit installed in the house.

Beardsley et al. (2003) examined combining pilot I/I reduction with system modeling in East Providence, RI. This paper

outlined the remediation process followed by the City and included I/I investigations, pilot I/I remediation, sanitary sewer system modeling, and implementation of CMOM initiatives. Carter and Hassell (2003) reviewed the City of Gladstone, MO's collection system study and identified and quantified I/I entering the collection system. Hannan (2003) presented the results of investigations into why sewers overflow and backup, steps management can implement to mitigate SSOs, and examples of successful solutions to particular overflow problems. Reported causes and rates of overflow available in the public domain would be documented and effective measures utilities have adopted would be reported. Rabbaiq et al. (2003) investigated 'unaccounted-for' flows during dry weather conditions through an organized plan to located dry weather I/I (DWI/I). This paper described the key challenges of performing the DWI/I evaluation in Detroit's large urban combined sewer system, and presented the key project task methodologies utilized to meet these challenges.

Dent et al. (2003a) compared rehabilitation of deteriorated pipelines and laterals as part of an SSO abatement program to other methods (conveyance improvements, storage, and treatment). The authors presented a new method for identifying where I/I is occurring and how cost-effective rehabilitation is when compared to other alternatives. Dutt (2003) presented the pipeline rehabilitation program developed for Richland, CA. The program focused on isolating the worst inflow and infiltration (I&I) problem areas and then using a holistic basin rehabilitation approach to effectively rehabilitate the pipelines in the basin. Edwards et al. (2003) reviewed the advantages and challenges of trenchless rehabilitation of a sewer pipe on a vacuum sewer system in Portsmouth, VA. McCormack et al. (2003) demonstrated the effectiveness of eco-friendly, lightweight Weholite pipes for upgrading the sewerage network and avoiding CSOs in times of heavy rainfall. Ellis and Barnas (2003) reported on the four methods of rehabilitation selected for a 110-year-old brick intercepting sewer in Milwaukee, WI.

Kimbrough et al. (2003) compared sewer flow meter performance and advocated for the Environmental Technology Verification (ETV) Program. The ultimate goal of the ETV Program, according to the authors, is for consumers to require third-party verification reports as a necessary reference in awarding flow monitor procurements. Jurgens and Kelso (2003) presented the results of where the City of Fayetteville, AR returned to an area that was rehabilitated ten years earlier to determine what worked, what failed, and what events occurred in that time period to cause additional failures in the collection system. Few few defects were found on pipe segments that had been repaired in the earlier rehabilitation project.

Weiss et al. (2002) performed a long-term analysis of infiltration and inflow in 34 combined sewer systems in Germany. The results showed that significant control of pollution can occur by reducing I/I. Schultz et al. (2002) presented an overview of the provisions and programs that the Milwaukee MSD has developed to more effectively control infiltration and inflow into the interceptors and community sewers. The presentation emphasized those provisions where the rules, standards specifications and design documents have been improved by incorporating feedback from field observation of construction practice. The contribution of foundation drains connected to the sanitary sewer system in Elmira, Ontario, Canada was investigated by Waite et al. (2002). The connections were found to be the primary source of I/I flow. Wilson (2002) reviewed the cost effectiveness of I/I rehabilitation in Enumclaw, Washington after 25 years of smoke testing, storm separation, pipe joint grouting and lining. The results showed that building a new treatment plant may be more cost-effective over the life of the plant and system than rehabilitation; however, rehabilitation may be a good investment so capacity is available for future growth and development.

TenBroek et al. (2002) reviewed the use of footing drain connections to correct basement backups in Ann Arbor, Michigan. A review of the system concluded that 70% to 90% of the wet-weather flows in residential areas were from connected foundation footing drains that convey drainage from around most homes into the collection system. Sherman et al. (2002) reviewed the City of Ann Arbor, Michigan's program on footing drain disconnection (FDD) program. The initial phase of the project included a footing drain flow monitoring program in an area of the city with capacity problems, and the prioritization of future disconnect areas. The results of the program to date were presented in terms of financial costs, treatment cost savings, and the construction requirements. Salim et al. (2002) reviewed the effectiveness of downspout disconnection in Detroit after implementing downspout disconnection in side by side test pilot sites. The cost of disconnection was \$243 to \$278 per downspout and 50 to 83% of the downspouts were disconnected. The Continuous Greater Detroit Regional Sewer System Model showed an annual reduction in CSO volume of 2 billion gallons.

Keefe and Kimbrough (2002) discussed how to measure successful rehabilitation of sewer systems. Success has typically been measured as I/I removal and the paper presented a rigorous method for calculating the I/I removed from a system. As reported by Lai and Field (2001), the USEPA has conducted a series of research, development and demonstration projects on the characterization, cause, consequence, and control of infiltration/inflow (I/I) in both sanitary and combined

sewers. The research addressed (1) state-of-the-art problem assessment; (2) pressure sewer systems; (3) polymers to increase sewer carrying capacity; (4) sealing methods and materials for sewer rehabilitation; (5) demonstration and evaluation of Insituform; (6) trenchless sewer installation by “plowing in;” (7) house lateral rehabilitation; and (8) impregnated concrete pipe to increase corrosion resistance and strength. This review was designed to assist communities that will be implementing the soon-to-be-issued SSO Rule. Moisis and Barton (2001) reviewed the design standards for sewers used by the Metropolitan Sewer District of Greater Cincinnati (MSDGC). The MSDGC maintenance program was designed to avoid SSOs due to poor maintenance. What had been documented was that replacement pipes were designed to the standard of new sewers and therefore I/I for the older sewer system was not accounted for in the calculations. The new revisions to the design standards will incorporate I/I contributions for older areas, thus allowing the installation of replacement pipes that can carry the flows from older areas. O’Sullivan et al. (2001) reviewed the implementation of a private sanitary sewer lateral replacement program (SSLRP) in Mobile, Alabama. The SSLRP performed in two distinct processes that used separate contractors – the testing and identification of defective private sanitary sewer laterals (PSSLs) and the replacement of defective PSSLs essentially at the cost of the property owner. A detailed program methodology, consistent penalty system, and close coordination between Water and Sewer System, the engineer, and the contractors were the keys to the program’s success.

Hilderhoff and Wendle (2001) recommended a mini-basin or mini-watershed approach to sewer rehabilitation, as was used by Susquehanna and Lower Paxton Townships. Total rehabilitation by mini-basin means that all sewer system components including mainline, manholes, service laterals and building sewers located in one mini-basin were repaired to meet the same acceptance testing standards as new sewers. This work was completed at the expense of each Authority and not the property owner. Blakley and Summers (2001) reviewed the approach taken by the McCandless (Pennsylvania) Township Sanitary Authority for I/I control and recommended this synergistic approach to other communities. The approach combined strengths of five different strategies (dye testing, line replacement, pipe relining, line grouting and manhole rehabilitation), creating a synergistic effect, that balanced cost with gain. Field and O’Connor (2001) recommended communities develop a strategy for SSO pollution abatement because extensive sanitary sewer rehabilitation without planning is (1) relatively costly, (2) time-consuming, and (3) extremely disruptive to traffic, property owners, etc. I/I control studies have demonstrated that just correcting I/I in street sewers will not necessarily correct the problem because building connections contribute as much as 60% of the infiltration load. Building connection rehabilitation may be unfeasible economically. Inflow elimination or reduction, cost-effective sewer rehabilitation, and collection system inspection with associated clean out and repair must be performed in all cases, and must be part of an integrated economic and feasibility analysis.

Lukas et al. (2001) reviewed the WERF project to identify and develop Predictive Methodologies for Determining Peak Flows after Sanitary Sewer Rehabilitation Projects. The first result of the municipal surveys was the lack of documentation on rehabilitation projects and particularly, their effectiveness. The paper by Watts and Forbes (2001) analyzed the procedures used to rate I/I defects located during the recent Sanitary Sewer Evaluation Studies (SSES) conducted in Carolina and Luquillo, Puerto Rico. The methods used to prioritize appropriate rehabilitation methods were presented. Kurz et al. (2001) reviewed the City of Chattanooga’s permanent network of flow meters for monitoring sewer flows as part of their billing. In addition, the flow meter data assisted the city in its CMOM program by locating capacity problems. Nashville’s flow metering system identified over 10 million m<sup>3</sup> of I/I removal after rehabilitation. Jackson, Tennessee’s flow meters demonstrated that I/I rehabilitation solved what appeared to be a capacity problem in a major trunk line. Hollenbeck and Rieger (2001) outlined the Rock River Water Reclamation District program that was designed to mitigate basement backups in the District. This program identified and rehabilitated both public and private sources of infiltration in the study area. Post rehabilitation flow monitoring confirmed that 10-year storm protection from overflows and basement backups was achieved.

The condition of a combined or sanitary sewer influences overflows from the system, and sewer inspection and prioritization of repair efforts are important parts of overflow control. Continual improvement and streamlining of an inspection and evaluation program for the condition of a system of interceptor sewers and CSO facilities in the Cleveland (Ohio) metropolitan area resulted in an innovative and widely applicable approach to locating, identifying, and inspecting interceptor and CSO facilities. This approach significantly reduced field time and greatly increased the accuracy of the data collected (Krizmanich et al. 2000). Hahn et al. (2000) described an expert system, Sewer Cataloging, Retrieval and Prioritization System (SCRAPS), that prioritizes sewer inspections to target information collection from critical portions of the network. Kelly et al. (2000) reported on a process successfully used in New Orleans (Louisiana) to quickly and effectively address manhole rehabilitation needs. This process consisted of standardized data collection, computerized decision-making and implementation of appropriate rehabilitation methods. Merrill et al. (2000a) presented a tool to help



utilities prioritize inspection of sanitary sewers to overcome problems/limits of available data and the limited ability to inspect and repair or replace sewer infrastructure. In validation exercises using case studies supplied by the experts, the tool was shown to outperform a group of experts in quantifying the need to inspect (Merrill et al. 2000b). In 1995, the Washington Suburban Sanitary Commission, which is located in Montgomery County and Prince George's County, Maryland launched a 4.5-year, multimillion-dollar I/I analysis and sewer system evaluation survey. The paper by Nguyen et al. (2000b) summarized the results of the Rock Creek I/I Analysis project, described the tools developed to analyze the voluminous amount of data, and discussed the method used to prioritize the repairs of the identified defective manholes and pipelines. Pomroy et al. (2000) reported on a statistical condition model that was used to forecast the future condition of selected small-diameter (4- inch to 10-inch) sewer pipes and to estimate necessary rehabilitation capital costs in the Central Contra Costa (California) Sanitary District. The authors reported that condition modeling provided an efficient means to plan future expenditures and staffing requirements. A highly-accurate dye dilution testing protocol was developed and used by Stonehouse et al. (2000) to quantify flow meter accuracy in the Greater Detroit Regional Sewer System. Many meters typically considered to be accurate had errors of more than 30%, with some meters having errors exceeding 70%. Overall, the average initial system accuracy for system meters was observed to be  $\pm 15.0\%$  of measurement with an overall bias of 6.1% (under-predicting flow). It was concluded that (1) there were observable accuracy differences between flow meter technologies; (2) objective standards like dye dilution testing were critical to good metering; (3) verifying installed accuracy was important, even for technologies considered to be highly accurate; and (4) the simplest technology that can be used often was the best.

Forbes (2000) examined the causes, diagnosis, impacts, and treatments for excessive infiltration/inflow (I/I), a significant cause of sanitary sewer problems, including SSO. Kurz et al. (2000) reported on a program in Nashville, Tennessee to improve system characteristics, recapture capacity, and reduce I/I so the sewers can carry the peak flow from their design storm without overflows. Accordingly, the authors recommended that sewer rehabilitation programs should include procedures to measure I/I removal effectiveness as a program progresses. A geographic information system (GIS) based system was developed to manage both sewer maintenance and I/I reduction programs. The system was designed to be used primarily for issuing work orders and responding to customer complaints, but it could also be utilized by engineers in conjunction with sewer line modeling needs (Shaffer and Greiner 2000). In 1992, Springfield, Missouri, began a long-term program of I/I reduction which included a comprehensive sanitary sewer evaluation, development of a hydraulic model, various manhole and pipeline renewal projects, and the addition of strategic relief sewers (Wade 2000). In Beverly Hills, Michigan, I/I into the sanitary system from public and private sources overloaded the sewer system and caused basement flooding and SSOs to local surface waters during large rain events. Sump pumps from residences were connected to the sanitary sewer system, so a project was undertaken investigate the effectiveness of removing sump pump connections to the sanitary sewer system in an effort to correct this I/I source. The results showed that sump pump removal would produce a quantifiable decrease in inflow (McCormack et al. 2000). Rehabilitation of two basins in the City of Olympia, Washington allowed direct comparison of the effectiveness of rehabilitation of the upper lateral versus the public sewer and lower laterals in order to reduce I/I, as well as the total removal that can be achieved when the entire system is rehabilitated (Merrill et al. 2000b). Trenchless technologies are often used for I/I control in sewers because they can be implemented with less traffic control, minimum conflict with other utilities, increased workers and community safety, and minimum dust and noise generation (Garcia-Marquez et al. 2000). The City of North Miami Beach, Florida initiated a system-wide I/I reduction program and selected formed-in-place liner installation for rehabilitation of damaged gravity mains. Through 1999, the City has installed 27,500 feet of liner, and a nearly 48 percent reduction in average daily flow has been seen to date (Rothman and Heijn 2000).

#### **Public education.**

Frank (2006) reviewed the pre-planning and communication that were undertaken as part of a smoothly conducted conduit rehabilitation project.

Hollander et al. (2003) reported on the actions taken by municipalities to respond to regulations and public demands that SSOs be eliminated. A risk-based, water quality-based approach to "C" coupled with a MOM program met the technology and water quality requirements of the Clean Water Act and focused the long-term remediation evaluation planning.

The paper by Chapman et al. (2002) described the processes and projects in Milwaukee that have been designed to overcome the older view that urban streams are an environmental nuisance and hazard. In this spirit the District has three completed or are implementing ongoing urban channel rehabilitation projects and several programs are underway to reduce flooding while supporting environmentally sustainable development. The paper focused on the evaluation and

selection of a monitoring tool for benchmarking their progress.

White (2001) reviewed the joint agency program of King County and the City of Seattle (in conjunction with the Seattle-King County Health Department) for public notification of combined sewer overflows. The program included posting warning signs at over 100 CSO locations, developing a website, information line, brochure, fact sheet and other materials. According to the review of Rozelman and Loncar (2001), the 1995 New York State Discharge Notification Act (DNA) (aka "Fisherman's Right to Know Act") caused the New York City Department of Environmental Protection to enhance their public education program regarding CSOs and encouraged the public to provide the City with early notification of sewer problems such as dry-weather discharges.

Public involvement and education play a role in WWF control programs. Barger (2000) reviewed Little Rock (Arkansas) Wastewater Utility's Captain Sewer Water Conservation Education Program. The program has focused on water conservation and Captain Sewer now visits at least twenty-four schools each year and has appeared in 24 states and two foreign countries. A campaign to involve the public in developing a control plan for CSOs in Edmonton (Alberta, Canada) has evolved into a significantly broader program. "Towards a Cleaner River" has raised public awareness of the condition of the North Saskatchewan River, the functioning of the drainage and sewerage systems, and how people can help improve the river's water quality (Barth et al. 2000a). The Project Working Committee, the City and their consultant team developed a long term CSO Control Strategy to mitigate the environmental impacts of Edmonton's combined sewer system (Barth et al. 2000b). To address the problems facing Pogues Run and the West Fork River (Indianapolis, Indiana) from 23 CSO outfalls, a multi-million dollar comprehensive plan was formulated. Due to the multiobjective nature of the project and its funding needs, many agencies and neighborhood groups were involved to help resolve issues such as short-term funding, handling special waste, compensatory wetland creation, allowance for dam overtopping, and even the project's name and purpose (Kirk and Beik 2000).

#### **Tunnels, Storage Tanks, and Interceptors**

Trypus et al. (2006) discussed the use of storage tunnels to prevent CSOs and SSOs. The authors suggested that good control of the hydraulic grade line during operation would reduce the potential for exfiltration and subsequent higher infiltration rates. Miller and Grinwis (2006) evaluated the operating and stormwater overflow behavior of a sewer with storage capacity and a central spillway. Landers (2006c, 2006f) presented the design of a solution to Detroit's (Michigan) CSO problem. This will include a 7.5-mi long CSO tunnel, as will the Indianapolis (Indiana) solution. Clarke (2006a) reviewed the improvements to the Wurzburg sewer system, including the use of a new tunneling machine.

Castronovo and Abbaspour (2003) reviewed the use of trenchless technologies combined with conventional methods to rehabilitate a sanitary sewer in St. Petersburg in order to prevent SSOs. Fleury and Decker (2003) reported on the Pima County (AZ) interceptor emergency rehabilitation project which became necessary after sinkholes caused a major SSO event. The project had two primary goals: • Reduce the flows tributary to the potentially damaged interceptor as soon as possible in order to lower the stress on the pipe. • Rehabilitate the remainder of the pipe at the earliest possible date. Holden et al. (2003) described the project approach taken in the redirection of over 70 percent of the collection system flow to a new lift station. The construction of this project's forcemain resulted in no additional land requirements, decreased construction costs, and significant minimization of construction impacts to the community by avoiding direct burial of piping around the City's main cemetery and soccer fields. Engstrom et al. (2003) developed long-term precipitation and infiltration records for use in a performance evaluation of a proposed regional drainage tunnel shared by the cities of Detroit and Dearborn, MI.

Glovick et al. (2003) investigated the formation of surges and geysers in deep tunnel systems used for the control of CSOs. Surge issues related to the design of deep tunnel systems and how the use of unsteady flow surge modeling software could be used were addressed. Wright et al. (2003) developed a laboratory model to provide insight into the geometrical and flow conditions that will develop large surges. Experimental findings indicated that the largest surges occurred when a hydraulic bore just formed as it approached the surge relief structure. The maximum surges also occurred when the tunnel slopes downwards from the surge chamber.

Bate and Plaumann (2002) reviewed the Milwaukee (Wisconsin) Central Metropolitan Interceptor Sewer (MIS) System Improvement Project and was designed to clean, inspect and repair nearly 50 miles of the District's oldest interceptors, siphons and flow control structures, with the ultimate goal of achieving an additional 50 years of service life. Much of the rehabilitation was to be accomplished by trenchless technologies (large diameter cured-in-place lining, slip lining, segmental lining, cementitious and epoxy coatings). Muindi et al. (2002) discussed the variable soil and groundwater

conditions encountered during design of near-surface CSO facilities in Providence, RI. It also reviewed the geotechnical-related construction issues and geotechnical instrumentation program implemented to mitigate the potential for damage of constructed facilities. Jones and Robinson (2002) reviewed the Chattahoochee Tunnel installed in suburban Atlanta to increase conveyance and reduce the number of SSOs into the Chattahoochee River. The five key features in the tunnel design included ideal tunneling rock; the lack of a need for tunnel supports in most of the length; fractured rock supports included rock bolts or steel ribs; low groundwater flow; and linings of cast-in-place concrete only in areas of fractured rock or significant groundwater flow.

Larsen and Garcia-Marquez (2002) reviewed trenchless technology application failures. After a review of failures experienced in South Florida, they proposed that the most common defects and failures are due to: sanitary sewer problem misdiagnosis, inadequate technology selection, poor design and inadequate specifications, improper installation, and/or inadequate inspection.

Gibbons et al. (2002) reviewed a case study of the Grant Street Pump Station flood mitigation in a West Allis, Wisconsin neighborhood. The paper presented the process for alternatives identification, stakeholder involvement, evaluation, and remedy selection and a description of the selected alternative for mitigation of localized flooding in the city of West Allis, Wisconsin. The constraints of the urban setting, and the need to consider environmentally sound remedies that will not degrade the existing watercourse, required a new look for an approach to meeting the objective.

Three major tunnel construction projects were presented during WEFTEC 2001. Jones and Robison (2001) reviewed the history, the design, and the construction of the Chattahoochee Tunnel in Metropolitan Atlanta. This tunnel was designed to accomplish two purposes: relieve the existing Chattahoochee Interceptor and provide flow equalization for the existing water reclamation facility. Wood et al. (2001) presented an overview of the decisions that went into the design of the interconnected Westside and Eastside CSO tunnels in the City of Portland. The analyses included comprehensive hydrologic and hydraulic modeling of the combined sewer drainage system and the tunnel system, RTC simulation of gates, weirs, and pumping facilities, and planning for instrumentation, monitoring, operation, control, and maintenance. Roll and Lannon (2001) reviewed the repair of the Falls Street Tunnel in Niagara Falls, New York. The repair was designed to reduce the 6-MGD of groundwater infiltration into the tunnel. The contractor payment for the project was based on the infiltration reduction, which was estimated to be approximately 4 MGD.

Ab Razak and Christensen (2001) investigated the benefits of the Milwaukee deep tunnel for temporary storage of storm water and sewage, on the water quality of the Milwaukee, Menomonee, and Kinnickinnic Rivers. Statistical analysis of BOD, phosphorus, suspended solids, fecal coliforms, zinc, and chloride indicated that the Menomonee River benefited the most from the deep tunnel since 1994 when the tunnel came on line. Fecal coliforms inside the CSO area, and to a certain extent BOD and zinc levels, exhibited the most significant decline.

Other research investigated various aspects of sanitary sewer systems that impact SSO and CSO control efforts. Spurred by the increased scrutiny by EPA and other regulatory agencies on SSO prevention, Jones and Schneider (2000) reviewed the elements that compose a pumping station design, including the results of client-consultant interaction that has resulted in exceptional reliability and reduced operational costs. The Western Carolina Regional Sewer Authority is completing construction of the largest sewer project in South Carolina to reduce SSOs and to protect water quality - 10 miles of deep trunk sewer up to 96 inches in diameter, located 20 to 45 feet deep along the fully developed Reedy River valley (Hildebrand et al. 2000). The North Central Sewer Separation Project will separate storm water and wastewater pipes in a section of downtown Columbus, Ohio, USA (Keefer and Chase 2000). The Milwaukee Metropolitan Sewerage District authorized an emergency project to design and construct a new CSO pump station using a fast-track approach, as discussed by Maurer and Bush (2000). This discussion reviewed the use of large submersible pumps for CSO service, design considerations, procurement methods, and the challenges of fast-track design and construction.

The Vortex Drop Structure has been shown to be an effective energy dissipater and aerator. It is designed to dissipate the flow energy and aerate the wastewater, preventing emission of odorous gases, oxidizing the hydrogen sulfides, and protecting the drop structure from corrosion and abrasive wear. The analysis of multiple wastewater samples taken simultaneously upstream and downstream of the Vortex Drop Structures shows a significant decrease of dissolved hydrogen sulfides and a sharp rise in the dissolved oxygen concentrations downstream of the structures (Moeller 2000). Private pump stations (commercial, industrial, institutional, etc.) typically have been constructed as an immediate fix when no nearby wastewater facilities exist or to overcome sewer elevation differences. However, in many cases, insufficient documentation and coordination between the developer, engineer, permitting agency, and sewer system

operator has rendered this component of the collection system seemingly non-existent (Huerkamp et al. 2000). Street storage refers to the temporarily storing stormwater in urban areas on the surface (off-street and on-street) and, as needed, below the surface close to the source. A case study approach, based on two largely implemented street storage systems, was used to explain the concept of construction and operation of street storage systems (Walesh 2000). Huisman et al. (2000) studied the propagation of surface waves on the operation of a urine separation system. The authors showed that the wave phenomenon had no adverse effects on the utility of the urine separation system, but could lead to the release of undiluted wastewater during a rain event.

Tunneling and interceptors play a role in WWF. The Columbia Slough Consolidation Conduit tunnel was a key element in alleviating CSO in Portland, Oregon. Rippe et al. (1999) described the design and construction of this soft ground tunnel project, with shallow ground cover and close proximity to an existing old concrete sewer, as well as the means of sharing risks between the owner and the contractor. Lannon and Roll (1999) described a challenging investigation of a deep tunnel interceptor blockage near the City of Niagara Falls (New York) that created persistent interceptor surcharging, prolonged upstream wet weather overflow following precipitation events, and an air release effect which propels wastewater over 27 meters (90 feet) upward from the interceptor through a drill hole during heavy rains. Roll (1999) described the diagnosis and restoration of diminished force main capacity in a wastewater transmission line linking the City of Niagara Falls, New York WWTP with its largest pumping station. The flow limitation reduced first flush capture from the combined collection system and occasionally resulted in manhole surcharging up to street level. Westoll (1999) described sewerage and sewage-treatment projects intended to control combined-sewer overflows that cause nuisance during rainfall in the town of Driffield (Yorkshire, England). The projects include a new interceptor, constructed using trenchless technology, and a four-basin cyclic activated-sludge plant.

#### **Litter, floatables, and settled solids.**

Sewer sediment accumulation and flushing were monitored long-term by Bertrand-Krajewski et al. (2006). Long-term sediment monitoring revealed: i) a regular asymptotic increase of both the sediment mass and the slope of its longitudinal profile, ii) a clear correlation between local sediment profile irregularities and sewer ancillaries.

McGregor (2003) made the case for cleaning sanitary sewers to prevent SSOs. The case study presented in the paper showed that an overflow problem might not have occurred if the municipality had adhered to a more proactive maintenance program. Pisano et al. (2003) summarized the design of passive automatic flushing systems installed in the City of Cambridge's storm and sanitary sewer system tributary to the Alewife Brook as part of a \$75 million sewer separation program. The flushing systems were sized to achieve wave velocity of 1 m/s at the end of the flushing segment with flush vault volumes ranging from 11 to 40 m<sup>3</sup> for the storm drain systems and 6 m<sup>3</sup> for the sanitary system. Pollert and Stransky (2003) evaluated the separation efficiency of solids in CSO through the use of a combined 1D and 3D models. Charts of concentration dynamics of suspended solids on the CSO inflow, outflow and overflow were presented (for particles with different characteristics).

Fischer and Turner (2002) reviewed the North Bergen, NJ Solids and Floatables Control facility, which uses a system of nine Netting TrashTrap® system and one mechanical screen and which cost 300% less than the next least expensive technology evaluated. Operations and maintenance costs on the facility have been approximately \$57,000 per year. Irvine (2002) discussed the Buffalo River (NY) floatables control using a floatables trap and the continuous water quality monitoring. Mean accumulations rates in the trap were significantly greater for CSO periods than for dry weather and the distributions in the traps had more wood and less plastic than floatables traps in New Jersey. The average mass trapped per unit volume was also less for the Buffalo watershed than for the two New Jersey watersheds monitored, possibly due to the sewer hoods installed in the Buffalo watershed.

Dettmar et al. (2002) investigated the performance and operation of flushing devices in both a German field and laboratory study. The results showed that the generated flushing wave shear stresses of investigated gates surpass 14 N/m<sup>2</sup>. The performance of the cleaning amounts to 0.5 kg sediment per m<sup>3</sup> of flushing water.

Fan and Field (2002) provided an overview of the causes of combined-sewer deterioration and the heavy pollutant discharges, along with a discussion of their control methods. Their results indicated that both the tipping flusher and the flushing gate technologies appear to be cost-effective for flushing solids and debris from CSO storage tanks, while the flushing gate appears to be the most efficient method for controlling combined-sewer sediment. The use of slotted invert traps for managing sewer sediments was reviewed by Buxton et al. (2002). The paper presented the results from a laboratory investigation that compared the trapping performance of three slot-size configurations of a laboratory-scale

invert trap and from 2-D modeling of stochastic particle tracking. The comparison of the two procedures showed that the modeling consistently overpredicted retention efficiencies observed in the laboratory model. The effect of a manhole drop on the hydraulics of combined sewer flow was investigated by De Martino et al. (2002). The main wave features were analyzed to give expressions that contain both the upstream filling ratio and the Froude number of the approach flow. The discharge capacity was also investigated and photographs were presented to show typical drop flow in combined sewer manholes.

The paper by Fan et al. (2001a) reviewed the causes of sewer deterioration and the control methods that can be used to prevent or postpone this deterioration. The remedy reviewed in the paper was inline and combined sewer overflow tank flushing systems to remove sediments and thus minimize hydrogen sulfide production in the sewer system. The two technologies reviewed were the tipping flusher and the flushing gate, both of whom have been demonstrated to perform well in facilities in Germany, Canada and the United States.

Sewer solids which are deposited in combined and sanitary sewers during dry weather make up a significant component of CSO and SSO pollution. Detailed research investigating all aspects of solids in sewer systems has been underway in Europe for nearly two decades. Recent research has characterized the nature of the solids getting into sewer systems, how they behave in terms of transport, and some of the main aspects of their effects. Ashley et al. (2000) has demonstrated that in a number of catchments, the majority of pollutants found in suspension during storms, and likely to be discharged from overflows, originate from the predominantly organic 'near bed solids' which accumulate in systems during dry weather. This knowledge has been used to improve the modeling of sewer solids behavior. The USEPA has also investigated the causes of sewer solids deposition and the development/evaluation of control methods to prevent sediment accumulation. Control of sewer sediment not only protects urban receiving water quality but also protects sewer structural integrity (Fan et al. 2000b). Chen and Leung (2000) demonstrated that the sediment phase played a key role in oxygen utilization in a sanitary gravity sewer. Their study indicated that the sediment phase contained more active biomass than the sewage phase. Del Giudice et al. (2000) examined supercritical flow in a bend manhole used in sanitary sewers, and introduced the bend cover, which allows air entrainment into the downstream sewer. The bend cover may significantly increase the performance and capacity of bend flow and may easily be added to existing manholes. A three-dimensional particle settling model was used to predict the benthic exposure zone to sewage solids for a large marine outfall and diffuser serving Nanaimo, Canada. The predicted exposure zone was determined largely by horizontal advection, and to a lesser extent by the relative amounts of floc and non-floc solids settling at two different rates (Hodgins et al. 2000).

Riverine litter and floatables occupy a spatial and temporal position in any systematic analysis of river systems and represent a problem that was increasing in scale. Quantifiable source factors of litter in the river Taff, South Wales, United Kingdom, system were found to be mainly sewage inputs through CSO and fly tipping. Sewage-derived material constituted approximately 23% of all items on the river, large quantities of waste, especially plastic sheeting, originated from fly tipping sites (Williams and Simmons, 1999). Burgess et al. (1999) reported that the City of Indianapolis developed five CSO control facilities as "pilot" facilities, for the purpose of establishing and demonstrating the local suitability and effectiveness of the various technologies that they employ. Preliminary results, with emphasis on the capture characteristics of the floatable debris netting trap facilities, were presented. Bridgeport's (Connecticut) Water Pollution Control Authority has recently faced the problem of floating debris and the sound's high tide. These drainage problems have been successfully solved by building new flow-control regulators with integrated automatic radio (wireless) and telephone-modem (wired) control, water-flow, and instrumentation technologies (Morrill and Sound, 1999).

Arthur and Ashley (1998) examined near-bed solids transport in combined sewers, developed a method to estimate the rate of sediment transport near the bed in sewers and concluded that near-bed transport of sediment may contribute to the first flush phenomenon in sewers. A study to quantify the first flush phenomenon in stormwater runoff failed to identify any consistent, strong indication that the first flush runoff from a storm contains higher concentrations of pollutants than the event average. Analysis of SS in the River Seine (Paris, Fr.) both upstream and downstream of major CSO showed that SS from wet-weather events settled rapidly, after which they are gradually mobilized from the river bed during dry weather (Estèbe et al., 1998). Dimensionless mass versus volume curves for 197 runoff events in 12 separate and combined sewer systems depended on the pollutant, the site, the rainfall event and the workings of the sewer system. No general relationships was established because of the complexity of the phenomena involved and the multiplicity of influencing factors (Bertrand-Krajewski et al., 1998). Only slight first flush effects for SS and conductivity of storm runoff were observed at single road inlets for two catchments in Yug. and Swed. and no first flush effect was recorded for pH or temperature. After a year of study, conclusions were that the first flush, if strongly present at the end of a drainage system,

is not generated by the first flush of pollution input and that regression curves are not very reliable for prediction of the first flush load of pollution input into drainage systems (Deletic, 1998).

#### **Real-time control (RTC).**

Ocampo-Martinez et al. (2006) discussed the application of fault-tolerant optimal controls of sewer networks in Barcelona, Spain. The main aim of this project was to protect against CSOs.

Cheung et al (2004) provided a review of current RTC issues and industry needs, available tools, and comparison of the RTC modules of current computer models, and experience in applying RTC for pre-design analyses and evaluation of wastewater treatment plant operation. Most dynamic sewer system models, such as XPSWMM, DHI-MOUSE, InfoWorks, and SewerCAT, now have RTC analysis capabilities, and special modules for simulating RTC devices.

A global predictive RTC strategy to minimize overflow volumes from combined sewers was presented by Duchesne et al (2004). The proposed strategy allows surcharged flows in the sewerage system. Flows and piezometric heads in the sewer are computed by a hydraulic simulation model. The system was tested in the Marigot interceptor in Laval, Canada. According to Khorchani et al (2004), overflow structures built in combined sewer systems are often the source of hydraulic failure during wet weather conditions. A new approach based on video monitoring of these structures is described. Image processing tools are used to determine the shape of the surface profile on the side weir and to transform image data into numerical data that can be used for modeling.

Moisio et al (2004) reported on the efforts of Cincinnati, OH, to develop a system wide hydraulic model. The computer hydraulic model of the sewer system includes all 12" and above sanitary sewers and all 18" and above combined sewers, the seven treatment plants. The model contains a RTC foundation. The district has successfully completed the model and has integrated it into its operations. Rosenberg et al (2004) described how the Northeast Ohio Regional Sewer District used RTC to evaluate filling and dewatering of approximately 10 miles of large diameter storage tunnels. Modeling challenges included using RTC to control surge and to systematically dewater portions of the system after a storm event.

Schultze et al (2004) presented a review of the current state of the art of RTC of urban wastewater systems, considering the sewer system, along with wastewater treatment plants, and receiving waters. An example using the Quebec Urban Community was also given. Zacharof et al (2004) described the use of the SYNOPSIS model for the integrated modeling of urban wastewater systems. SYNOPSIS was applied to a series of catchments (with and without real-time control) that were similar in most respects but had differences in key parameters such as total storage volume and river dilution. Optimization for DO benefits in the receiving waters did not necessarily reduce river ammonia concentrations.

The City of Atlanta, GA, is using a network of 125 flow monitors and 30 rain gauges to monitor the performance of their sewer system in real time (Stevens et al 2004). Managers with web access can quickly be notified of sewage spills, blockages or even partial blockages. The web-based IntelliScan™ system operates by learning both the flow pattern at each monitoring site and the response of each monitor basin to rainfall.

Comeau et al. (2003) described the design and implementation of a real-time flow control for a major trunk sanitary and relief tunnel system in the City of Ottawa, Canada. The flow control system consisted of a modulating gate-actuator assembly tied to the City's SCADA system. Duchesne et al. (2003) applied a global predictive real time control strategy that minimizes overflow volumes from combined sewers during rainfall to control flows entering the Marigot interceptor, Laval, Canada. Five minute control horizons were shown to be sufficient to guarantee control performance and safety when significant surcharges are allowed in the interceptor and when the controlled regulators are situated in the area of pressurized flow. Joyner et al. (2003) reviewed the use of real-time control for the combined sewer system in Cincinnati, OH to prevent CSOs. RTC modeling results were compared with model results for the current system operation. Petruck et al. (2003) proposed the real-time control of a combined sewer system using radar-measured precipitation. The system was verified in a pilot-study in Gelsenkirchen, Germany. It was found, that the volume of combined sewage overflow could be reduced by 5 per cent per year. Wagner et al. (2003b) reported on Hartford's automation program for monitoring and evaluation of the collection system. Analysis of system data would identify CSO discharges that will lead to further reductions in unwanted CSO discharges to state waters.

Formica et al. (2003) investigated the use of vortex valves to optimize regulator control for CSOs in Springfield, MA. The valves will also better assist in controlling the hydraulic grade line in the sewers. Matsuba (2003) reported on the establishment of a fiber optic network in Nagoya, Japan in sewer networks. Sewer networks were selected because of the

security of the cables during natural disasters. These in-sewer fiber-optic cables were also used for the Storm Drainage Information System, which can provide the Headquarters with real-time information about the operation status of each stormwater pump.

Nielsen and Nielsen (2002) evaluated the integrated real-time control system for the wastewater treatment plant and sewer system. The system was capable of adjusting the plant's hydraulic capacity based on loads as monitored by the real-time control system. The effects of real time control of sewer systems were evaluated by Frehmann et al. (2002b) using an integrated model with four submodels (surface runoff, sewer flow, wastewater treatment plant, and receiving water). The results showed that the effect of a control measure may be ambivalent in an existing system but that drainage system can be optimized toward environmental protection using real time control on the catchment scale. Klepyszewski and Schmitt (2002) compared a conventional, rule-based control of a combined sewer with a fuzzy-logic control through the use of hydrodynamic simulation of optimizing storage capacities of four combined sewer overflow tanks. The results indicated that both control systems were able to reach the objective and the use of the fuzzy-logic-based system provided no additional benefits, in spite of its additional costs. Sugita et al. (2002) performed a feasibility study on the real-time control of pumps for the reduction of CSOs. The use of RTC control made it possible to reduce CSO by roughly 50% for small rainfalls (total precipitation of < 20mm) by storing rainwater in the pipes and rainfall forecasting led to a CSO reduction of 80%.

O'Connor and Field (2001) reviewed the USEPA Capstone Report on control system optimization, including a management strategy that will maximize the use of the existing system. This will postpone construction of new facilities and will size storage volumes in concert with the treatment rate to obtain the lowest-cost storage-treatment system. The components, hardware, and strategies to create such a system were described. An RTC methodology was used to measure the discharge problem from an urban area (Yamada et al., 2001b), and was used in conjunction with a stormwater tank to retain flows. The results showed that COD in the stormwater runoff was reduced to approximately 0.45 mg/L.

The sewer system evaluation by the Milwaukee Metropolitan Sewer District (MMSD) proposed that flow regulation in the system be controlled not by specific flow rate from the tributaries but instead by maintaining a constant hydraulic grade line in the system, i.e., the flow allowed in the system will be determined by the available capacity of the downstream pipes (Bate 2001). The paper by Schultz et al. (2001a) explained how controlling the interceptor system, rather than just relieving it, enabled the Milwaukee MSD to achieve far more than merely reducing bypass and overflow frequency. The collection systems controls allow the MMSD to meet tight overflow restrictions in a manner flexible to variable precipitation patterns, growth patterns, and lake and groundwater levels. In addition to more efficient use of intercepting sewer capacity, the regulation strategy also provided a significant cost savings when compared to conventional flowrate regulation. The Louisville and Jefferson County Metropolitan Sewer District (MSD) is considering Real Time Control as a possible alternative in the Combined Sewer Overflow (CSO) Long Term Control Plan (LTCP) (Charron et al., 2001). Two successive studies have produced very promising results – the first implying an overall reduction of 64% in annual overflow, and the second currently showing similar results to the first.

Chowdhury et al. (2001) reviewed the RTC control model developed for the District of Columbia. The model was applied to evaluate existing and potential improvements to the system, and also used to evaluate the effectiveness of previously-installed controls. The model results indicated that significant reductions in overflows had been achieved through the controls installed in the past. Real-time control (RTC) operations strategies for the Quebec Urban Community (QUC) were discussed by Colas et al. (2001). Simulation of each RTC strategy using 32 real back-to-back rainfalls showed that the existing system performs better under RTC than with conventional control. Efficient in-system storage and treatment capacities and the elimination of flood risks were the main benefits of this type of real-time management. The results of the first year of operation of the optimized real-time control system for the QUC were presented by Lavallee et al. (2001). These results confirmed the model results for the benefits of the QUC RTC. RTC use in Philadelphia was reviewed by Marengo et al. (2001). The implemented RTC system provides the capability to prioritize capture of combined flow in the collection system, to minimize overflows to sensitive receiving streams, and to optimize the use of available interceptor sewer-system storage during wet weather. SWMM model simulations were performed to quantify the benefits of RTC implementation in PWD's SWDD.

Real Time Control (RTC) of wastewater systems involves using automatically adjusting weirs, flow separators, and similar devices to divert flow to unfilled portions of the collection system before overflow occurs. One of the more frequently applied RTC techniques in combined sewer systems (CSS) is the activation of in-line storage capacities by positioning regulators such as moveable weirs and gates into the collectors. Campisano et al. (2000) presented the results

of RTC application to the Roma Cecchignola CSS through the use of an advanced hydraulic model. Comparison of the results obtained with the tested strategies showed that a global control strategy reduced overflows considerably more than a local control strategy. Charron et al. (2000) presented the results of a study of RTC to reduce CSO in and around Louisville, Kentucky, which showed a global RTC strategy would enable a more efficient use of the existing system capacity and reduce the overall cost of the CSO control. Cigana (2000b) introduced the use of linear overflow devices to help municipal managers achieve increased retention of sewage in a sewer while protecting against flooding. Cigana's examples demonstrated that the required water head was reduced by 50% for the same overflow rate. Jain (2000) summarized the hydraulic characteristics of a two-ramp drop structure used for diverting flows from near-surface storm-sewer systems to underground storage tunnels. The construction of this structure may be more suitable in urban areas where an open-cut construction is not feasible. Lavallée et al. (2000) reviewed the RTC system installed for the Quebec Urban Community (QUC), Canada. The results showed that a Global Predictive Real Time Control (GP-RTC) strategy on the Westerly Sewer Network was successful in terms of proven efficiency. GP-RTC meant that only 4 storage facilities would be required instead of the 7 needed without GP-RTC, a 22% savings (Pleau et al. 2000). Pollution-based RTC, or PBRTC, is designed to reduce the potential pollutant load on receiving waters during wet weather without expansion of transport or storage capacity. In branched interceptor systems PBRTC reduced CSO pollutant loads by more than 20% compared to volume-based RTC (Risholt 2000). Stinson et al. (2000) presented results of two case studies of RTC on portions of sewerage systems near Paris, France and in Quebec City, Canada. Villeneuve et al. (2000) compared three RTC strategies used in a collection system in terms of optimization of the use of the system capacity and the cost of long-term CSO control. The Philadelphia Water Department used the SWMM EXTRAN and SewerCAT models investigate RTC in its Southwest Drainage District (Vitasovic et al. 2000). Schutze et al. (2000) reviewed RTC for an integrated system that included the collection system, the treatment plant and the river. The results of their work was the development of an algorithm for the complete urban wastewater system and the methodology for parameter optimization.

RTC of combined and sanitary sewer systems aims to reduce overflows by better utilizing the existing storage in a systems using real-time data such as rainfall and water level data to control adjustable weirs or pumps. Gonzalez et al. (1999) worked on the development and simulation of RTC systems for urban or metropolitan drainage systems with CSO or flood problems. They reported some conclusions and encourage the use of RTC systems on sewer systems. In response to floods in 1982, the Urban Community of Bordeaux decided to make improvements in their stormwater management system. Studies indicated that CSO have a significant effect on the environment. Therefore, emphasis will be placed on improving the management of the sewer system during rains and on the design of new storage structures and new treatment plants (Briat et al., 1999).

Artina et al. (1999) presented an evaluation of the benefits given by different configurations of storage tanks in a virtual but likely urban pilot site. The study showed that RTC, even if always useful for the reduction of overflow volume and frequency, in some cases can increase the discharged loads, under the hypothesis of complete mixing without settling in tanks. Fuchs et al. (1999) described the results of a study of the potential of real-time control of CSO for the combined sewer system of the city of Dresden. The results showed a significant 5% to 90% (mean more than 35%) reduction of the overflow volumes and loads for the controlled state compared to the uncontrolled one.

To address the problem of optimal water distribution to a range of retention reservoirs in an urban sewer network during rainfall events, Marinaki et al. (1999) proposed a linear multivariable feedback regulator that was developed via a systematic design procedure, including a simplified model, a quadratic minimization criterion, and subsequent application of the linear-quadratic optimization method. Simulation tests for a particular large network and various inflow scenarios indicate that significant overflow reductions were achieved by the application of the linear-quadratic regulator. Pfister and Cassar (1999) described measurement and modeling techniques developed for using X-band radar estimates of precipitation for RTC in a combined sewer system.

Villeneuve et al. (1999) presented a study of three types of RTC alternatives and conventional static control, applied to the Western section of the Quebec (Canada) Urban Community (QUC) sewer system. At the end of the long term CSO control plan it was projected that the QUC will control more than 85% of the CSO, for a total cost of US \$107,000,000 which was 37% less than what had been estimated before the introduction of RTC. Risholt et al. (1999) reported on a project to document current discharges of pollutants and to find potential reduction by implementing RTC of the wastewater system in Fredrikstad, Norway.

Offline simulations carried out with a variety of control conditions suggest that great benefits were to be expected using global control with precise forecast information compared to a static system with local control only. Quirnbach et al



(1999) presented an approach to joint operation of an urban drainage system and the corresponding sewage treatment plant. This operation was based on real-time flood forecasts, which were computed with the aid of radar rainfall measurements to minimize the combined negative effects of the hydraulic load (water quantity) and the pollution load (water quality) in the receiving waters during floods. Schmitt et al. (1999a) developed a new management strategy of the City of Nancy's sewage system (Lorraine, France) in order to reduce rainwater pollution overflows using a model which simulated flows in interceptors, transport of dissolved and solid pollutants, and precipitation, flocculation and sedimentation in WWTP. This new management strategy, optimizing the use of existing infrastructures, aims to conciliate flood risk management and the reduction of pollution overflows into the Meurthe River (France). Soeda et al. (1999) presented a case study of proposed improvements to combined sewer systems with no construction of new facilities and effective utilization of existing facilities through various modifications of stormwater pump operations. This system proved an effective means of reducing overflows and reducing pollutant loads from combined sewer systems.

Weib and Brombach (1999) examined the application, advantages, and hydraulic performance of devices for water level control like movable weirs (self-regulating or auxiliary powered) or siphons which were frequently used at overflow structures in urban drainage. Special focus was given to possible critical points and limits of application. Yagi and Sheba (1999) applied fuzzy logic control and genetic algorithms to achieve improved pump operations in a combined sewer pumping station. It was found that current pump operations can be improved by adding the sewer water quality to the input variables and to the fitness function; the improved operations can reduce not only floods in the drainage area but also pollutant loads discharged to the receiving waters.

#### **CSO tunnels, storage tanks and structures.**

Chandler et al (2004) described the Richmond, VA, 5,900 feet long deep tunnel, Farnan et al (2004) reviewed the history and performance of Chicago's Tunnel and Reservoir Plan (TARP), and Munsey et al (2004) reviewed the 10-year operation and maintenance history of Milwaukee's deep tunnel.

Oksuz et al (2004) and Shafer et al (2004) described how hydraulic modeling demonstrated that the metropolitan interceptor system on Milwaukee's northwest side would surcharge by 2010, resulting in significant basement flooding and wet weather overflows. A \$120 million relief system project incorporating the existing deep tunnel (405 million gallon capacity), is being constructed to alleviate these problems. This program will add more storage and increase the capacity of treatment systems.

Guo et al (2004) reported a test of vacuum flushing of sewer sediment from combined sewers and CSO storage tanks. They found that the sediment removal efficiency of the vacuum-flushing device is practically the same as for a conventional gate-flushing device. Smith et al (2004) described the accelerated testing of the flushing chambers of the West Side Consolidation Conduit at Augusta, ME, using synthetic materials.

The Portland, OR, CSO project "Big pipe" was described by Burke (2004). The city is required to obtain a 94% reduction of CSO discharges into the Willamette River and 99% into the Columbia Slough by the year 2011. Murphy et al (2004) described the CSO storage project in Bangor, ME, that used precast v-bottom box sections. The city now has 3.8 million gallons of extra capacity within its sewer system, provided at a total cost of less than a third of the initial projected costs for constructed-in-place facilities.

Couture et al. (2003) reviewed factors influencing the occurrence of CSOs. In addition, the paper presented four methods to eliminate or reduce CSO problems including in-line retention storage, off-line retention storage, high-rate clarification treatment and sewer separation.

Andrews et al. (2003) presented an update of the 4 million gallon storage and treatment tunnel in Rainier Beach south of Seattle, WA as part of the CSO abatement program. Anonymous (2003g) reported on the novel, plastic stormwater/CSO retention system that was developed for the Jewel-Osco store in Elmhurst, IL. This technique reduced the volume of earth that had to be excavated for the same storage volume.

Anonymous (2003h) reported on the improvements made to the Columbia Blvd. Wastewater Treatment Plant in Portland, OR, including installation of a reinforced pipeline to collect wastewater and stormwater from the combined sewers and transport them to the plant. Chandler et al. (2003) presented the construction of a deep tunnel retention structure in the riverfront area of the James River in Richmond, VA. The problems encountered included steep entry slopes requiring energy dissipation and flushing of the system to prevent solids buildup.

Kaunelis et al. (2003) investigated whether CSO basins could accept more flow without constructing additional capacity based on the results of a sampling program designed to test the ability of the Inkster CSO Basin (Rouge River) to achieve adequate disinfection through a 20-minute contact time. The potential cost savings of using this approach is nearly \$12 million or \$30,000 per acre.

Ku et al. (2003) described in detail the design and construction of in-line storage systems using inflatable rubber dams for combined sewer overflow control in Indianapolis, IN. Murphy et al. (2003) presented the optimization of in-system storage capacity to enhance sewer system operation in Bangor, ME. Operators have discovered that the additional collection system capacity also provided significant benefits regarding management, operations, and maintenance.

Ashley et al. (2002) analyzed the effects of introducing extended in-sewer storage at CSOs on downstream sewerage and treatment. The study combined the Hydroworks model and a new model developed at Aalborg University to describe the range of conditions, including flow, odor generation and nutrient removal, that can be found in the collection system. Lau et al. (2002a) reviewed the use of optimizing storage volumes in sewer systems to control the concentration of specific pollutants in receiving water bodies. An integrated simulation tool (SYNOPSIS) was used to determine the specific storage volume needed, with the results showing that an optimal solution can only be achieved sometimes and there are times that compliance with the standards will not be achieved, regardless of the storage volume provided.

Baki et al. (2002) reviewed the design and operation of the O'Hare Chicagoland Underflow Plan (CUP) Reservoir in the Greater Chicago area. The purpose of this underground 343 million-gallon reservoir was to collect and retain combined sewer flows until they can be pumped to water reclamation plants for treatment. Ridgway and Rabbaig (2002) reviewed the use of inflatable dams to provide in-system storage devices to reduce CSOs. A second important design criterion was to minimize the number of level sensors required since the sensors require frequent maintenance. Bate et al. (2002a) provided an overview of the inspection of the mainline storage tunnels that comprise Milwaukee's Inline Storage System, while Bate et al. (2002b) reviewed the flow-regulation evaluation of Milwaukee's Central Metropolitan Interceptor Sewer with the goal of optimizing the flow through the conveyance system while preventing overflows.

Ashley and Jack (2002) investigated the impact of retaining CSO flows in the sewer system on an activated-sludge treatment plant. It was concluded that the storage caused little or no benefit with respect to ammonia emissions from the plant but there was an overall benefit with respect to BOD total emissions.

The paper by Sonderup et al. (2002) compared rainwater tanks and detention basins for CSO abatement in Denmark. The result was that rainwater tanks were found to be less efficient and the tank volume would need to be 3 – 40 times larger than a downstream detention basin to obtain the same reduction of mean annual CSO volumes due to the fact that rainwater tanks are often partially full and cannot hold the complete peak flow. Rabbaig et al. (2002) presented an overview of Detroit's three CSO treatment basins that discharge to the Rouge River, including ramifications of in-system storage provided by the facility, quantification of "sanitary trash," facility operation and maintenance staffing recommendations. Rickard and Darter (2002) reviewed the selection of rectangular basins over vortex separators for CSO treatment in West Lafayette, Indiana. The comparative benefits of the rectangular basins were 20 minutes of chlorine contact time, greater solids removal and the ability to store larger volumes of water at the same capital costs as the vortex separators. Bode and Weyand (2002) reviewed the installation of about 500 stormwater/CSO detention facilities in the Ruhr river basins and the significant drop in pollution from stormwater runoff after the basins were installed. The tank volume for stormwater could be minimized by using real-time control for dynamic operation of all detention facilities.

Carr et al. (2001) reviewed the use of street-storage systems to prevent combined sewer overflows and mitigate basement flooding, based on the idea of accepting the complete volume of water but reducing the inflow rate of the stormwater to the sewer system. System components included street berms, flow regulators and surface and sub-surface storage facilities. Charlotte-Mecklenberg Utilities also found that they were able to service new development without creating overflows by storing peak flows upstream (Crowley and Howard 2001), thus delaying a system-wide expansion. Carter et al. (2001) reported on the evaluation of inflatable dams for use in Philadelphia as part of its Long Term Combined Sewer Overflow Control Plan (LTCP). These dams were operated under real-time controls to storage and treat flows upstream, thus reducing the frequency and volume of CSOs. Based on model results (using EXTRAN) with three inflatable dams operated by RTC, a 70% (50-million gallon) reduction in average annual CSO volumes to the Schuylkill River would be expected.

Murphy and Ring (2001) reviewed the use of pre-cast concrete box sections to create CSO storage facilities. The savings from using pre-cast versus cast-in-place boxes was estimated at \$3.1 million dollars for the 1.2-million gallon Kenduskeag East CSO Storage Facility. The Pollution Control Plan (PCP) for Hamilton-Wentworth recommended the construction of 10 – 12 underground storage tanks to intercept CSO waters for subsequent conveyance to the treatment plant (Stirrup 2001). The sizing of the tanks was performed using SWMM. The premise was that continuous modeling would be the only reliable way to ensure that the tank performs to those control criteria under real operating conditions for long periods of time. Freedman et al. (2001) reported on the use of unused aeration basins for receiving and equalizing industrial and CSO flows to the treatment plants in Rockland, Maine.

Temporary storage at CSO and SSO outfalls, with effluent returned to the system for treatment when system loading subsides, was a widely practiced method of WWF control. Some authors focused on modeling and design of storage structures. Harwood and Saul (1999) described how the computational fluid dynamics software Fluent was used to simulate the hydraulic and particle retention efficiency performance of three extended stilling pond CSO chambers in the United Kingdom. It was concluded that where the effective retention of neutrally buoyant particles was a design criterion, increasing the size of the chamber may not be the most appropriate solution. Hobbs et al. (1999) discussed the use of flow equalization basins (FEB) for control of SSO and CSO. FEB increases systems capacity dramatically by retaining excessive flows until the collection system was better able to handle them and cost considerably less than more traditional methods. Maglionico (1999) proposes a methodology for the design of CSO tanks aimed to control first foul flush in sewer networks, based on a five years period of field continuous measurements carried out on rainfall, discharge and water quality in an experimental catchment near Bologna (Italy). Stovin et al. (1999) compared the results of simulated flow patterns and gross solids separation predictions with field measurements made in a full size storage chamber within an urban drainage system. Although estimates of total efficiency based on the observed settling velocity distribution differed from the measured values by an average of  $\pm 17\%$ , the simulated efficiencies agreed with the field observations in identifying the most efficient configuration. Van Mameren (1999) presented a method of using the results of rain series calculations as a design tool for stormwater sedimentation tanks, and demonstrated the method with an example.

Other papers presented case studies of CSO and SSO storage. For a better understanding of the spill over into the receiving waters, recorded data from 90 CSO tanks with a collective monitoring time of more than 300 years were compiled and analyzed by Brombach et al. (1999). A ranking procedure was proposed for an easy to handle evaluation of the overflow activity of CSO tanks. Hartshorne and Cadman (1999) described the design and construction of a 12,500 m<sup>3</sup> capacity stormwater storage tank in Westbourne Avenue, Rhyl (United Kingdom). The finished structure was completely buried and incorporates new pumping plant to pump dry-weather and storm flows. Kearney and Schoettle (1999) described methods of cleaning dewatered CSO-storage basins at the Spring Creek Auxiliary Water Pollution Control Plant, which was used for temporary storage and treatment of CSO in New York City. Murphy et al. (1999) report on an in-line CSO storage facility constructed of bolted together precast box culvert sections that was designed and built by local engineers and contractors in the City of Bangor, Maine. This inexpensive CSO storage option has numerous advantages over the alternatives. A cost-effectiveness analysis conducted by the City of Slidell, Louisiana demonstrated that an offline storage-facility would produce a substantial capital cost savings over multiple, decentralized line repair projects to achieve the same level of SSO control. The completed project applies commonly accepted technology to produce a system that worked within the funding constraints, was acceptable to the general public, and was easy to maintain for the operators (Prellop, 1999). Wada and Miura (1999) attempted to reduce CSO using a large-scale storage pipe, which was constructed for flood control. Using a movable diversion structure permitted use of the storage pipe for both flood control and CSO control.

The influence of the experimental procedure for separating a sample by settling-velocity fractions was demonstrated. This not only takes into account the settling-velocity characteristics of wastewater and stormwater SS but also considers SS which influence settling velocities, ultimately impacting the design and management of sewer networks (Lucas-Aiguier *et al.*, 1997). The settleable and nonsettleable SS concentrations were measured during a storm event at a combined WWTP in Sacramento, Calif. (Whalberg *et al.*, 1997). While influent settleable and nonsettleable SS concentrations varied throughout the storms, the primary-sedimentation tanks were 100% efficient in removing the settleable solids the tanks were designed to remove.

### **CSO Treatment**

CSO treatment using a plant-covered retention soil filter was evaluated by Frechen et al. (2006). The paper presented the technology, design, operation and construction for these filters, in addition to the results of a long-term study on an existing filter. Landon et al. (2006) discussed the Columbus, Ohio, decision to use ballasted flocculation to treat wet-

weather flows. The results showed that wet startup provided better performance than dry startup and that it took two hydraulic residence time periods to achieve the targeted level of performance.

Bendick et al (2004) and Neufeld (2004) evaluated cross-flow microfiltration, with and without backpulsing, for the treatment of dilute primary sewage effluent, representing CSO wastewater for the Allegheny County Sanitary Authority. The 0.2  $\mu\text{m}$  alpha alumina ceramic membranes produced a permeate of acceptable water quality for surface water discharge, at a suitable treatment rate (almost undetectable levels of fecal coliforms, E. coli, and enterococci, along with greatly reduced levels of BOD<sub>5</sub> and SS).

Kharaghani et al. (2003) proposed that the City of Los Angeles' separate sewer system be directed towards treatment, ending the idea of a separate storm sewer system whose water would not be treated prior to discharge in the Pacific Ocean. Glasgow and Morrow (2003) investigated alternatives to storage for preventing CSOs during times of intermittent flow. The selected alternative, known as Equivalent Treatment, was to treat the overflow to a desired standard (such as by using clarifiers, filters and UV disinfection) and discharge it. TSS concentrations, UV transmissivity and fecal coliform concentrations could be improved to a level where ultraviolet disinfection would be viable. Szabo et al. (2003) investigated the performance of a wet weather treatment facility (off-line sedimentation tanks, fine screening and chemical disinfection) in Cincinnati, OH on CSO control. Most pollutant removal occurred during sedimentation and storage in the treatment tanks, with removal efficiencies of 20-50% for BOD<sub>5</sub> and 25-70% for TSS commonly observed.

The paper by Andoh (2002) reviewed the evolution of Hydrodynamic Vortex Separators in the context of their use as high rate rotary flow separators for achieving water quality improvements. The applications reviewed included treatment of CSOs, SSOs, stormwater and wastewater, and misconceptions about their use were addressed.

Heath et al. (2002a) reviewed the challenges associated with the design of the MWRA Union Park detention/treatment facility, which will provide treatment for wet weather flow discharged from the Boston Union Park Pumping Station (UPPS). Some of the more significant challenges include: siting the facility in a densely developed, urban residential/commercial setting; institutional challenges associated with a facility to be jointly owned and operated by two public agencies; maintaining the flood control function provided by the existing UPPS; and other technical challenges. This paper presented the design features and approaches developed to address project challenges, many of which may be faced by others tasked with implementing similar wet weather pollution control projects in urban areas.

Matson (2002) presented the results of a pilot study on the City of Salem's (Oregon) high rate process train that treats SSO wastewater. The results from the pilot programs showed that the effluent produced by a peak excess flow treatment facility would be equivalent to the effluent from conventional secondary processes treating similar flow (> 85% removal of TSS and 60% removal of BOD was consistently achieved). Dorsch (2002) described the Muddy Creek-Westbourne high rate treatment facility in Cincinnati and discussed ways to reduce or eliminate CSOs. The structure was designed to blend into its environment and was designed to separate flow from the trunk line at a diversion chamber and run it through a coarse screen and over a grit pit. Excess flow is retained in a detention tank. Yoshida and Tomita (2002) discussed the development of a high-speed combined sewerage stormwater treatment system. The new system was capable of effectively removing the high pollutant concentrations in the first-flush and that O&M was inexpensive. Hunt and Eckley (2002) presented the City of Salem's (Oregon) peak excess flow treatment facility consisting of preliminary treatment, high-rate clarification and UV disinfection. This project has been designed and constructed to take the load off the City's wastewater treatment plant and to reduce the number of annual SSO discharges into the Willamette River.

Schafer and Gray (2002) reviewed the proposed chemically enhanced high rate separation system to be added to the Sycamore Wastewater Treatment Plant in Cincinnati, Ohio. The addition would allow for treatment of peak wet-weather flows of up to 50 MGD total and should provide treatment sufficient to ensure that the discharge does not degrade the Little Miami River, a State and National Resource Water for Primary Contact Recreation. Sampley and Sullivan (2002) reviewed the CSO facility in East Bremerton. The facility uses the ACTIFLO ballasted clarification processes that combines conventional water clarification with microsand. Jacobsen and Hong (2002) reviewed the use of microsand ballasted flocculation and clarification for high-rate treatment of stormwaters and sewer overflows.

Andoh et al. (2002) reviewed the use of screening for treating CSOs in the UK through the short-term testing of CSO screen and chamber configurations. The system, including a novel non-powered self-cleansing screening system with no moving parts, provided robust, reliable, flexible and effective screening of CSO wastewater. Ungar and Schnipke (2002) reviewed fine screening for CSO control in Lima, Ohio for 90% treatment of the four-month storm. The fine screening

equipment has 4-mm openings that will not only trap floatables but also provide CSO treatment by acting as a barrier to solids. Takasou et al. (2002a) performed a study on the control of CSOs by a fine CSO screen. This review included investigating their performance, structure, application, installation, maintenance, head loss coefficient and filtration rate.

Takasou et al. (2002b) researched the potential use of a high-speed, space-saving fiber filter to reduce the discharge load of CSOs in Japan and evaluated its practical performance and applicability. The results showed that a high-speed fiber filter can be used to decrease the amount of primary treatment wastewater overflow on rainy days.

An evaluation of the effectiveness of UV disinfection of CSO processed through Continuous Deflective Separation (CDS) devices was reported on by Akridge et al. (2002). The combination of treatments was found to provide a three-log reduction of fecal coliforms in a preliminary study. Boner et al. (2002) evaluated the use of bromine disinfection for wet-weather flows at the Uptown Park CSO facility in Columbus, Georgia. Disinfection capabilities of BCDMH (1-bromo, 3-chloro, 5,5-dimethylhydantoin), in a suspension form manufactured by BioLab, Inc were examined on a bench-scale level along side of other chemical disinfectants to quantify disinfection performance at different CSO strengths. BCDMH dosing system set-up, tests and calibrations were performed.

Turner et al. (2002) reviewed the steady-state bacteria delisting approach in Georgia. Study conclusions and recommendations called for a full-scale demonstration to provide embankment stabilization, peak flow attenuation, flushed pollutant removal and disinfection. Stormwater treatment facilities will attenuate wet weather flows in the upstream channelized-reaches; remove pollutants from impervious area flushes and disinfect dry weather as well as a portion of the wet weather flow using ultraviolet light (UV disinfection).

Wojtenko et al. (2001a) reviewed the chapter of the EPA Capstone Report on control and treatment of CSOs, SSOs, and stormwater runoff. The paper discussed inline and offline storage systems as well as in-receiving water storage systems. Three major types of treatment systems and their associated costs were also discussed: (1) physical (screening and sedimentation), including comparing high-rate vs. conventional processes; (2) physical/chemical (filtration and high-rate sedimentation); and (3) biological (trickling filters, activated sludge, aerated lagoons, and rotating biological contactors).

Gaffoglio et al. (2001) reviewed the City of New York's \$1.8 billion Citywide CSO Program that addressed CSO discharges from the more than 450 CSO locations within the City. Four open water projects (East River, Jamaica Bay, Inner Harbor and Outer Harbor), and four tributary projects (Flushing Bay, Paerdegat Basin, Newtown Creek, and Jamaica Tributaries) were included in the program. The paper described the CSO facilities NYC is building and planning under this major capital planning and construction effort, and it discussed the challenges faced by the City in implementing the program. Mynhier et al. (2001) summarized the City of Atlanta's recommendations for their Long-Term Control Plan for CSOs. The City proposed three options ranging from separating about 80 percent of the CSO service area (\$1.25 billion) to solely adding large consolidated storage and treatment facilities (\$710 million). The preferred option was between the two extremes, with some separation and consolidated storage and treatment facilities capable of treating all storm water runoff from the CSO area (\$950 million). Turner et al. (2001a) reviewed the CSO technology-testing program implemented in Columbus, Georgia. Results included protocols for characterization, model calibration and watershed yield quantification. Overall program findings included load generation rates and yields for aquatic biology indices. CSO treatment demonstrations indicate high-rate compressed media filtration as a cost-effective technology that may also be applied to stormwater as an impervious area flush-control. Schenk et al. (2001b) presented an overview of the EPA's Environmental Technology Verification (ETV) Program, with a focus on two areas of technology: flow meters and stormwater source-control devices. The Wet Weather Flow Technologies Pilot (WWF Pilot) program balances the desire for comprehensive testing (full characterization of equipment performance under a variety of water quality and facility conditions) against the need to keep testing costs reasonable.

### Disinfection

The efficacy of UV disinfection was tested by Baker et al (2004) for the City of Winnipeg. The results from a large number of bench scale tests indicated that UV disinfection of secondary effluent would be effective during dry weather conditions, but during wet weather conditions, it would be difficult to meet the disinfection standard.

The City of Richmond, VA, re-evaluated its original 1988 CSO Long Term Control Plan (LTCP) (Chandler 2004). They found that 79% of the entire CSO volume is discharged through the City's largest CSO outfall, Shockoe Creek, at a peak flow rate of 5,000 MGD. Ultraviolet (UV) irradiation and chlorination/dechlorination were evaluated during a disinfection pilot-scale study, with UV appearing to be a feasible technology for meeting their 80% bacteria reduction

goals. McKern et al (2004) described different disinfection test results and solids separation processes based on particle size distribution, TSS and turbidity. They eliminated UV disinfection as an option due to low transmissivity and colloidal particle residuals. High rate chemical disinfection testing of screened and filtered flow was conducted throughout the CSO hydrograph representing different waste strengths and chemical demands.

Maurer et al (2004) described Detroit's long-term CSO control plan for the control of CSO discharges to the Detroit and Rouge Rivers. The \$187 million Conner Creek CSO screening and disinfection facility has a storage capacity of 30 million gallons. Their goal is to meet the daily and monthly fecal coliform limits of 400 and 200 cfu/100 mL with 5 minutes of contact time.

An ozone treatment facility at the Salt Creek outlet to South Monarch Beach in South Orange County, CA, was described by Rasmus and Cover (2004). This facility will treat dry weather storm drain outfall flows. Ozone was selected after evaluating chlorination/dechlorination, UV light, and ozone alternatives, given the creek's relatively high levels of turbidity, total suspended solids (TSS), iron, and manganese.

LaGorga et al. (2003) reported on a project to identify and communicate the benefits and risks of disinfecting wet weather flows by evaluating available disinfection technologies and identifying disinfection by-products and their potential risks to aquatic and human life. A decision-making framework was developed that could be used. Based on the literature review and disinfection demonstration, hazards associated with wet weather flow disinfection appeared low, but the potential for public opposition could be high.

Anonymous (2003j) reported on the use of UV disinfection to treatment urban runoff entering Moonlight Beach, San Diego, CA. Stumwoehrer et al. (2003) reviewed the influence of changes in wastewater composition on the applicability of UV-adsorption measurements at CSOs. An individual evaluation of each single event resulted in an acceptable correlation between the UV absorption and the pollution measured as COD. A combined evaluation of the different events exhibited a very poor correlation which could not be used as pollution control parameter.

Yamamoto et al. (2003) investigated the feasibility of bromine disinfection for CSO treatment using a full-scale experiment station in Tokyo, Japan. The results confirmed that an injection rate of 2 – 7.5 mg/L (chlorine equivalent) reduces 103 - 106 counts of coliform group to less than the standard value of 3,000 CFU/ml. Evaluations were also made in terms of acute toxicity, mutagenesis, impacts on aquatic organisms, formation of trihalomethane and bromate ions, proving that BCDMH is comparable with sodium hypochlorite concerning biological safety.

Atasi et al. (2001c) presented the work performed by the City of Detroit Water and Sewerage Department (DWSD) that evaluated chemical disinfectants for the Baby Creek CSO water. EPA's ETV Program developed generic protocols for the testing of mixing needs in high-rate disinfection, such as that needed for CSO treatment (Moffa et al., 2001). The ETV program is also investigating alternative disinfectants. The New York City pilot study addressed, and an ongoing WERF project is addressing, alternative technologies. As part of the ETV Program, the WWF Pilot investigated the potential of high-rate disinfection technologies for wet-weather flow applications (Schenk et al., 2001a). The benefits of using simulated flows were described, as were the potential limitations associated with applying the data to actual wet weather collection systems. Wojtenko et al. (2001c) presented the results of several major pilot-scale studies to evaluate the effectiveness of UV light to disinfect CSO flows. UV light irradiation, when correctly applied, was found to be an effective alternative to chlorination for CSO disinfection. However, the success of disinfecting with UV light seemed to be strongly dependent on water quality. Wojtenko et al. (2001d) reviewed the chapter of the EPA Capstone Report on disinfection. Locating effective alternate disinfectants has proved to be very difficult.

#### High-rate clarification (including ballasted flocculation)

Jolis and Ahmad (2001) reviewed the use of high-rate clarification at the wet-weather treatment plants in San Francisco. The process was found to be highly effective for CSO pollutant removal. Suspended solids removal in excess of 80% of influent concentrations were achieved consistently. COD and BOD<sub>5</sub> removal exceeded 60%. Keller et al. (2001) reviewed the design of a ballasted flocculation system for the Lawrence (Kansas) WWTP. The ballasted flocculation system was used to treat excess flows from wet-weather events. The paper reviewed the jar test results, the performance of liquid versus dry polymers, and other design issues. The City of Rocky River, Ohio reduced their SSOs through expansion of the WWTP's primary treatment capacity (Leffler and Harrington 2001). The primary-treated effluent in excess of what the secondary treatment could handle was then blended with fully-treated effluent waters prior to discharge to the receiving water. This blending allowed the overall plant effluent to meet regulatory standards with the concurrent

elimination of headworks bypassing. Ballasted flocculation to improve WWTP performance during wet-weather flow periods was reviewed by Scruggs and Wallis-Lage (2001). Based on pilot and bench scale testing performed at three facilities, the ballasted flocculation technology was found to be compatible with client needs. In all cases, the ballasted flocculation system removed 75 to 95% of influent storm flow TSS at hydraulic loading rates varying from 60 to 80 gpm/sf when ferric chloride was used as the coagulant. The use of ballasted flocculation was also cost-effective at the three plants.

#### Filtration

Three western New York State treatment plants have retrofitted their existing sand filters to a coarse monomedia (Bentivogli and Smith 2001). The new media filters use less peak backwash water, have increased filter run times and have maintained the same effluent quality as the older sand filters with the smaller diameter media. Testing is ongoing for CSO treatment. The Niagara County Sewer District No. 1 Water Pollution Control Center installed mono media filtration to increase capacity in order to treat additional flows during wet-weather events. The result is that the Sewer District has met their goal of increasing filtrating capacity and filter run times, while eliminating filter bypassing.

#### Flow control in WWTP

In Flanders, a maximum of  $3Q_{14}$  (where  $Q_{14}=1.7$  times the dry weather flow) is treated biologically, while the excess flow (up to a total treatment plant flow of  $6Q_{14}$  or about ten times the dry weather flow) undergoes only physical treatment in storm tanks. Bixio et al (2004) described a high-flow activated sludge process, consisting of the treatment of the full storm sewage flow in the biological train and of the use of the storm tanks as additional secondary clarifiers. After successful testing, 56 treatment plants were switched to this high-flow activated sludge process. They reported that high-flow biological treatment provides a substantial reduction in total wet weather pollutant discharges, while also maintaining acceptable operating conditions.

Wet weather flow treatment improvements at the Toledo, OH, Bay View treatment plant will consist of fine screening, grit removal, high-rate clarification, flow equalization, and disinfection, and will double the existing treatment capacity to 400 MGD (Nitz et al 2004). Flow treated by the wet weather facility will be blended with the dry weather (secondary treatment) plant flows prior to discharge. Pilot testing of Actiflo and Densadeg high rate clarification systems (both found to be capable of meeting the treatment goal), followed by testing of medium pressure and low pressure high output ultraviolet disinfection systems. Filamentous organisms within the existing system and peak wet weather flow events were the cause of numerous permit violations at the Lewiston-Auburn, ME, wastewater treatment plant. Hankins et al (2004) described how Selector-Contact-Stabilization (SCS) using an anaerobic selector, reduced the filamentous organism problems without the benefit of excess phosphorus. The process has also periodically been able to provide excellent removal of suspended solids during peak wet weather flow events. Hanner et al (2004) described pilot-scale tests of the Actiflo process (for wet weather flow supplemental treatment) at the Rya WWTP in Goeteborg and the Sjoelunda WWTP in Malmo, Sweden. The process was shown to remove suspended solids and phosphorus well, with  $BOD_5$  being reduced by 50-60%. Miller et al (2004) described how the City of Indianapolis pilot tested several technologies (high rate clarification using the Kruger Actiflo system and the Infilco DensaDeg system; and conventional clarification using a WesTech Solids Contact Clarifier) to increase peak wet weather treatment capacity. The needed degree of treatment was between advanced primary treatment and full secondary treatment, with enhanced nitrification. They are considering the installation of a bio-roughing solids clarifier (BRSC) that would allow the existing two-stage nitrification system to be uncoupled at its Belmont treatment plant that could potentially double the treatment capacity. The performance of a newly developed Japanese CSO treatment process was described by Kosanda et al (2004). The high rate clarification process removed between 78% and 91% of TSS at treatment rates of  $50 \text{ m}^3/(\text{m}^2 \cdot \text{h})$  and between 64% and 85% removal of  $BOD_5$ . The process was effective over a wide range of influent concentrations, without any need for controlling chemical dosage rates.

Martin et al (2004) discussed how the Jones Island treatment plant in Milwaukee, WI, optimized its secondary treatment process to maximize its wet weather flow capacity, including the use of inline storage (deep tunnels). They also decreased secondary clarifier solids loading rates during peak wet weather flow events by implementing a step-feed system in aeration basins. The Stantec treatment system, including dual on-site equalization basins for peak flow storage, utilization of a multicomponent bioreactor with internal recycles, and the presence of over-sized secondary clarifiers to capture and store excess biomass, was used at Elmira, Ontario, for the control of wet weather flows (*Canadian Consulting Engineer* 2004).

In Flanders, Belgium, the potential to treat additional flow in the biological system of a WWTP was investigated by

Carrette et al. (2001). The concept was that higher hydraulic loadings could be treated within the biological treatment area if additional secondary clarifier volume was supplied. This operation scenario was successful and the overall pollutant discharge was significantly reduced. Chen and Beck (2001) also reported on using practical controllers to maximize the flow through the biological treatment system of a WWTP, with the result being the minimization of bypass flows. The results of the tests illustrated that the tested controllers could regulate the flows through activated sludge process sufficiently to maximize the treatment plant performance. Niemann and Orth (2001) modeled three modifications to traditional WWTPs in order to maintain a high efficiency of treatment during wet-weather flows. The three measures were increasing the nitrification volume, bypassing the primary sedimentation, and adding flocculants before secondary sedimentation. All three measures were effective.

Another approach to CSO and SSO control was to treat the effluent before it enters a receiving water. One widely-used approach to CSO and SSO control is to improve the ability of wastewater treatment plants (WWTP) to adequately treat high volume wet weather flows. The Binghamton-Johnson City Joint Sewage Treatment Plant, New York, is expanding its wastewater treatment facilities for three purposes: (1) to meet effluent limits for discharge to the Susquehanna River; (2) to increase the primary treatment capacity to treat peak storm weather flows up to 60 MGD; and (3) to increase the secondary treatment capacity to a minimum of 35 MGD. Aridgides et al. (2000) conducted a pilot-scale evaluation of biological filters that would fit within the existing site limits and allow elimination of the peak wet weather bypassing. In order to minimize CSOs to local receiving waters, the Philadelphia Water Department began a program to maximize flow treated by the existing WWTPs during periods of wet weather. As part of this effort, Ferguson et al. (2000) documented the effect of variations in influent characteristics, operational procedures, and minor physical modifications on clarifier performance. In the City of Edmonton, Alberta, Canada's CSO Strategy, a preferred method of control was to convey more flow to the WWTP for treatment and expand treatment capacity. In order to understand and evaluate the hydraulic relationship between the upstream collection system and the WWTP, a detailed hydraulic model was developed as part of the collection system hydraulic model (Gray et al. 2000).

Kurtz et al. (2000) presented the results of pilot testing of high rate physical chemical treatment technologies in a New York City WWTP. All units performed well when operating correctly, removing between 69% and 84% of TSS on average. King County, Washington modified their continuously- operated Alki Treatment Plant to an intermittently-operated wet weather facility, and they successfully demonstrated that treatment of wet weather flows was possible after modifications to the existing primary treatment facilities (Maday et al. 2000). An analysis by Moffa et al. (2000) demonstrated that retrofitting existing wet-weather flow facilities was technically feasible in most cases (a function of site-specific conditions and treatment requirements) and may be more cost effective than construction of new conventional control and treatment facilities. A related paper by O'Connor and Goebel (2000) indicated that retrofitting processes better enabled communities to meet the U.S. EPA's National CSO Policy and stormwater permitting program requirements. The Arlington County (Virginia) WWTP underwent a retrofit to meet a proposed mandatory ammonia and voluntary total nitrogen standard and to reduce wet-weather plant bypasses. The main components of the wet weather management plan were the new flow equalization basin, the operational flexibility in terms of the feed to the individual aeration tank passes, the flexible aerobic/anoxic swing zones and the retrofitting of the secondary clarifiers (Pitt et al. 2000c). Camp Dresser & McKee Inc. used microsand-ballasted high-rate clarification in WWF treatment for a wastewater collection and treatment system (Vick 2000). Chemically enhanced high rate separation has been shown to offer a robust treatment alternative for CSO, SSO and excess WWF at WWTPs, and will be evaluated by USEPA's ETV Program (Zukovs et al. 2000).

Hufnagel et al. (1999) reported on the collection and analysis of data from six CSO demonstration facilities in the Rouge River watershed (Michigan) from June 1997 through September 1998, and discuss performance, operational experience, and insight gained on design of facilities from an operational perspective. Andoh et al. (1999) presented the results of testing of a novel self-cleaning CSO device at the United Kingdom National CSO Test Facility at Hoscarr WWTP, Wigan, and concluded that CSO screening systems offering 4 mm two directional screening standard were significantly more efficient than 6 mm screens and might not entail any additional cost. Averill et al. (1999) described pilot-scale process development and full-scale demonstration work, and discussed considerations for the implementation of a high-rate physical-chemical treatment process that has been developed for use in satellite treatment systems to control CSO in Ontario, Canada.

The HydroSwitch consists of a control structure on a storm sewer, a diverting pipe to a receptor sewer system, a special slow control gate enclosed within a baffled inner compartment and a hinged boom trap to collect floatables. An installation in the District of Karlsruhe, Ger. removed 48% of SS and 32% of COD (Pisano, 1998). The Hiawatha CSO



regional Treatment Facility in Syracuse, N.Y. demonstrated and tested vortex and storage abatement strategies with high-rate disinfection. The estimated construction cost for the 1.84 m<sup>3</sup>/s (65 ft<sup>3</sup>/s) CSO facility is \$3.5 million or about \$1.9 million/m<sup>3</sup> (50 000/ft<sup>3</sup>) (Miller et al., 1998). A pilot-scale study for CSO treatment was conducted in Toronto, Ont., Can. with a CSO which had highly variable SS that settled poorly. Polymer coagulants improved solid/liquid separation efficiency and provided an effluent suspension amenable to ultraviolet (UV) disinfection (Averill and Cairns, 1998).

The NORSD operates three WPCP capable of handling 5.167 million m<sup>3</sup>/d (1 365 MGD) of WWF (Debevec, 1998). An extensive flow monitoring and sampling study, including analysis of the influent and effluent BOD, SS, bacteria, NH<sub>3</sub>, and seven metals at the NORSD's Westerly CSO Treatment Facility indicated improvements are needed for inlet hydraulic conditions and peak design loading rates should be reduced (McMasters et al., 1998).

Field and O'Connor (1997a) presented a strategy for the abatement of pollution from storm-generated SSO by maximizing flow to the WWTP, maximizing treatment capacity, and using CSO-control technology methods in addition to inflow reduction, cost-effective-sewer rehabilitation, and sewer-system inspection and associated cleanout and repair. Field and O'Connor (1997b) described a strategy to optimize CSO-control systems maximizing the use of existing system before new construction and sizing the storage volume in concert with the WWTP capacity to obtain the lowest-cost storage-treatment system.

The Actiflo<sup>®</sup> method is a compact physical-chemical water-treatment system that is being used increasingly for treating wastewater and CSO. The method uses weighted settling combined with lamella settling and typical efficiencies are: SS-85%, COD-60%, TKN-18%, total P-85% and also removes heavy metals efficiently (Plum et al., 1997). An urban stormwater-treatment system has been designed in order to obtain treated effluent satisfactory for bathing. This process combines air flotation, sand filtration, and UV disinfection (Laine et al., 1997). An alternative stormwater treatment practice, bioretention system was proposed and consists of a rock berm and alternating strips of native grasses and stiff grass hedges for control of stormwater quality in Austin, Tex. (Murfee et al., 1997). Treatment of urban-stormwater runoff was studied using a field-scale submerged aerobic-biological filter (SABF) system. The study showed that a SABF system may be suitable for stormwater treatment (Anderson et al., 1997).

Field et al. (1997b) discussed the application of swirl and vortex separators for the control of pollution from CSO and stormwater discharge. Design, application, and performance were presented for the U.S. EPA swirl concentrator, Storm King<sup>®</sup>, and Fluidstep<sup>™</sup> technologies. Smith and Andoh (1997) discussed a new generation of hydrodynamic separators with an integral self-cleaning-screening system termed the Hydro Swirl-Cleanse<sup>™</sup>. This system ensures the removal of all material larger than a specified aperture size, e.g., 4 mm — 6 mm. A scaling protocol describing the residence-time characteristics of hydrodynamic separators, was discussed in terms of its importance for the removal of pollution from wastewater (Tyack and Fenner, 1997). A study evaluated various CSO-treatment technologies, e.g., vortex separator, circular clarifier, horizontal-flow-plate clarifier, and an inclined-rotary-drum screen and indicated that the vortex separator and plate clarifier are capable of 50% SS removal and 30% BOD removal (Schmidt et al., 1997).

Daligault et al. (1999) reported on two settling devices treating rainwater from urban drainage areas and equipped with secondary sludge treatment, which were monitored over a period exceeding one year. From analyses of the settled or extracted sludge it was possible to characterize the pollutants retained in the lamella settlers. To estimate the effect of enhancing settling in CSO storage basins by flocculation, a free growth and break-up model was developed and implemented by de Cock et al. (1999). Del Giudice and Hager (1999) discussed design and performance parameters for sewer sideweirs, which in a combined sewer system were used for diversion of excess discharge during rainfalls. Also discussed was the throttling pipe, which was a simple device to limit the discharge to treatment facilities. Dormoy et al. (1999) reported the results of a simulation of a WWTP with activated sludge, and concluded that it was advisable to allow for increased sludge production, O<sub>2</sub> requirements and also sludge quality (fermentability) when stormwater was treated. Faram and Andoh (1999) described the results of a program of numerical studies that were undertaken in order to assess and optimize the fluid-dynamic performance of a novel non-powered self-cleansing CSO screening system, the Hydro-Jet Screen<sup>□</sup>. Observations of the operation of both model and prototype scale units have indicated good qualitative correspondence with the predictions in terms of overall flow patterns, and have confirmed the superiority of the recommended design in terms of its self-flushing capabilities.

Green et al. (1999) examined the performance of constructed reed beds from a WWTP with storm treatment reed beds and another site with a combined storm and tertiary treatment reed bed. The results illustrated that sites with combined storm and tertiary treatment reed beds experienced a level of performance matching that of sites with tertiary treatment

systems, with averages of 2.2 mg/L BOD<sub>5</sub>, 3.0 mg/L TSS, 1.25 mg/L NH<sub>4</sub>-N and 12.2 mg/L TON. Luyckx et al. (1999) compared the separating efficiency of an improved high-side weir overflow and a hydrodynamic Storm King separator. They show that when higher removal efficiencies were wanted, the hydrodynamic separator can technically as well as economically compete with simpler structures. The District of Columbia CSO Abatement Program included construction of a 400-MGD swirl concentrator at the outfall of the District's Northeast Boundary combined sewer; an outfall responsible for approximately 50% of the total CSO from the District. Extensive pre- and post-construction monitoring of instream DO concentrations up and down stream of the outfall indicate that the separator has had a dramatic impact on DO concentrations downstream of the outfall; cumulative frequency analyses indicate virtually no difference in DO concentrations between the upstream and downstream meters since the swirl concentrator went online (Murphy et al., 1999). The problems created by sediment deposits in combined sewer systems (sanitary and storm) include a loss in conveyance due to these deposits which contributes to hydraulic overloading, leading to flooding, premature operation of CSO, and the washout of sediments through CSO into urban watercourses during times of storm. Skipworth et al. (1999) described an experimental laboratory investigation of the erosion and subsequent suspended sediment transport of an in-pipe, fine-grained, organic, cohesive-like sediment deposit analogous to those found in sewers. Vaes and Barlamont (1999a) discussed the implications of new design and analysis techniques and combinations of new and older components in combined sewer systems based on an evaluation of the various approaches and technologies used over the last eight years in Flanders, Belgium.

Schindewolf *et al.* (1997) reported on the construction of Houston, Tex.'s wet-weather-control facilities. The 1.2-billion dollar project includes unique wet-weather facilities that have storage, treatment, and discharge functions. Stirrup *et al.* (1997) of Hamilton-Wentworth, Ont., Can. plan to reduce pollution caused by CSO into Hamilton Harbor through construction of several offline detention-storage facilities and the implementation of a RTC system. Sherrill *et al.* (1997) presented the methodologies and results of the rating of the Detroit, Mich. collection system to both transport and store combined, which are general enough to have widespread application throughout the CSO community. The optimization of the insystem storage within the collection system, including the impact of maintenance considerations is also discussed. Portland, Oreg. began an extensive CSO program in order to meet requirements of the Oregon Department of Environmental Quality regarding the reduction of CSO. A new pipeline will convey wet-weather CSO to the City's 300 mgd WWTP to store flows exceeding the treatment capacity during the peak wet-weather event (Williams *et al.*, 1997). The process and monitoring for bypassing during storm events was found to be inadequate at a small WWTP in Ontario, Can. Modifications were made to the bypass lines and to other areas of the plant and the staff was trained on these modifications. Consequently, BOD loadings were reduced by 89%, SS loadings by 83% and NH<sub>3</sub> loadings by 93% (Hegg *et al.*, 1997).

A CSO with a perforated screen (6mm aperture), which prevents passage of large solids, was evaluated at a WWTP with flows up to 180 L/s. Both raw and treated wastewater were used to simulate CSO at different strengths and the system was found to operate satisfactorily with no moving components (Jeffries *et al.*, 1997). Wong (1997) described the fundamental mechanism behind continuous deflective separation (CDS) technology and outlined the potential application of the technology for pollution abatement in stormwater systems and other WWF applications.

Field and O'Connor (1996a and 1996b) discussed the design, evaluation, and application practice enhancements for swirl and vortex technologies in their dual use for flow regulation and reduction of settleable solids, as part of a CSO- and stormwater-pollution-control system. Wong *et al.* (1996) described development of an innovative solids filtration system from stormwater, which shows advantages over traditional gross pollutant traps and over some vortex separators as well. By utilizing the circular flow action, this system prevents the filtration screen from blockage and, unlike vortex separators, maintains its effectiveness with increasing flowrates. The system is based on a continuous deflective separation (CDS) mechanism developed by Pollutec Ltd. (now CDS, Inc.). Application of this technology can be also extended to CSO management. Advantages of a plate settler versus a conventional settling tank for management of CSO in Osaka City, Japan, were evaluated by Takayanagi *et al.* (1996). The plate settler achieved desired removal of SS at influent quality fluctuations, was easy to maintain, and required one-third of space required for a conventional settling tank.

A pilot study conducted by Columbus Water Works using the Storm King vortex separator projected annual SS reductions of 80% and COD of 70% at a hydraulic loading of 0.23 m<sup>3</sup>/m<sup>2</sup>/min (5.7 gal/ft<sup>2</sup>/min). At higher hydraulic loading of 0.73 m<sup>3</sup>/m<sup>2</sup>/min (18 gal/ft<sup>2</sup>/min) SS reductions of 50% were observed (Water Eng. & Mgmt., 1996).

Based on pilot test results, Briat and Delporte (1996) discussed the Densadeg lamellar separator from the Degremont

Company for treatment of WWF. The Densadeg separator accomplishes optimized flocculation with the contact mass and effective lamellar settling. It is compact, flexible, and efficient and can be used either alone or in connection with a storage basin.

Averill *et al.* (1996) discussed interim results of a Canadian multi-agency initiative to test technologies for the treatment of CSO under realistic field conditions. A modular, automated pilot plant, composed of an elevated tank, interchangeable CSO treatment technologies, and a conventional clarifier, is located in the City of Scarborough, near Toronto, ON, Canada. The Storm King<sup>®</sup>, a vortex separator, has been the first CSO technology tested and has shown promising results to date. The data collected in this study will add to the knowledge of vortex field performance that is otherwise limited but necessary for a design of a full-scale facility.

Pfister (1996) discussed a laboratory study on the use of Fenton's Reagent, which is hydrogen peroxide coupled with divalent iron salts, for treatment of CSO in existing overflow tanks. Addition of the Fenton's Reagent to the CSO tank combines physico-chemical processes with chemical oxidation and can reduce COD by 30-50% and the bacterial content as well. Studies with real CSO are planned.

Herviou *et al.* (1996) presented results of a pilot-plant study with dissolved-air flotation for treatment of stormwater runoff. Dissolved-air flotation was shown to be effective for removal of SS, COD, and total hydrocarbons. This technology seems to be particularly suitable for hydrocarbon-contaminated stormwater. Also, this technology tolerates variations in the pollutant concentrations in the influent and can be used as a component of a treatment train (air flotation + filtration + UV disinfection) for the complete treatment of stormwater.

Brombach and Pisano (1996) presented results of a four-year performance evaluation of a rotary-drum-sieve filter for removal of floatables from CSO. The sieve, activated during storm events, treats the overflow of a CSO tank that serves a community of 3,000 in Birkenfeld, Germany. In four years, the sieve treated 97% of the overflow, which was 110,000 m<sup>3</sup> of CSO, and removed gross solids effectively. Sieve maintenance was also discussed.

The use of magnetite assisted sedimentation and high-rate filtration, which combine the advantages of chemical coagulation with high-rate separation of flocculated solids, for treatment of storm-induced-sewer overflows was discussed by Booker *et al.* (1996).

Field and O'Connor (1996c and 1996d) presented an overview of SSO control as part of the EPA WWF research program. It was concluded that CSO technology should be considered for SSO control in addition to inflow reduction, cost-effective sewer rehabilitation, and sewer-system inspection and associated cleanout and repair.

Pujol *et al.* (1996) presented test results conducted in the Summer of 1995 on the Biofor<sup>®</sup> prototype (from Degremont) at the Acheres wastewater treatment plant of the Paris, France, metropolitan area. The prototype, an upflow biofiltration facility with heavy granular material, showed ability to treat high ammonia loading rates at high water velocities and to accept wet-weather conditions while maintaining good WWF performance. This process can be used in plants that accept periodic WWF.

**Disinfection.** Disinfection of CSO and SSO was practiced in many places. Disinfection of overflows is used to attempt to minimize the human health risks of CSO and SSO. The New York City Department of Environmental Protection performed a pilot study to evaluate the acute toxicity of CSO treated via ultraviolet irradiation (UV), chlorination/dechlorination, and chlorine dioxide. Toxicity effects observed in the treated effluents were associated with the untreated wastewater rather than the disinfection processes. Poor correlation was seen between field Microtox analyses and the off-site laboratory WET analyses (Santos *et al.* 2000). The Uptown Park CSO facility in Columbus, Georgia is the home of a national demonstration program for technology testing with peer review by a team of experts coordinated by the Water Environment Research Foundation (WERF). Four disinfection technologies have been examined in full-scale side-by-side comparisons to evaluate performance and operation criteria under similar CSO quality conditions. Vortex separators were used as contact chambers for three types of chemical disinfection, including sodium hypochlorite (with and without sodium bisulfite dechlorination), chlorine dioxide and peracetic acid. A compressed media filter followed by UV disinfection was also evaluated at various vortex pre-treatment levels in order to provide high quality control for the more frequent, more concentrated events. Turner *et al.* (2000) described methods for quantifying the statistical distribution loading on the receiving waters for a given solids removal and disinfection control scheme, and for operation of disinfection process control.

Wojtenko and Stinson (2000) provided a state-of-the-art review of the performance and effectiveness of ultraviolet (UV) light disinfection for CSO applications, and concluded that UV irradiation has potential for use in high-rate processes. As part of the expansion of 100-MGD WWTP in Wayne County, Michigan, a UV disinfection system design was provided - the largest of its type in the US. The UV system was designed to disinfect (measured using fecal coliforms) the “blended flow” from the primary and secondary treatment processes, and would be expected to provide disinfection that meets permit requirements for wet weather flows up to 175 MGD (Christeson and Fath-Azam 2000). Safety concerns and more stringent regulations regarding gaseous chlorine use have forced reconsideration of disinfection practices, with UV seen as an attractive alternative. However, varying flows pose a challenge for UV systems. Faisst et al. (2000) reported on the implementation of UV disinfection at two coastal communities carried out in response to these challenges. Wojtenko et al. (2000) presented a state-of-the-art review of chlorine dioxide ( $\text{ClO}_2$ ) for high-rate CSO disinfection. In general,  $\text{ClO}_2$  appeared to be effective for high-rate disinfection and a suitable  $\text{Cl}_2$  replacement. The New Orleans Sewerage and Water Board has attempted to control the odor and disinfection problems common to SSOs through the use of Nok-Out, a blend of oxidative chlorine compounds and non-charged amines. Since its inception, the use of this blend has effectively controlled both odor and disinfection problems (Austin et al. 2000). The City of Atlanta’s four westside, high-rate CSO facilities used coarse and fine screening followed by sodium hypochlorite disinfection. Disinfection optimization studies found that the CSOs exhibit a first flush, that the water quality varies throughout an event and between events, and that the CSOs are currently contact-time limited during the first flush in regards to disinfection (Richards and Gurney 2000).

One concern with using the standard methods for measuring microbial indicator concentrations in sewage before and after disinfection is that they fail to measure particle-associated microorganisms, thus underestimating the total concentrations present. A related concern is that particles and other matter in the water interfere with a disinfectant’s ability to contact and, therefore, inactivate microbes. EPA researchers presented the results of two projects which examine the effects of particle association on measurements of microbial indicator concentrations in CSOs, and determine the effectiveness of four treatment trains for CSO disinfection and the effects of removing solids on the disinfection effectiveness of chlorination and ultraviolet (UV) light irradiation (Perdek and Borst 2000a and 2000b). The USEPA has begun advocating that beach managers monitor marine water quality at bathing beaches using enterococcus, rather than the present approach which is usually use of a coliform indicator. Rex (2000) explored the potential impacts of changing from the fecal coliform indicator to the enterococcus indicator in three areas: (1) monitoring disinfection of wastewater, including CSO; (2) monitoring receiving water quality for the relationship between fecal coliform and enterococcus; and (3) monitoring changes in receiving water over time as improvements in CSO infrastructure are made. The analyses suggest that there is a potential impact on the ability of CSO facilities and wastewater treatment plants to meet new water quality standards.

Stinson et al. (1999) discussed high-rate disinfection technologies for CSO, including ultraviolet light irradiation, ozone, chlorination/dechlorination, chlorine dioxide, peracetic acid, and high-voltage electron beam irradiation. Discussions of the technologies included commercial availability and extent of use, state-of-development when not commercial, and where available, performance data and cost of either full-scale or pilot-scale installation. Also discussed was utility of increased mixing in concert with any disinfection technology. In 1996, the Vallejo Sanitation and Flood Control District (California) replaced an outdated chlorine gas disinfection system with a state-of-the art medium pressure UV system, in combination with a liquid chemical system for use as backup during wet weather periods. Tekippe et al. (1999) reviewed VSFCDD’s three-year operating history, and presented a summary of startup and post-startup problems and their resulting solutions.

Four pilot units representing three different technologies were investigated at the Hartford, Conn. WPCP to determine the disinfection ability of UV on secondary effluent, CSO flows and combined secondary and CSO flows. Based on technical, operational and cost comparison of the pilot study, the disinfection of the secondary effluent using UV radiation and sodium hypochlorite ( $\text{NaOCl}$ ) for CSO was recommended (Amirhor and Roach, 1998). Four alternative disinfection technologies pilots (UV, ozone, chlorine dioxide and chlorination/dechlorination) were evaluated for the Spring Creek Auxiliary Wastewater Pollution Control Plant in NYC. All technologies provided three to four log bacterial reductions and chlorine dioxide and chlorination/dechlorination were determined to be the most cost-effective technologies for the facility (Smith et al., 1998). A full-scale CSO demonstration in Columbus, Ga. evaluated side-by-side treatment methods for removing wet-weather contaminants and disinfection by sodium hypochlorite, chlorine dioxide, peracetic acid, and medium pressure UV (Boner et al., 1998). Stinson et al. (1998) presented the applicability of four high-rate disinfection technologies for treating CSO and SSO including ozone, UV, chlorine dioxide and high-voltage electron beam irradiation.

**Coagulation and Ballasted Flocculation.** Annadurai et al. (2003) examined the floc characteristics and removal of turbidity and humic acid from high-turbidity stormwater. Loose flocs were promoted by an acidic suspension and moderate PACl dosage and alkalinity level. For large flocs, pH neutrality and high PACl dosage were optimal. Park and Yoon (2003) investigated using weighted coagulation with glass and diatomite for stormwater treatment. The weighted coagulation process removed suspended solids (SS), chemical oxygen demand (COD), and total phosphorus (TP) in only 17 min (25 m<sup>3</sup>/m<sup>2</sup>/h). The chemical sludge was effectively dewatered, and could be reutilized as a soil conditioner after heat treatment in the temperatures of 750 to 800°C.

Wagner et al. (2003a) presented Lawrence, KS's new ballasted flocculation treatment facility which combines coagulation, flocculation and a settling zone. Keller et al. (2003) performed full-scale testing of a SSO ballasted-flocculation system at the Lawrence (KS) Wastewater Treatment Plant. During the optimization and process performance test, foam was generated at the plant's outfall as a result of the operation of the ballasted flocculation facilities and surfactants within Lawrence wastewater flow. Kurtz et al. (2003) presented the results of pilot-scale testing of high-rate physical-chemical treatment (HRPCT) technologies at a wastewater treatment plant in New York City. All units performed well when optimized, removing between 69% and 84% of TSS on average. The testing also provided information on hydraulic loading, chemical dosage rates, recirculation rates, ballast dosage rate, operating ranges, as well as time to full performance after start-up and sludge quality

Anonymous (2003i) discussed the high-rate treatment system used in Bremerton, WA to treat and therefore minimize CSOs. The treatment process combines conventional clarification with microsand addition to speedily treat effluent with the final stage being UV disinfection. Constantine et al. (2003) investigated in a pilot-plant study two chemically-enhanced primary treatment technologies, ballasted flocculation and inclined plate settling, for treating wet-weather flow in Edmonton, Canada. The parameters measured were ultraviolet transmissivity (%UVT), in addition to the removal of TSS. Li et al. (2003) reported on the Windsor (Ontario) combined sewer overflow treatability study which used chemical coagulation to improve solids settling. The results of the long column settling tests showed that the characteristics of the wet-weather sewage during CSO events were similar to those of samples collected at actual overflow sites along the Windsor Riverfront. Settling rate distributions demonstrated that polymer addition to the wet-weather sewage significantly improved the settling characteristics.

**Disinfection, Screening and Solids Separation.** Andoh and Saul (2003) investigated the use of hydrodynamic vortex separators and screening systems to control wet-weather discharges including CSOs, SSOs and stormwater runoff. Recent developments and innovations in HDVS technologies were discussed, focusing on their combined use as solids liquid separators, contact vessels for wastewater disinfection, the incorporation of self-cleansing screening devices for the control of aesthetic pollutants (e.g. floatables) and the use of computational modeling for optimization. Freedman and Davis (2003) evaluated screening technology for wet-weather discharges such as CSOS, SSOs, and stormwater discharges in MS4 systems. Netting systems are also included. Laplace et al. (2003) investigated the use of a flushing gate to remove the organic surface layer in combined sewer sediments. The organic layer that has formed on the surface of deposits could be washed out before rainstorms occurred using the cyclic flushing technique. Lee et al. (2003) examined the vortex concentrator for treatment of suspended solids in synthetic stormwater. The SS removal efficiency was increased by increasing retention time, and the optimum retention time was 0.15-1.0 minutes.

**Residuals Management.** Krielow et al. (2003) studied the ability of cement-based solidification/stabilization (S/S) for the treatment of heavy metal-laden storm water residuals was evaluated for compressive strength and leaching characteristics. Two types of cement, type I portland and slag, were chosen and employed in the application of the S/S technology. Ratios of 1:1 between the type I and slag cements were mixed and used as a third cement tested in the application of S/S.

### **SSO Control**

Field (2004) presented a strategy for the abatement of pollution from SSOs. Because of the great lengths of sanitary-sewer systems and associated vast numbers of service laterals, it is often less expensive and more feasible to use alternatives to sewer rehabilitation for infiltration/inflow (I/I) and SSO control. I/I control studies have found that just correcting I/I in street sewers will not necessarily correct the problem because building connections contribute as much as 60% of the infiltration load. SSOs can be abated using CSO control methods, as both SSOs and CSOs are both mixtures of municipal sewage, stormwater, and groundwater. McCulloch et al (2004) described an alternative approach to SSO control that would achieve water quality standards. It provides SSO elimination within two years by maximizing in-system storage and using all existing CSO Retention/Treatment Basins. The regulatory challenges proved to be far more difficult than the

technical issues. The choice between providing relief sewers or implementing I/I reduction programs is not always clear, according to Mamid et al (2004). The master plan for McDowell Creek Basin, Charlotte-Mecklenburg, NC, is described. Hydraulic analysis of this system used dynamic hydraulic modeling. A cost-benefit analysis of 13 comparable projects revealed that I/I reduction programs could provide cost savings of up to \$1.6M.

Nelson (2004) discussed various aspects of the new Capacity, Management, Operations, and Maintenance (CMOM) regulations. The main objective of CMOM is to ensure that agencies responsible for the sanitary sewer systems have the appropriate legal authority, staffing, budget, and tools to properly manage the collection systems and prevent overflows. Robertson et al (2004) described a CMOM Lite Tool Kit and gave an example used for a central Florida utility. Wisconsin has initiated efforts to revise and refine existing rules and policies related to the periodic discharges from sanitary sewers before the wastewater reaches a treatment facility (Schuettpelez and Saltes 2004). A primary objective of new regulations is to assure that this component of municipal infrastructure receives the on-going attention that it deserves. Implementation of CMOM programs should be required for all collection systems, and system owners should be required to report on these efforts, an activity that has been well accepted by communities throughout the state.

Adams et al (2004) reviewed how the San Antonio Water System met the CMOM requirements of the EPA's proposed SSO rule. The key elements of a sound CMOM program include: planning to ensure adequate capacity during both dry and wet weather; effective system management, including mapping, maintenance tracking, training, and supervision; and efficient operations, as measured in spending, equipment performance, and efficiency. Craven and Lunch (2004a and 2004b) described how Janesville, WI, is addressing collection system improvements, using CMOM, particularly downstream of areas with high development potential. Janesville has experienced several major sewer failures resulting in significant expenditures. Malone et al (2004) reviewed the Phoenix, AZ CMOM program. The sanitary sewer system consists of about 4,000 miles of sewer mains, with about 85% being 8-inch in diameter. The sewer system was designed with adequate capacity for normal peak flows and I/I is generally minor. The majority of the SSOs are the result of grease or roots, with a small percentage attributed to construction activities, or vandalism.

The sanitary sewer system in Norfolk, VA, is one of the oldest in the US and therefore has special SSO problems (Fortin et al 2004). It includes 143 sewersheds, 867 miles of pipes and 152 pumping stations within 52 square miles. The long-term control plan needs assessment is based on the results of the field investigation program, the conditions of the sewers system assets and hydraulic modeling. Taylor et al (2004) described how Detroit began a collaborative process to examine solutions to eliminate the public health and water quality impacts of SSOs in the regional collection system in 2001. The purpose was to find a cost-effective solution for SSO elimination in the service area. The following alternatives were evaluated: elimination of the sources of high infiltration/inflow (I/I) that cause SSOs; local storage or treatment of SSOs, and regional transmission, storage, and treatment of SSOs. San Diego has established an optimization program which provides internal consulting services in the areas of competitive assessment, process re-engineering and performance management (Toth et al 2004). When sewer overflows occur, the city has a response plan to collect information that can help prevent future overflows.

While modeling efforts are critical to system assessment and planning, models must be supported and complemented by thorough reviews of existing records, input from system operators and managers, and, most importantly, field verification of existing system conditions (Hogan et al 2004). The 100 yr-24 hr storm (4.7 inches in 24 hours) is used by the Michigan Department of Environmental Quality as the criteria to measure the future performance of SSO elimination measures. Hawkins et al (2004) described an intense rain event at Lethbridge, Alberta, and subsequent modeling evaluations. During a 65 hr period in June, 2002 a total of 137 mm (5.4 in) of rain fell, representing a rainfall event greater than the Lethbridge's 100 yr return frequency leading to sanitary sewer backups, and, in three locations, to SSOs. The performance of the sanitary sewer system was analyzed using RT-SWMM and I/I into the sanitary sewer was simulated using SWMM's Runoff Block. The impacts of future Lethbridge developments were also considered. Cincinnati, OH, has completed a stormwater removal program, conducted flow monitoring and hydraulic modeling, and prepared a remedial measures plan to reduce SSOs and basement flooding (Moisio et al 2004). A hydraulic model (MIKE SWMM) was calibrated using flow monitoring data collected during the study period and verified using historical monitoring data. The study resulted in a combination of system improvements at an estimated cost of approximately one third of the original estimates to reduce SSO and basement flooding.

Mmeje et al (2004) described Los Angeles' efforts to reduce SSOs and its CMOM program by implementing an aggressive fats, oil, and grease (FOG) control program. Fats, oils, and grease blockages are one of the two major causes of dry weather overflows, the other being root intrusion. They are focusing on the 10,000 food service establishments in the

city. The number of grease related sewage spills was cut by approximately 40 percent within two years of implementation of the program.

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