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*Wetlands Research Program*

# Wetlands Engineering Handbook

Compiled by Donald F. Hayes, Trudy J. Olin, J. Craig Fischenich, and Michael R. Palermo

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# Preface

This handbook is the end product for Work Unit 32758 under Task Area 5 of the Wetlands Research Program at the US Army Engineer Research and Development Center (ERDC). Task Area 5 was managed by Dr. Mary Landin, Environmental Laboratory (EL). Work Unit 32758 was executed by the Environmental Engineering Division, EL by Ms. Trudy Olin, Dr. Craig Fischenich, and Dr. Michael R. Palermo. Vegetation components of the handbook were coordinated by Dr. Mary C. Davis, Wetlands Ecology Group, EL. Hydrology information and techniques were coordinated by Dr. Lisa C. Roig, Hydraulics Laboratory (HL). Mr. Roy Leach, Geotechnical Laboratory (GL), coordinated sections of the handbook related to soils and geotechnical engineering. This handbook was prepared by a number of ERDC and contractor authors. Dr. Donald F. Hayes (University of Utah), Ms. Olin, Dr. Palermo, and Dr. Fischenich compiled the final handbook.

This handbookwas reviewed by Mr. Tony Dardeau (EL), Mr. Sam Collinson (CECW-OR), Mr. Dick DiBuono (CECW-EH-W), Mr. Owen Dutt (CELMS-PD), Mr. Don Dunwoody (CWMRD-CO-R), Mr. Larry Oliver (CENED-PL-L), Mr. Jake Redlinger (CENPD-CO-O), Mr. Mike Lee (CEPOD-CO-O), Mr. Don Hill (CESAC-CO-P), Mr. Dwight Quarles (CESWF-OD), Mr. Bob Blama (CENAB), Mr. Mitch Isoe (CENCD-CO-O), Mr. Rodney Woods (CEORD-CO-OF), Mr. Donnie Kinard (CESAJ-CO-OR), Mr. Larry Vinzant (CESPK-CO-R), Mr. Rob Hauch (CESWG-CO-M), Mr. Bob Gunn (CEMVN-OD-G), Mr. Ron Ventola (CEMVN-OD-G), Mr. Neal McLellan (Hartman and Associates), Ms. Monica Chasten (CENAP-EN-H), and Mr. John McCormick (CENAP-EN-H). These reviewers provided valuable suggestions and contributed materially to the final product.

Mr. Norman Francingues provided overall supervision of this project as Chief, Environmental Engineering Division, EL. Dr. John Keeley, Director, EL, provided general supervision. Dr. Russell Theriot provided overall technical guidance as Program Manager, Wetlands Research Program.

At the time of publication of this handbook, Dr. Lewis E. Link was Acting Director of ERDC, and COL Robin R. Cababa, EN, was Commander.

# Symbols

$\Delta S$ = change in water storage in the wetlands impoundment, $m^3$
$P$ = direct precipitation on the wetland impoundment, $m^3$
$I_r$ = runoff through overland flow into the wetland, $m^3$
$I_s$ = streamflow directly into the wetland, $m^3$
$I_f$ = inflow from adjacent stream flooding, $m^3$
$G_i$ = wetland inflow from groundwater, $m^3$
$T_i$ = tidal inflows, $m^3$
$P_i$ = inflow from pumping, diversions, or other artificial water source, $m^3$
$E$ = evaporation from the wetland surface, $m^3$
$T$ = transpiration, $m^3$
$O_s$ = outflow from streams leaving the wetland, $m^3$
$O_f$ = overland outflow due to wetland flooding, $m^3$
$G_o$ = groundwater percolation below the root zone, $m^3$
$T_o$ = tidal outflows, $m^3$
$P_o$ = outflows from pumping, diversions, or other artificial sinks, $m^3$
$n$ = size of sample (number of sample units) required
$s$ = sample standard deviation
$t$ = a factor obtained from Statistical Tables of t
$E$ = maximum acceptable error between the sample average and the unknown population average
$R$ = the range of values from samples obtained (i.e., the maximum test value minus the minimum test value)
$s_o^2$ = overall measurement variance
$s_q^2$ = variance due to material quality (i.e., the combined variance due to material composition and placement process variability)
$s_t^2$ = variance due to the testing process.
$q_{ult}$ = ultimate bearing capacity, kPa
$c$ = cohesion (50 percent of unconfined compressive strength), kPa
$\sigma$ = normal force on the shear plane, kPa
$u$ = pore water pressure, kPa
$\tan \phi$ = coefficient of internal friction, unitless
$Q$ = flow rate, $m^3$/sec
$C$ = discharge coefficient, $m^{0.5}$/sec
$L$ = the effective horizontal length of the weir in feet, m
$h$ = the height of the energy line above the weir in feet, m
$V$ = horizontal velocity of flow, m/sec
$g$ = gravitational acceleration, m/sec$^2$
HGL = hydraulic grade line
EGL = energy grade line
$W_L$ = actual weir length, m

$W_L$' = actual weir length, m
$\Delta W_L$ = change in weir length (note that all changes *shorten* the weir length), m
$W_{obstruction}$ = width of weir obstruction at widest point, m.
U = wind speed, m/sec
$U_A$ = wind stress, m/sec.
H = wave height, m
d = water depth, m
F = wind fetch, m.
T = wave period, sec.
W = weight of an individual armor stone (N)
H = wave height (m)
$S_r$ = specific gravity of the armor stone, unitless,
cot θ = slope of the structure expressed as horizontal units / vertical unit
$K_D$ = stability coefficient
$w_r$ = unit weight of the rock ($N/m^3$)
$w_w$ = unit weight of water ($N/m^3$)
$D_{30}$ = riprap size of which 30 percent is finer by weight, m
$S_f$ = safety factor, unitless
$C_s$ = stability coefficient for incipient failure, thickness
$D_{85}/D_{15}$ = gradation uniformity coefficient
$C_v$ = vertical velocity distribution coefficient
R = centerline radius of bend
W = water surface width at upstream end of bend
$C_T$ = blanket thickness coefficient
d = local depth of flow
$\gamma_w$ = unit weight of water
$\gamma_s$ = unit weight of stone
V = local depth averaged velocity
g = gravitational constant
$K_1$ = side slope correction factor
$N_s$ = stability number (lower value more stable), unitless
$H_s$ = significant wave height, m
$D_{50}$ = median stone diameter, m
$w_r$ = unit weight of the stone, $g/cm^3$
$w_w$ = unit weight of water , $g/cm^3$ (fresh water: 1.000 $g/cm^3$, seawater: 1.025 $g/cm^3$)
$L_o$ = deepwater wavelength, m
$H_s$ = deepwater significant wave height, m.

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# Wetlands Engineering Handbook

## Section 1

## Introduction and Project Management

# Section 1
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# Section 1
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# 1-1 Introduction[1]

## Purpose and Scope

### Purpose

Wetland restoration requires the establishment or reestablishment of conditions conducive to the development of a viable wetland ecosystem. Wetland restoration or establishment is a long-term process, so these conditions must be sustained for an extended period of time to allow natural maturation into a viable wetland. Wetlands are dynamic ecosystems, continuously changing in response to new site conditions.

Some fundamental conditions are necessary for a wetland to exist. These include a favorable hydrology and a substrate capable of supporting hydrophytic vegetation. The existence of these conditions allows natural biological, chemical, and physical functions that make wetlands such valuable ecosystem components to occur without impediment. Establishing site conditions to support a set of desired wetland functions over an extended period requires carefully developed design plans which utilize natural site characteristics and considers the unique construction and management requirements of wetland projects. Our limited understanding of wetland systems, however, precludes the development of designs that assure complete achievement of all project objectives. Thus, wetland restoration or creation projects require careful monitoring to determine the project's progress toward established success criteria.

### Scope

This handbook discusses engineering procedures for establishing necessary hydrologic conditions, geotechnical design, and soils handling for site modification, selecting appropriate vegetation and planting schemes, and establishing substrate conditions conducive to the desired functions. It also discusses baseline assessments of existing site conditions, monitoring strategies to determine long-term success, and contracting considerations.

The handbook is not intended to be a comprehensive reference that allows a single individual to develop a complete wetland design. Much of the guidance is general in nature and applies to projects in a variety of settings. The general discussions apply whether a project involves enhancing an existing wetland or creating a new wetland area in an upland environment. Certainly, some variations in approach are necessary for different environments (i.e., coastal

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[1] By Donald F. Hayes

versus inland); these are indicated where appropriate. Additionally, individuals can familiarize themselves with aspects of wetlands projects other than those associated with their own technical discipline. Increased familiarity with overall design requirements improves coordination between project components and design team members. A common nomenclature has been adopted to further enhance communication between disciplines.

Including extensive details of all possible engineering approaches in a single reference is not feasible. Thus, this handbook includes abbreviated discussions of common approaches for which details can be found elsewhere; references that include these details are provided where appropriate. Engineering concepts and designs involved in wetlands projects are often rather simplistic and fundamental. Hence, some discussions in this handbook may seem trivial to persons familiar with a specific subject area. However, these same discussions should prove enlightening to persons with other backgrounds. A successful wetlands design, no matter how small, requires the expertise of an interdisciplinary team.

## Organization

This handbook is divided into five major divisions that follow the normal sequence of wetland restoration or creation projects: Introduction, Site Assessment, Design, Construction, and Monitoring. It is further divided into eight descriptive sections plus a collection of supplemental materials that may be helpful during various phases of a project. The sections are closely tied to one another so that duplication of material is kept to a minimum. Each section includes its own Contents, Figures, Tables, and References.

This section, Section 1, provides a general introduction to the handbook, its contents, its purposes, and its usage. Section 1 also discusses a general decision-making process involved in wetland restoration or creation projects. The outline of this handbook generally follows this logical decision process. Thus, the decision process is a fundamental component of the engineering guidance.

**Section 2** describes methodologies and requirements for data collection and site assessment. Section 2 discusses fast, low-cost, field-based sampling and data gathering techniques that can be performed at candidate wetland restoration or creation sites during initial screening. Since many of the same techniques are used in more extensive sampling and data gathering efforts, Section 2 also discusses procedures normally used for more extensive site assessment even though these normally would be applied only after the site is selected.

**Section 3** describes the development of conceptual designs for candidate project sites based upon existing site conditions and desired wetland functions. Since designs must provide conditions that facilitate the desired functions, Section 3 provides an introduction to the hydrogeomorphic (HGM) approach and the development of design criteria. A more detailed report, ***Design Criteria for Wetland Restoration and Creation***, is being prepared which provides specific design requirements for a large matrix of functions and site conditions.

**Sections 4, 5, and 6** form the nucleus of this handbook. They provide guidance to develop a detailed design which provides the desired conditions based upon a conceptual design. Each section focuses on one of the fundamental components of the design - soils, hydrology, and vegetation.

**Section 4** covers geotechnical aspects of wetlands restoration or creation projects. Wet, soft soils associated with most wetland projects present special challenges for earthmoving and soils handling. This section describes soils handling and earthwork techniques for these soft soil environments including dike construction, excavation, and containment of dredged material. Section 4 also discusses desirable substrate characteristics, obtaining substrate from other natural sources, and the natural and laboratory development of substrate from nonhydric soils.

**Section 5** describes methodologies for establishing hydrologic conditions within the wetland environment that are conducive to the desired wetland function. Surface water and groundwater aspects of wetland hydrology are discussed in detail. Section 5 also discusses the design of water control structures for surface water retention.

**Section 6** presents considerations and requirements for establishing desirable vegetation at a wetland restoration and creation site. The section discusses plant selection, material sources, and planting schemes.

**Section 7**, ***Site Construction and Management***, discusses pragmatic considerations associated with the construction phase of the project including contracting recommendations, scheduling, and contractor selection.

Following construction, wetlands require a substantial amount of time to become fully productive ecosystems. Thus, evaluating a wetland in light of its success in meeting the project objectives requires that its progress toward achieving those objectives be monitored during the interim period. Section 8, ***Monitoring and Evaluating Success***, discusses monitoring strategies and requirements to evaluate wetland success and progress toward success.

# 1-2 Decision Process for Restoration or Creation Projects[1]

Restoring or establishing a wetlands system can be a complex process. Often, success requires integrating expertise from disparate technical disciplines into a comprehensive and coherent design. A fully successful design must satisfy project objectives, provide the desired wetland functions, fit seamlessly into the landscape, and remain viable for the expected life. It must also fit a niche within the ecosystem for which a demand exists. Frequently, wetland projects are expected to accomplish these lofty goals in a very short period as compared to the many years required for a natural wetlands to mature.

When present, these complexities and goals require that a carefully developed sequence of events be followed to achieve specific project goals. This same event sequence applies whether the wetland project is only a small part of a much larger project or it is a singular focus altogether. Palermo (1993) provided a simple, yet comprehensive, design sequence for wetland restoration and establishment which formed the basis for Figure 1-1. The organization of this handbook generally follows this design sequence. Additionally, similar flowcharts that fit within Figure 1-1 are presented at other crucial locations in the handbook such as the major design sections on vegetation, hydrology, and soils. These detailed decision sequences also evolved from the design sequence presented by Palermo (1993).

The use of these flowcharts does not ensure that the design process will yield a successful design. Similarly, following a different path will not necessarily result in design difficulties. The purpose of this design sequence is to present a logical, methodical process for all parties involved in the design process. This approach provides a benchmark of how far along the process is at any point in time. This section provides a brief discussion of each major component of the decision sequence.

Wetland mitigation efforts must be based in solid science. Often, the adoption of engineering protocols is the best way to ensure good implementation of the science--the real reason for this handbook. The value of a mitigation cannot be judged based on the complexity of the mitigation or the cost of the mitigation. Simple low-cost mitigation efforts can be as meaningful as complex expensive efforts.

[1] By Donald F. Hayes and Andrew C. Connell

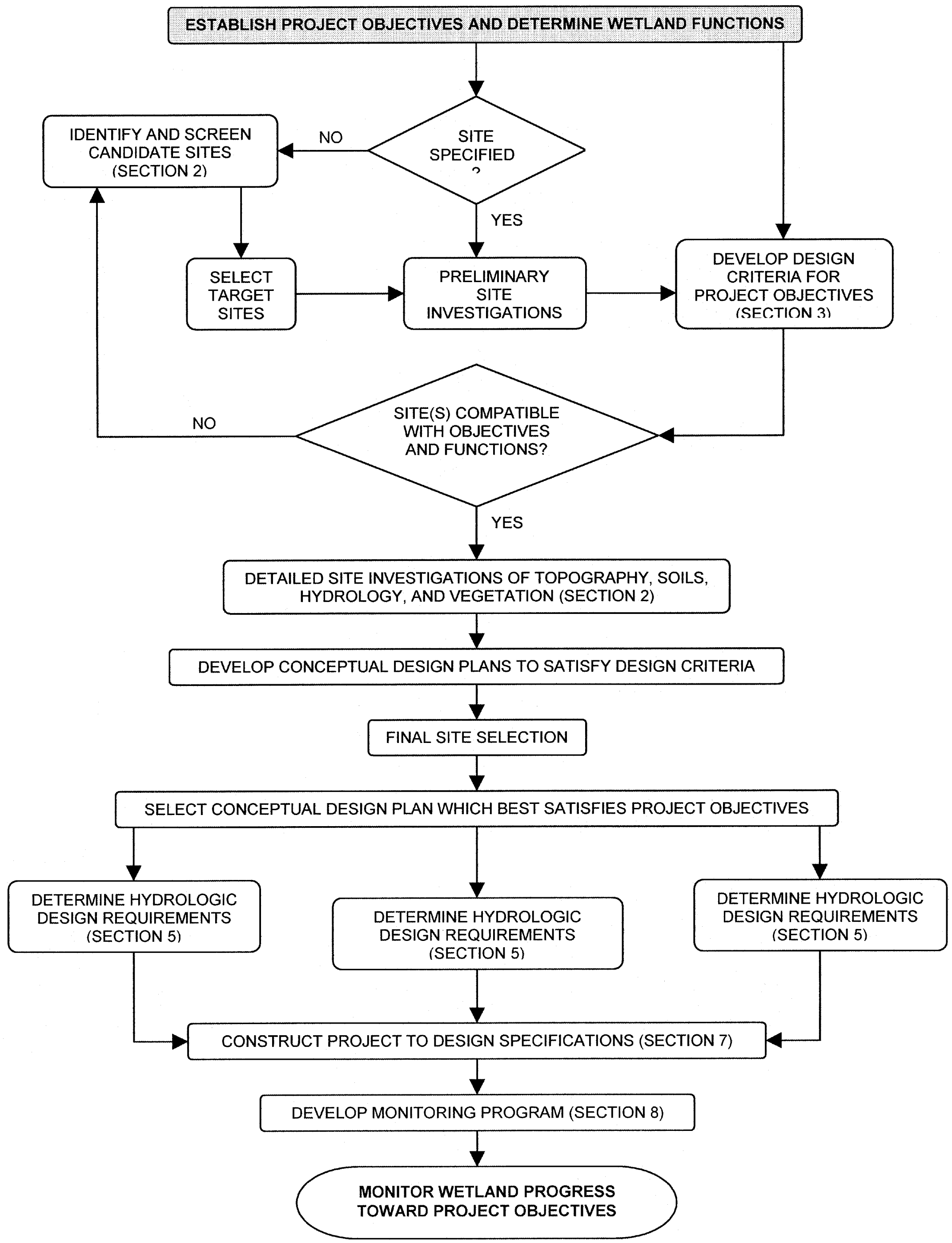


Figure 1-1. Decision sequence for wetlands restoration and creation projects.

## Project Initiation

Despite the many similarities between the large number of wetland restoration or establishment projects that are undertaken, the ways in which the projects are initiated vary dramatically. In some cases, wetland projects mitigate for anticipated or historic wetland losses. In other cases, the public or some public agency may desire to restore or establish a wetland system that provides missing or needed ecosystem functions.

Regardless of how a project is initiated, there are two distinctly different project types - those for which a site is specified and those that seek to identify a site capable of satisfying the project objectives. This distinction greatly impacts the remainder of the design process. Projects designed for a specific site must fit within the constraints and limitations of the site itself. The design challenge is to modify the site topography, soils, and hydrology to ensure the creation or restoration of a wetland into an integral part of the landscape and ecosystem. Many wetland projects are associated with a specific site; seldom is there the luxury to locate the most compatible site for already established project objectives.

The primary difference in the design process for projects which are considering multiple locations is the additional burden of identifying candidate sites, screening the candidates for those that are most compatible with the project objectives, and performing preliminary designs for the most promising sites. This additional burden, however, may be well rewarded. The best wetland projects are usually those that require the least modification to existing conditions. Sites that have all components in place but that need only minor modifications to become a viable wetland ecosystem usually offer the most cost-effective solutions and are the most likely to be successful. Additionally, they are easiest to integrate into the existing landscape. In short, the design process is simplified when the site is conducive to the development of a wetland system.

## Defining Project Goals and Objectives

Wetlands restoration and establishment enjoys an immense popularity with the public. Many governmental and nonprofit organizations are undertaking wetlands projects because of this strong popularity. In other cases, wetland restoration or establishment is required as mitigation for historic or anticipated damage to existing wetland systems.

Regardless of the driving force behind the project, the goals and objectives must be clearly defined early in the process. Specific, well-defined project objectives are necessary for the design process to be successful. Objectives should be stated in simple and straightforward terms, easily understood by all parties and carefully prioritized. Some wetlands functions cannot coexist with other functions or cannot be provided in certain wetland types; thus, primary and secondary objectives need to be established so that appropriate trade-offs can be made.

## Site Compatibility

Appropriate hydrologic conditions are the key to the successful establishment of wetland vegetation and wildlife assemblages. Although wetland-like conditions may be produced at virtually any site by means of extreme engineering measures, this approach is discouraged. The chosen site should have hydrologic characteristics that will not require elaborate control structures or intensive maintenance. Projects that are self-maintaining are more likely to produce a stable wetland ecosystem that mimics natural conditions. The continuous maintenance required for expensive and elaborate engineering works is not only disruptive to the developing ecosystem, but also expensive. Additional information on developing designs that are compatible with site characteristics and constraints is presented throughout this handbook.

# 1-3 Ecosystem Considerations[1]

## Ecosystem Characteristics

For the purposes of this discussion, an ecosystem is defined as (from WRP Glossary - TA6 1995),

> "*Any unit that includes all of the organisms (community) in a given area interacting with the physical environment so that flows of energy and nutrients lead to clearly defined trophic structure, biotic diversity, and material cycles within the system; the interactive system of producers, consumers, and decomposers and their abiotic environment in a more or less defined area.*"

The flow of energy and nutrients through all ecosystems starts with energy (e.g., sunlight, wind, tides) and nutrient inputs (e.g., rainfall, floodwater) into the system. Plants transform these inputs to forms of energy and nutrients that are then available to animals and decomposers of the ecosystem (Odum 1983). The primary reason for the focus on wetland vegetation establishment for successful wetland restoration or creation is that plants are the critical basis for energy and nutrient flows within all natural ecosystems.

Ecosystems vary dramatically in size, and boundaries are usually determined subjectively (Odum 1983). The entire planet Earth can be correctly defined as an ecosystem just as a watershed or a wetland. For the purpose of wetland restoration, however, the term "wetland ecosystem" usually refers to the wetland itself and immediate surrounding uplands, but usually excludes the larger surrounding upland areas. However, ecosystems are not closed systems and, as such, cannot continue to function without inputs from outside the ecosystem (Odum 1983). Energy, water, and nutrient inputs into wetland ecosystems include those from the surrounding landscape (Johnston 1993). A knowledge of these inputs is particularly important in wetland restoration. A wetland project is not likely to be successful if exchanges with the surrounding ecosystems are not considered, whether those surroundings are natural or include human influences (Marble 1990, Adamus *et al.* 1991).

Characteristic ecosystems develop under similar conditions (Odum 1975), but the concepts of nonequilibrium vegetation dynamics and disturbance emphasize the unpredictability of community development (Pickett and White 1985; Zedler 1996). Effects of temperature and rainfall are evident in the regional distributions of vegetation types in North America (Bailey 1976). For example, boreal forests are located in northern climes, deserts occur in the southwest,

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[1] By Mary M. Davis

and pine forests are common in the southeast. Further distinctions of ecosystems on a subregional basis depend on local hydrogeomorphic settings (Brinson 1993). For example, prairie potholes are depressional wetlands that occur within the northern Great Plains; cypress domes are depressional wetlands that occur within the Southeastern pinelands; and limited riparian and high altitude depressional wetlands occur in the arid Southwest. Regional wetlands have characteristic hydrologies, soils, vegetation, and fauna. The best wetland model for a wetland restoration or establishment project is the locally dominant wetland type that is situated in conditions as similar to the project site as possible. If hydrology, energy, and soils of a project site are similar to reference native wetlands, the probability is increased that vegetation similar to native wetland vegetation can be supported.

If levels and types of inputs into an ecosystem change, the ecosystem will change (Odum 1983). Changes in water supply, nutrients, or other factors have direct impacts on the plant species composition, structure, and productivity that in turn impact the consumers and decomposers of the ecosystem. The "greenhouse effect" is a commonly referred to example of predicted changes in global energy cycles that will have dire impacts on the present distribution and types of ecosystems. For another example, eutrophication of wetlands can result from excessive nutrient inputs into wetlands that are beyond the utilization and trapping capacity of the existing system. As a consequence, the characteristic plants and animals of the eutrophic wetland ecosystem are different from previous conditions (Neill 1990, Stewart and Nilson 1993, Ehrenfeld and Schneider 1993). Altered hydrology is a primary cause for shifts in vegetation species and structure in wetlands (Fredrickson 1978, Mitchell and Niering 1993).

In addition to human influences on inputs, natural variations in water supply and climate affect wetland ecosystems. Annual differences in rainfall amounts are particularly important for wetland restoration and establishment project success during the early developmental stages. For example, in forested wetlands, extended period of drought during the growing season lowers seedling establishment compared to establishment during periods of normal rainfall (Johnson and Krinard 1985). Severe or unpredictable climatic conditions may retard natural revegetation of an area or preclude survival of transplants. It is not uncommon for western riparian mitigations to include irrigation elements to facilitate the initial plant establishment.

Ecosystems change with time (Odum 1975). The maturation process of natural ecosystems is termed “succession” (Drury and Nisbet 1973) or ecosystem development (Niering 1987). Ecosystems develop from two starting conditions. The first type of development, often called primary succession, takes place on newly formed areas where no ecosystem has ever occurred before, such as on volcanic flows, which can eventually support diverse, mature forests. In this situation, ecosystem development is extremely slow. Soils must form. Colonization by microbes, plants, and animals is slow at first due to the extremely harsh and stressful conditions. Wetland establishment on mined landscapes can be considered to be primary succession. Ecosystems, however, more commonly develop following a disturbance that is severe enough that ecosystem development is set back to earlier developmental stages or the system must develop anew (Drury and Nisbet 1973). This second type of ecosystem development is called secondary succession. An example of secondary succession is the development of a forest over many years after an agricultural field is left fallow. In this situation, ecosystem development is more rapid. Soils capable of supporting plants are already formed. Site conditions are not as harsh and colonization is rapid. The types of plants and animals present will change over time. For example in old field succession, annual grasses and forbs are often dominant in the first year. These annuals are most competitive on bare mineral soils. As colonizing plants become established, conditions for plant growth change and different species become dominant that were not tolerant of the earlier site conditions. Shrubs may dominate early and mid developmental stages. Trees begin to colonize a site during early succession, but do not dominate the site structurally until mid to late successional phases. Under the developing tree canopy, a different suite of shade-tolerant shrubs may then develop. Eventually, the rate of new species introductions decreases, the plants on site regenerate themselves, and the species composition stabilizes. At this point, the system is considered to be in a "climax" or a relatively steady state (Odum 1975, Neiring 1987). Most cases of wetland restoration can be considered to be related to secondary succession because project site conditions still retain some of the components of the degraded wetland system.

Disturbance is a common force in ecosystem dynamics. As systems are developing toward a steady state, disturbances of various types and levels of intensity occur that can alter the vegetation developmental process. Disturbances can affect the types and structures of plant populations in a community by

- changing species mixtures by eliminating propagules (i.e., seeds and vegetative propagules) of some species,

- creating harsh conditions for seed germination or vegetative growth for some species or enhanced conditions for others,

- reducing or increasing competition for available resources by removing dominant vegetation,

- altering growing conditions that change species survival, growth, and reproduction rates, hence shifting species dominance, composition, and structure.

Ecosystems that are regularly subjected to low-intensity disturbances (e.g., fire in Southeastern pine forests and inundation in wetlands) have characteristic species associations that are adapted to these conditions. If the communities are mature, there is little species turnover after a low-intensity disturbance, and the species complement remains in a relatively steady state (see Figure 6-2). The occurrence of disturbance can act to reduce competition from species that would invade in the absence of the disturbance (such as a pine forest developing into a mixed hardwood forest in the absence of fire or a wetland forest developing a more mesic mixture of species when drained). "Disturbance" can be a misleading term; fire and water, for example, are natural disturbance forces in the landscape that are necessary to maintain certain types of communities.

High-intensity natural disturbances usually occur with less frequency and are more catastrophic than low-intensity disturbances. Intense disturbances can remove all vegetation and set back succession to the initial developmental stages. For example, prolonged flooding creates conditions beyond the tolerance threshold of many wetland species, and they eventually succumb. As described above, fallow agricultural fields have been subjected to intense land use practices that remove all natural vegetation. The resulting successional plant communities develop and change with time.

Steady-state ecosystems and those near steady state have characteristics that are desirable goals for ecosystem restoration. Ewel (1990) described a successfully restored ecosystem as:

1. capable of regenerating itself without management

2. resistant to invasion by new species

3. able to maintain a balance between productivity, herbivory, and mortality

4. capable of retaining sufficient nutrients to sustain itself

5. composed of organisms with complex interactions

These points assume the presence of a mature ecosystem at a relatively steady state. The establishment of a relatively steady-state ecosystem is often the unstated goal of wetland restoration and establishment projects. Restoration and establishment efforts are intended to accelerate many wetland ecosystem development processes and shorten the time required to reach the desired system (Best *et al.* 1987). For instance, planting desired plant species should force a site to skip or accelerate the initial colonization stages and allow the establishment and growth of the target plant community. This goal is likely to be met in a short time frame if the target species are grasses and herbs that can rapidly dominate a wetland project site. If the target wetland ecosystem is a swamp, however, meeting the goal becomes more tenuous (Kusler and Kentula (1990), but see Clewell and Lea 1990). Furthermore, when the target plant community is attained, the community should be able to maintain itself with a minimum of intervention. Wetland project goals must allow leeway for natural wetland ecosystem processes to develop when setting the time frame for determining project success.

## Wetland Ecosystems

Wetland ecosystems are located along a moisture gradient between well-drained uplands and deepwater aquatic systems. Although there is not an accepted ecologic definition of wetlands, they are characterized by:

1. the presence of water

2. unique soils that differ from upland soils

3. the presence of vegetation adapted to saturated conditions

Hydrology is the most important determinant for the establishment and maintenance of specific types of wetland plants and wetland processes (Mitsch and Gosselink 1986). The depth, duration, and frequency of inundation or saturation and flow limit the distribution of wetland species richness and composition (Bedinger 1978, Fredrickson 1978), primary productivity (Mitsch and Ewel 1979), organic matter accumulation and export, and nutrient cycling (Gambrell and Patrick 1978). Soil saturation, however, regulates most biological and chemical processes in wetlands (Ponnamperuma 1972, Rowell 1981). Saturation or inundation of soils is critical to wetland processes because:

1) a barrier to oxygen diffusion is formed that limits the oxygen required for respiration;

2) biogeochemical transformations take place in the absence of oxygen that affect nutrient availability

3) detoxification and diffusion of toxins away from living tissues are limited.

## Effects of Inundation on Biogeochemical Processes

As water levels rise in a wetland, air is displaced from the soil pore spaces. Living organisms in the soil (e.g., fungus, bacteria, invertebrates) continue to respire for some time (Rowell 1981).

*Aerobic respiration* is the process by which oxygen is metabolically combined with an energy source, such as the organic matter on the wetland floor, to produce energy in the form of ATP. Energy is required for maintenance of living tissue, growth, and reproduction. The end products are water and carbon dioxide.

Free oxygen (i.e., $O_2$ rather than oxygen contained in other molecules) is eventually consumed from the saturated soils, and aerobic respiration is no longer possible. Oxygen is not readily replaced in saturated soils due to slow diffusion rates through water.

Many organisms found in wetlands, however, are capable of anaerobic respiration. Anaerobic respiration takes place in the absence of free oxygen and is the process by which a molecular acceptor of electrons other than $O_2$ is combined with an energy source to produce ATP. Anaerobic respiration produces less ATP than aerobic respiration. End products include acetic acid, lactic acid, and ethanol. There is, therefore, less energy available under anaerobic conditions for the same amount of organic matter consumed under aerobic conditions. In addition, high concentrations of the end products of anaerobic respiration are toxic to living organisms (Rowell 1981). Life under anaerobic conditions must be able to subsist on less energy and have adaptations to minimize effects of toxic end products.

Molecular oxygen is generally consumed from wetland soils within several hours of inundation (Ponnamperuma 1972). Organisms incapable of anaerobic respiration must either escape or die. As anaerobic respiration proceeds, several biogeochemical changes occur (Ponnamperuma 1972). Electrons are transferred to oxidants, which are molecules that easily accept electrons (i.e., in order of ease of electron acceptance: $O_2 > NO_3 > Mn^{+4}, Fe^{+3} > SO_4 > CO_2$). As oxidants accept electrons, their oxidation state is reduced (i.e., becomes more negatively charged). The reduction-oxidation (redox) potential of the soil becomes reduced, and the system becomes more acidic followed by another pH change toward circumneutral. Forms and availability of nutrients are changed. For example, nitrogen, phosphorus, and many micronutrients become more soluble. These nutrients are more readily available for plant uptake. As a consequence of increased solubility, however, nutrients can be washed away or leached from the system, especially calcium and potassium. It is in this manner that nutrients required for plant growth can be lost from anaerobic systems.

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# Wetlands Engineering Handbook

## Section 2

## Site Investigations

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# 2-1 Site Investigations[1]

Knowledge of the existing site topography, soils, hydrology, and vegetation, along with other pertinent site information such as climate, water rights, and site history, is essential to the development of a successful design for the restoration or creation of a wetland. The sources and amounts of information to be obtained about the wetland site will change as the site investigation process proceeds from the screening of candidate sites, through specific site studies, to the design and its implementation at a specific site.

This section discusses information needed for effective decision making about specific design or evaluation activities. This chapter describes the stages, or tiers, of site investigation activities developed in a typical wetland restoration or creation project. Methods and procedures for gathering site information and, where possible, typical costs for site investigation or data gathering exercises are included. Because data gathering activities at all stages of the investigation process depend on sampling and testing, the general concepts used in selecting sampling plans and treatment of the data are described below. These data gathering and analysis concepts are applicable to all areas of site investigation -- topography, soils, hydrology, and vegetation.

## Tiered Site Investigations

Site investigation for developing design information is an evolutionary process that begins with the first reconnaissance survey of the site and continues through project construction. Information required for making decisions is obtained when it is needed. Early decisions on site selection and evaluation can often be made successfully solely on the basis of the information gathered during a literature search and one or more site visits. Later decisions affecting design may require quite detailed data that can only be obtained during a construction monitoring program. Consequently, site investigations are most effective when conducted in *stages*, or *tiers*.

Site investigation usually follows a progression of events such as shown in Figure 2-1. The decision flowchart shown in that figure indicates the stages, or tiers in forming the site investigation:

[1] By S. Joseph Spigolon and Donald F. Hayes

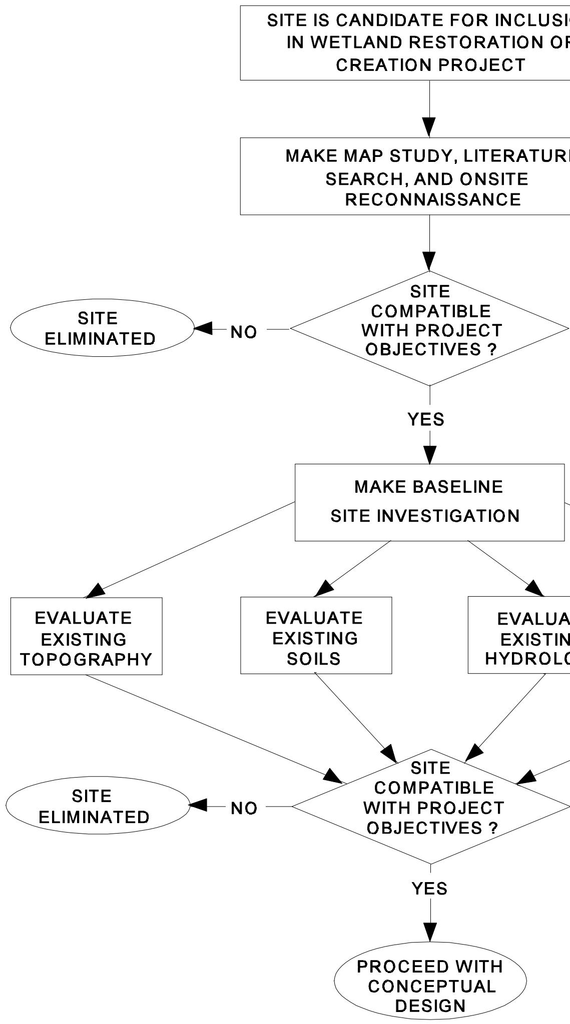


Figure 2-1. Flowchart of general site investigation process.

*a. Reconnaissance surveys of candidate sites.* A preliminary site survey is made to screen each of the candidate sites for compatibility with project objectives. One or more individual sites are selected for inclusion in the wetland restoration or creation project.

*b. Baseline site investigation.* Each site selected for construction is subjected to a baseline site investigation. The investigation obtains the information about the existing character of the topography, soils, hydrology, and vegetation needed for design and as a baseline for evaluating project success.

*c. Detailed subsurface investigations.* Detailed, geotechnical subsurface investigations of soils for structures and earthwork are made at specific sites for the work during the baseline site investigation if the preliminary site design concepts establish the locations. If the locations and character of any structures or earthworks are established after the baseline investigation is completed, then additional subsurface investigation is made when needed.

## Reconnaissance surveys of candidate sites

Projects not associated with a specific site require that sites suitable for wetland creation or restoration be identified and screened for consideration. The size of the area investigated for possible sites depends on overall project objectives, but may be limited to the immediate watershed or some portion of that watershed. Several potential sites should be identified for consideration in the screening process.

The screening survey should start with identification of all candidate sites on topographic, soil survey, geologic, land use, and ownership maps of the area. This may be augmented by the knowledge of the area by the environmental arms of the federal, state, or local governments, or of local environmental organizations. These sites should be selected on the basis of their geographic location, favorable topography, ability to support a wetland, and compatibility with project objectives.

Those sites selected for additional consideration should then be further investigated. A *literature search,* or a *desk study,* is made of the available literature about the site, both published and unpublished. The surface of the site and of road cuts, the drainage patterns, and the existing vegetation are viewed during a personal site inspection, or *field reconnaissance*. The reconnaissance is often greatly enhanced by one or more overflights in a light aircraft or helicopter.

## Baseline site investigations

One or more candidate sites are selected for design and construction based upon the reconnaissance surveys. Before analyses or designs can be implemented for a wetland restoration or creation site, a *baseline site investigation* should be conducted. The baseline site investigation serves two objectives: (1) to determine the *existing* conditions at the wetland site (i.e., the initial topographic, soils, hydrologic, and vegetation conditions) in sufficient detail that effective design decisions for creation or restoration can be made, and (2) to establish a baseline against which the value and effectiveness of all planned and actual site modifications can be measured. These objectives are generally accomplished by field observations and measurements and by the testing of samples of soil, water, and vegetation.

## Wetland site attributes

The four components of a wetland site whose attributes must be characterized from the baseline site investigation are (a) the existing topography, (b) the existing near-surface soils, (c) the existing hydrologic system, and (d) the existing vegetation. A general summary of the kinds of information that will be needed is given below. Individual projects may require additional information.

**(a) Topography.** Topographic maps prepared at a suitable scale show the horizontal location of all natural and man-made features on the wetland site, including the shoreline configuration of all bodies of water. These maps also show elevations at contour intervals so that slope angles, slope aspects, and water flow lines can be determined with reasonable precision.

**(b) Soil properties.** The near-surface soils, and particularly those comprising the solum, should be tested for permeability and for fertility, organic content, salinity, pH, texture, structure, density, moisture content, compaction (pans), and other pertinent attributes. The subsoils may also be tested for texture, consistency limits, permeability, and in situ strength, particularly if it is known, or suspected, that a structure will be built or an excavation will occur at a specific location.

**(c) Hydrologic system.** The project hydrologist needs information about the topography, the vegetation and its distribution, the character of the near-surface soils as they affect potential erosion, weather records, and hydrologic records. For vegetation analyses, it is necessary that the soils be tested for nutrient content, pH, texture, and organic content. Water may be tested similarly for turbidity, hardness, and heavy metals.

**(d) Vegetation.** The types and densities of the various plants existing at the wetland site and their distribution over the landscape must be established.

### Detailed subsurface investigations

If information about existing or potential substrate sources or/and the geotechnical character of the subsurface soils at major structure sites and excavation areas is required, a *detailed subsurface investigation* is made. The subsurface investigation may be done in conjunction with the baseline site investigation, if substrate sources or/and structure locations are reasonably well known at that time, or may be made at a later time when the locations have been identified. The objective of the detailed subsurface investigation is considerably different than that of the baseline site investigation. It is generally directed toward obtaining information about modifying the project's soils rather than determining their existing wetland characteristics.

## Statistical Treatment of Site Investigation Data

During a site investigation, tests or observations are typically made of the significant attributes of the soils, hydrology, vegetation, and other factors that affect the wetland site. All attributes of a wetland are naturally variable, i.e., they are not uniform. The data obtained as a result of tests or observations are used to estimate the character of each of the tested attributes within the entire area or volume investigated.

### Variability of wetland site attributes

A *plot, or deposit,* is defined as a limited area or volume of material (ground surface elevation, soil horizon, pool of water or section of stream, or plot of vegetation) of essentially the same composition and produced by essentially the same formation process. In statistics, this is referred to as a *population*, or *universe*. There will be a number of such plots, or deposits, within the typical wetland site for each of the attributes of interest. Variations in wetland site attributes within a plot, or deposit, occur because of (a) natural variations in the composition of the material, (b) natural variations in the material's formation process, and (c) variations due to the sampling and testing methods or to the observation procedure. Differences of individual attribute test values from each other and from the mean (average) value for that attribute are due to a combination of two causes: random variations and nonrandom, or systematic, variations.

**Random variations.** Random variations occur without apparent aim or reason, determined only by chance. In reality, *chance* is a term used to encompass all of the real causes of variation that are unknown or unmeasurable. This source of variation results in test values that are clustered about a central, mean (average) value and whose magnitude is defined by the variance, or the standard deviation, of the data. In general, the variation in an attribute's values within a relatively small, contiguous area or volume is random.

**Nonrandom, or systematic, variations.** Nonrandom, or systematic, variations are due to some significant, assignable cause or causes. The averages of attribute values tend to vary systematically with distance, horizontal or/and vertical, because of changing material composition or formation process. The cause of a nonrandom deviation with distance may be abrupt, such as a change from one soil type to another in a vertical profile. Or it may be gradual, such as the variation that often occurs in the elevation of the ground surface or the type of vegetation.

## Characterizing frequency distributions

The test or observation data collected about any single wetland attribute from a single population varies randomly. The population from which the data were derived has a frequency distribution of the occurrence of the attribute's values, and the distribution of values can be summarized as a central value, the mean or average, and a measure of dispersion about the mean, the variance.

Test or/and observation data can be either discrete or continuous. *Discrete* quantities vary only by finite increments, by observable jumps, such as numbers of items. *Continuous* quantities vary gradually, by infinitesimal amounts, such as length, time, temperature, force, etc. Usually, for convenience or because of limitations of the measuring instruments, continuous data are recorded as discrete values, such as length to the nearest centimeter (inch) or time to the nearest day.

Data can be evaluated by either of two methods, graphical or numerical, for (a) calculating the parameters of the distribution (i.e., average and variance) and (b) estimating the form of a mathematical model for the population frequency distribution. In pre-computer times, it was common to use data grouping to facilitate calculation of the population parameters. The probable form of the population frequency distribution could be inferred visually. With the advent of electronic calculators and computers, the population parameters are now determined without grouping. A mathematical model of the population's distribution of the frequency of occurrence of the attribute's values is estimated, from the estimator's experience or from preparing a frequency histogram (see below) from grouped data, and then verified by calculating the "goodness of fit" of the grouped data to the model.

Graphical methods involve grouping the data and making *frequency histograms* or/and plotting the grouped data on special graph paper. Data can be arranged in order of increasing or decreasing values and then grouped into discrete cells or classes. The resulting grouping can then be arranged as a frequency polygon, or histogram, as shown in the bar chart of Figure 2-2, or as a graph of cumulative frequency versus values of the variable. Grouping such as this is not generally advantageous for less than about 50 data points in the total data set. The number of classes should be made between 10 and 25 (a) to keep chance variation from dominating if small numbers appear in each class and (b) to keep the characteristics of the distribution from being obscured by large class intervals. Class limits should be integers or even fractions.

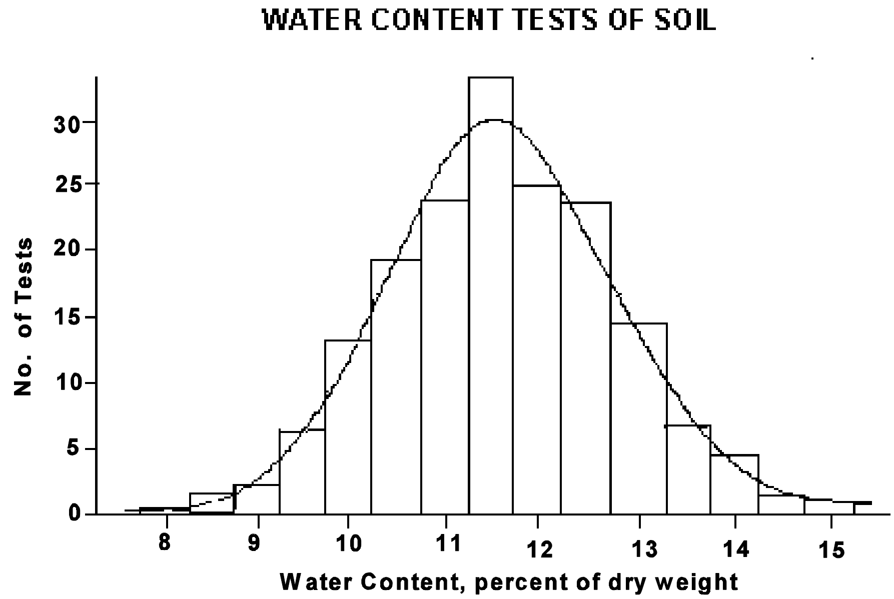


Figure 2-2. Example of a histogram of a wetland site attribute.

The test or observation values used to form Figure 2-2 can be summarized in two parameters, the arithmetic mean and the variance. The *arithmetic mean*, or average, is a measure of the central tendency of the distribution and is the summation of all individual data values divided by the number of data values. These sample parameters are used to estimate the parameters of the underlying population. The *variance* is a measure of the dispersion of data values about the mean and is calculated as the average of the square of the variations of individual data values from the mean. The *standard deviation* is calculated as the square root of the variance. In mechanics terms, the arithmetic mean is the centroid of the frequency distribution about the y-axis, the variance is the moment of inertia of the distribution, and the standard deviation is the radius of gyration.

There are a large number of theoretical frequency distributions for modeling populations of naturally occurring attributes. Some of the more commonly used are presented in Table 2-1. The equations for these, and other, frequency distributions and their derivations are beyond the scope of this handbook. They can be found in virtually all textbooks on probability and statistics and the interested reader is referred to the texts.

**Discrete distributions.** The *binomial distribution* deals with the probability of success of an experiment, consisting of a number of trials, in which only two discrete outcomes are

**Table 2-1**
**Theoretical Probability Distributions for Naturally Occurring Events**

| Name | Description |
|---|---|
| **DISCRETE DISTRIBUTIONS** | |
| Binomial | Determines probability of exactly *r* successes in *n* independent trials, with probability of success, *p*, constant. Sampling with replacement. |
| Hypergeometric | Determines probability of exactly *r* successes in *n* independent trials, with probability of success, *p*, not constant. Sampling *without* replacement. |
| Geometric | Determines the number of independent trials, *n*, with probability of success, *p*, that will occur before the *first* success occurs, where only two outcomes are possible, success or failure. |
| Pascal | Determines the number of independent trials, *n*, with probability of success, *p*, that will occur before *r* successes occur. This is a generalization of the geometric distribution. |
| Poisson | Determines probability, *p*, of an isolated event occurring a specified number of times, *n*, in a given interval (time or space) when the rate of occurrence, *np*, is fixed. |
| **CONTINUOUS DISTRIBUTIONS** | |
| Normal (Gaussian) | Symmetrical, bell shaped curve. Derived from binomial distribution for probability of success, *p*, constant and number of independent trials, *n*, approaching infinity. Normalized values extend from minus infinity to plus infinity. |
| Gamma | Used to represent distribution of quantities which cannot be negative or which have a definite lower limit for values. |
| Exponential | Special case of the gamma distribution, where factor a = 0.. |
| Beta | Used to represent distribution of quantities which have both a definite upper limit and a definite lower limit for values. |
| Rectangular | Special case of the beta distribution, in which all x-values have an equal probability of occurrence. |
| Gumbel Extreme-Value | Distribution of “extreme” values occurring during a cycle in time or space; may be the largest or the smallest values. |
| Weibull Extreme-Value | Time to failure when a system is composed of components and failure occurs due to “most severe” flaw among large number of flaws in the system. |
| **MODIFIED DISTRIBUTIONS** | |
| Shifted | Shift of origin of curve to account for abnormal or impossible data. |
| Transformed | Skewed curves. Data can sometimes be transformed into a symmetrical Gaussian curve by substituting log x, square root of x, 1/x, etc. for x-values. |
| Folded | Occurs when data are recorded without sign, so negative values “folded” over. |
| Truncated | Data values above, or below, a limiting value are not included in the data. |
| Censored | Occurs when values above, or below, a limit are not measured but placed into a group of “greater than, or less than” the limiting value. |

possible - success or failure, right or wrong, left or right, etc., in which there is sampling with replacement. It is applicable, then, to tests or observations in which the attribute's outcome can be one of two values -- either one or the other, pass or fail, above or below a limit, etc. The *hypergeometric distribution* is similar to the binomial, but assumes that sampling is done without replacement. This is of concern when the population is of limited size.

*Geometric distribution* deals with the probability of the number of trials of an experiment before a success occurs and the *Pascal distribution* is an extension of the geometric distribution to the probability of a number of trials before a given number of successes occurs. The *Poisson distribution* indicates the probability of an isolated event occurring a specified number of times in a given interval of time or space when the average rate of occurrence is known and fixed. In the Poisson distribution, the number of time or space intervals is very large and the probability of occurrence during any interval is very small. This distribution has been applied to queuing problems, traffic problems, equipment breakdowns, and other similar situations.

**Continuous distributions.** Continuous distributions generally stem from discrete distributions in which the number of events is very large and the class interval approaches zero. The most commonly used distribution model for natural data is the *normal, or Gaussian, distribution*, an example of which is shown in Figure 2-2. It is derived from the binomial distribution. This distribution seems to characterize a number of natural events in which the outcome depends on a large number of small, random events, none of which dominate the outcome. For example, tests of the hydraulic conductivity of a soil stratum, based on field tests made within a limited horizontal area, will approach a normal distribution if a sufficiently large number of tests is made. The *Gumbel distribution* (Gumbel 1958) is a model for the distribution of the occurrence of *extreme* values in a cycle, such as the highest rainfall in a year, or maximum flood, or maximum drought. Other theoretical distributions, such as the *gamma and beta distributions,* are used to model data under specific conditions, such as the occurrence of upper or/and lower limits to the data.

**Modified distributions.** Several of the standard theoretical frequency distributions can be modified by the manner in which the data are measured or/and recorded. Data from a normal distribution, which is symmetrical, will often yield a skewed, or asymmetrical, distribution. This occurs, for example, in the grain-size distribution of natural sand because the size of the sand particles is the equivalent spherical diameter whereas the corresponding weight is based on the volumes of the particles which are based on the cube of the diameter. Therefore, a *log-normal distribution* fits those data well. Many types of skewed distributions can be transformed to a symmetrical normal distribution by substituting a function of the variable, such as log x or square root of x, for each variable. In another situation, data may be recorded without regard to sign or direction, so that plus or minus, left or right, up or down, result in the same value. Such data will result in a *folded distribution.* A truncated distribution occurs when data above or below a certain value are not included in the tabulation. This may occur, for example, in recording water levels in a pond when the water level drops below the bottom during a dry period. Similarly, a *censored distribution* occurs when test or observation values above, or below, a limit are not measured but placed into a group of "greater than, or less than" the limiting value.

**Fitting frequency distributions.** The "goodness of fit" of experimental data to theoretical frequency distributions of the type given in Table 2-1 can be done by two methods: graphical or mathematical. *Graphical curve fitting* is done using specially prepared graph paper in which one axis is proportioned according to the frequency distribution. By plotting values of the attribute versus cumulative percent larger or smaller, a perfect fit with the theoretical distribution will yield a straight line. Graph paper for the normal (Gaussian) curve is commercially available, with the remaining axis either arithmetic or logarithmic (for fitting a log-normal curve). Other transformations for the normal curve can be evaluated using the transformed variable on the arithmetic axis.

*Mathematical curve fitting* uses one of several techniques, which are described in textbooks on statistics. The most popular of these is the chi-square test. In this test method, the data are grouped by magnitude and the actual cumulative frequencies are compared to the theoretical cumulative frequencies for the given type of distribution. The chi-square distribution itself, which defines the probability of a reasonable fit of the data, has been tabulated and appears in most statistics textbooks.

### Estimation of population parameters

Before an informed decision can be made about the population of values of a wetland attribute, both the form of the frequency distribution and its parameters, the central value (mean, average) and the dispersion of the values about the mean (variance), must be reasonably estimated. It is not practical to sample and test all of the possible items in a population of a given attribute. Therefore, a sample is taken and tested. The sample has an *arithmetic mean and a variance*. Those parameters are the best available estimators of the equivalent population parameters.

**Central limit theorem.** The *central limit theorem* of statistics is very useful for estimating population parameters. If a large number of independent samples, all with the same number of elements, *n*, are taken from a population having a finite variance, and the samples are replaced in their original form and locations after each sampling event (i.e., sampling with replacement), each of the individual samples will have an average and a variance. The average of the group of sample averages will tend toward the unknown population average and the average of the sample variances will tend toward the unknown population variance.

If a frequency distribution is formed of the *averages* of these samples, the resulting distribution will tend to be normal (Gaussian) *regardless of the distribution of the original population*. The larger the sample size, *n*, the greater is the tendency to normality. Similarly, if a frequency distribution is formed of the *variances* of the samples, the resulting distribution will tend to be the *chi-square distribution*.

**Confidence interval estimates.** Given a random sample composed of *n* sample units (size = *n*), there is no way of knowing how good an estimator of the population average it is because it is not known how much the average of that specific sample deviates from the unknown population average. However, recognizing that (a) the distribution of the sample averages is normal, and (b) that the variance of the distribution of sample averages is equal to the population variance divided by the sample size, *n*, then a confidence interval can be established for the unknown population average.

The confidence interval extends symmetrically about the sample average and its width is determined by the variance of the distribution of sample averages times a factor (number of standard deviations of the mean) for a chosen probability level, based on the normal distribution. Then, the following statement can be made: "The unknown population average lies somewhere within the confidence interval," with the chosen probability that the statement is true. Obviously, the larger the sample size, the narrower the confidence interval for a given probability that the statement is true, and the better the estimate. And, the higher the chosen probability that the statement will be true, the wider will be the confidence interval. A similar confidence interval can be established for other population parameters, including variance, range, etc. The interested reader is referred to standard textbooks on statistics.

### Selection of geotechnical sample size for small samples

As indicated above, the estimation of the shape of the population frequency distribution requires samples containing at least 50 sample units, and preferably much more. In some instances, the cost of obtaining and testing an individual sample unit is relatively large, the shape of the population frequency distribution can be reasonably estimated, and the major parameter of interest is the population average. In those cases, project economics may indicate that relatively small samples, much less than 50 sample units per sample for any given attribute, be used. It has been demonstrated experimentally that samples as small as size $n = 4$ will have a normal distribution of the sample averages when taken from normal, uniform, or triangular parent distributions. For highly skewed parent distributions, larger samples are needed.

The total number of *sample units, n,* needed from each soil deposit, water sampling location, or vegetation plot to form a *sample* for estimating the population average of any wetland attribute can be established by (a) classical statistics or (b) judgement, experience, or specification requirement. Classical statistics tells us how large a sample is needed for "no prior" information, i.e., if nothing is known of the variability beforehand. Judgement sampling does not permit a rational estimate of needed sample size for a given confidence.

**Sample size by classical statistics.** The sample average is the best available estimator of the unknown population average. In the absence of knowledge of the population standard deviation, the sample standard deviation is usually used. The sample average invariably differs from the unknown population average by some unknown amount. However, it can be stated that the difference (error) between the known sample average and the unknown population average does not exceed a certain value, with a given probability, or confidence level, of being correct in making that statement, i.e., it lies within a confidence interval. Then, the required sample size is:

$$n = t^2 \cdot \frac{s^2}{E^2} \qquad (2\text{-}1)$$

where *n = size of sample (number of sample units) required; s = sample standard deviation; t = a factor obtained from Statistical Tables of t; and E = maximum acceptable error between the sample average and the unknown population average.* Because the factor *t* is a function of a given probability level and of sample size, *n*, it is necessary to solve Equation (2-1) by successive approximations.

As the sample size, $n$, approaches and exceeds $n = 30$, the value of $t$ becomes constant and is no longer a function of sample size. As a result, the use of sample sizes larger than about 30 to establish a confidence interval for the average of any wetland attribute is totally cost-inefficient. Furthermore, the relationship between the factor $t$ (used for sample sizes $n \leq 30$) and sample size, $n$, is fairly steep for small sample sizes but flattens rapidly for sample sizes greater than about $n = 10$, with each additional sample unit providing less and less additional confidence. Therefore, the information to be gained from the sampling and testing of samples with sizes greater than about 10 sample units should be carefully analyzed; the larger samples may not be worth the extra cost. It may be more desirable, for the same cost, to obtain additional small-size samples to determine trends, in the horizontal or vertical directions, of individual areas or volumes of material attributes.

**Sample size by judgement or requirement.** Sample sizes are sometimes specified in test protocols, or published standards, or may be chosen on the basis of the sampler's judgement. If a random sample of size $n$ is obtained to estimate the average of a wetland attribute, the confidence interval, with a confidence level probability of including the population average, is established whether the sampler intends it or not.

Equation (2-1) shows that the choice of any two of the three factors (sample size, confidence level, and confidence interval) determines the remaining one. The population variance is independent of the sample size. Therefore, for any given confidence, or probability, level about the average of the sample as an estimate of the population average, the maximum error, E, has been established. This relationship is dependent on a random selection of sample units. If the sample units are selected with bias or prejudice, as is often the case, then the confidence interval is greater, or the confidence level lower, or the necessary sample size is larger than expected.

## Sampling Plans for Wetland Site Attributes

Obviously, the entire plot or deposit (population) cannot be sampled and tested without destroying the entire plot or deposit. Therefore, samples are taken and tested and the sample data are used to estimate the population average and variability. A *sample unit*, or *specimen*, is a small portion of the material obtained from a plot or deposit for the purpose of testing or visual inspection. That part of each sample unit actually tested is called a *test portion*. The test results form the basis for judging, or estimating, the population characteristics of the entire plot or deposit. The test results from a number of sample units from a single plot or deposit may be combined mathematically into a *sample*. The horizontal and vertical locations for sample units selected to represent the plot or deposit can be established by (a) judgement, experience, or policy, or (b) statistical random selection.

### Judgement sampling

Judgement sampling has been the traditional method of sampling for attributes, based on a deterministic (non-statistical) attitude toward variability and the concept of the so-called *representative* sample. This usually involves the careful selection of several sample units, or even of a single sample unit, to "represent" the population. In some instances, the elements of the several sample units are blended into a single sample portion to be “representative” of the whole, i.e., a sample of the “average” of the plot or deposit.

The judgmental selection of the sampling location(s) is usually left up to the sampler, or his or her superiors, making the entire process dependent on the validity of the sampler’s judgement, with its inherent tendency toward bias. It is common for a sampler to select the “worst case” rather than a random sample. This introduces considerable bias in the sample results. This type of sampling is valid only in those situations where it is known, or can be assumed, that the remainder of the population has a higher quality level than the “worst case” and if the biased, judgmental sample meets some minimum requirement, the rest of the population is also acceptable.

Unfortunately, the single sample unit or the blending process does not yield a sample variance by which an estimate can be made of the plot’s or deposit's variance. Without that value, no evaluation can be made of the nearness of the “representative” test result to the actual population value. This is not meant to imply that judgement samples cannot and do not deliver useful results, but rather that the reasons why they do when they do are not well understood (Deming 1950).

### Random sampling plans

Whether intended or not, every sample used to estimate plot or deposit population parameters (average and variance) is a statistical sample. All units of a *random sample* must meet several criteria: (a) the sample must be selected without bias or prejudice; (b) all conditions must be the same for all items in the sample; (c) there must be no underlying differences between areas or volumes from which the sample elements are selected; and (d) the components of the sample must be completely independent of each other.

Statistical random sampling is essential for securing a sample whose parameters will be used to estimate the average and variance of the population from which it was taken. Hald (1952) has described several designs of sampling plans: uniform random sampling, systematic sampling with a random start, and two-stage sampling. Each of these plans deals with sampling from a single “homogeneous” population.

**Uniform random sample**. The *uniform random sample* makes every potential sampling unit in the plot or deposit equally likely to be selected. Uniform random sampling does not provide efficient coverage for obtaining information on systematic trends in soil properties over the length, area, or volume sampled. Some zones of the deposit will have a different variance than other zones because of the random, non-uniform sample density, or numbers of sample units.

Random sampling locations within a two- or three-dimensional population may be determined by any one of several methods for generating random numbers. After a sample size has been chosen, an equal number of random numbers is then used to establish each horizontal coordinate (and vertical depth) from which to take each sample unit. Tables of random numbers appear in many statistics textbooks. Unbiased games of chance may be used, such as cards, dice, roulette wheels, etc. Computers can be used by, for example, selecting a four-digit number at random using another method. Then, the four-digit number is squared, and the four central digits recorded. These digits are again squared and the four central digits again recorded and used to generate the next random number.

**Stratified random sampling.** When the plot or deposit to be sampled contains well-defined subsections, each with its own distinct mean and variance, but a single estimate of mean and variance for the whole is desired, then stratified sampling may be used. *Stratified random sampling* involves taking random samples from each stratum with sample sizes (number of sample units) *proportional* to the length, area, or volume of the several subsections. If the systematic variation in attributes for a plot or deposit over a site is fairly uniform, but random variation is not, subdividing the deposit into subsections, or strata, for sampling permits sampling economy by maintaining a consistent sampling variance.

**Systematic sampling with a random start.** An often used sampling method is *systematic sampling with a random start*. This method involves the selection of successive sample units at uniform intervals of length, area, or volume. This is the methodology used in the checkerboard method of topographic surveying and in several other commonly used sampling plans.

Hald (1952) argued that if the first sample unit from that population is randomly selected, then all successive sample units are randomly located also. Baecher (1983) has observed: "The advantages of such plans are that they are easy to design and administer, little time is lost in locating test positions, and at first glance they seem to provide better coverage of the site than do other plans. From a statistical standpoint of view this last advantage is at times fallacious, however systematic sampling in many cases leads to higher probabilities of detecting inhomogeneities in a . . . (soil) mass than do other plans."

**Two-stage sampling.** The basic premise of *two-stage sampling* is that the primary plot or deposit can be rationally divided into discrete zones. A random selection is made of the zones to be sampled and a secondary random selection of sample units is made from each primary zone selected. This is useful when, for example, sample borings are considered as the primary zones, each boring being located in the soil deposit in a uniform random manner or in a systematic manner with random start (see discussion above). Then, within each soil stratum in the boring, the secondary sample units are located vertically at random. Another example is the sampling of vegetation in which a number of small areas, say one square meter (square yard) each, are selected randomly from a homogeneous plot (population). Within each primary sampling location, a sample unit is selected at a random location within the square meter (square yard) of vegetation.

Deming (1950) and Hald (1952) discussed this procedure with respect to secondary sample size (number of sample units) considering the cost of obtaining a primary sample unit (making a boring or pit, or reaching a vegetation plot) and the cost of sampling and testing each secondary unit. The greatest efficiency found, assuming that the costs of mobilizing sampling equipment at the site, the act of physical sampling, and the testing are the same, occurs in sampling only one secondary unit from each primary unit. A similar analysis, comparing the indirect costs of moving to and making a boring or pit and the cost of obtaining and testing soil sample units may be very instructive.

# 2-2 Defining Existing Topography[1]

Most wetland restoration or creation projects will involve some site modification. Because these modifications usually involve some earthwork or topographic adjustment, the existing topography of the site must be defined. Comparing the existing topography with the final site plan allows earthwork calculations to be made and provides valuable information on variations in the character and distribution of soils, hydrology, and vegetation.

Topographic maps are the fundamental tool used to convey information about the configuration of the surface of the site. A topographic map is a two-dimensional representation of a portion of the three-dimensional surface of the earth. A map typically shows the locations of physical features such as hills, valleys, bodies of water, roads, structures, and property lines. Horizontal distances are drawn to scale. Vertical distances are shown as *contour lines*, lines connecting points of equal elevation above some stated datum. Similarly, *bathymetric* maps show contours of the depth of the bottom below the surface of a body of water such as a river, pond, or lake. Aerial photographs can provide current information about the site topography to supplement older topographic map data.

## Map Sources

There are several sources of existing topographic maps (containing contours) covering sections of virtually all of the United States, nearly all of them being government agencies. These maps are generally of a small scale with fairly large contour intervals. They are most useful for an overall picture of a wetland site, especially as the wetland relates to its surrounding areas.

*a.* *Quadrangle maps*. The federal government, through the U. S. Geological Survey (USGS) and the U. S. Army Corps of Engineers (USACE), has developed topographic maps of virtually all of the United States. These maps use one of two scales: 15 minute maps at a scale of 1:62500 (1 cm = 625 meters, 1 in. = 5208 ft.) and 7.5 minute maps at a scale of 1:24000 (1 cm = 240 meters, 1 in. = 2000 ft.). The topography for the most recent maps (past 50 years or so) was developed using photogrammetric methods (discussed below) from aerial photographs. Contour intervals are typically 3 to 15 meters (10 to 50 ft.).

*b.* *Soil Survey maps*. The Natural Resources Conservation Service (formerly the Soil Conservation Service) provides maps in its county-by-county soil survey publications. Although they are not true topographic maps, with contours, SCS Soil Survey maps do indicate surface soil types and slope ranges. The more recent (past 30 years or so) maps

[1] By S. Joseph Spigolon

are segments of aerial photographs with physical features and soil type boundaries superimposed. They are generally made at a scale of 1:20000 (1 cm = 200 meters, 1 in. = 1667 ft.).

c. *State geological survey maps.* All states have a State Geological Survey which publishes maps, reports, and other documents about the geology and mineral resources of that state. The maps often contain contours and the scales used are similar to those of the USGS.

d. *Other map sources.* State Departments of Transportation often develop maps for use in planning and designing new routes or modifying portions of existing ones. Usually, these are developed using photogrammetric methods from aerial photographs. Counties and cities also maintain maps of their infrastructure. If topography is not available directly, it can sometimes be determined from spot elevations of such features as roads and streets and sewers. County and city permitting agencies are usually the depositories for topographic maps prepared for various types of public or private land developments.

## Choosing Map Scales

Map scales are usually chosen to conform to (a) the needed or desired accuracy, both horizontal and vertical, (b) the needed or desired contour interval, and (c) the cost of obtaining a map of the needed or desired accuracy relative to the overall project cost. Typically available maps, such as the U. S. Geological Survey 7.5 minute topographic quadrangle map, with a scale of 1:24000, are quite suitable for most field work. However, most of these maps are several years old (many are based on surveys made prior to 1975) and may not reflect current modifications. They are also not sufficiently detailed for earthwork calculations or for determining the extent of vegetative cover.

## Contour Lines

Each contour line represents the edge of the land surface as if all of the land above that elevation had been removed (sliced off horizontally) and then viewed vertically downward from a great distance above. Therefore, all contour lines must close on themselves either within or outside the borders of the map. A closed contour line on a map always indicates a summit or a depression. Contour lines cannot cross each other or merge except at a vertical or overhanging land surface. The distance between contour lines is inversely proportional to the slope. Consequently, large contour spacings indicate relatively flat topography and closely spaced contours represent steep slopes. Along plane surfaces the contour lines are parallel to each other and straight.

Contour lines run perpendicular to the direction of steepest slope and, therefore, perpendicular to the direction of surface water flow. Contour lines are perpendicular to both ridge and valley lines where they cross such lines.

### Choice of Contour Interval

Table 2-2 represents conventional good practice for selecting contour intervals under usual conditions. The cost of map making increases almost exponentially, for a given scale, as the contour interval is decreased simply because the necessary number of elevation measurement points is increased.

**Table 2-2**
**Relation Between Map Scale, Ground Slope, and Contour Interval (Adapted from Urquhart 1950)**

| Map Scale | Scale Range | Ground Slope | Contour Interval |
|---|---|---|---|
| Large | 1:1200 or less<br>1 cm =12 meters or less<br>(1 in. = 100 ft. or less) | Flat<br>Rolling<br>Hilly | 0.2 m (1 ft.)<br>0.2 or 0.5 m (1 or 2 ft.)<br>0.5, 1, or 2 m (2 or 5 ft.) |
| Intermediate | 1:1200 to 1:12000<br>1 cm = 12 to 120 meters<br>(1 in. = 100 to 1000 ft.) | Flat<br>Rolling<br>Hilly | 0.2, 0.5, or 1 m (1, 2, or 5 ft.)<br>0.5 or 1 m (2 or 5 ft.)<br>1 m or 3 m (5 or 10 ft.) |
| Small | 1:12000 or more<br>1 cm = 120 meters or more<br>(1 in. = 1000 ft. or more) | Flat<br>Rolling<br>Hilly<br>Mountainous | 0.5, 1, or 3 m (2, 5, or 10 ft.)<br>3 or 5 m (10 or 20 ft.)<br>5 or 15 m (20 or 50 ft.)<br>15, 25, or 50 m (50, 100, or 200 ft.) |

## Preparing Site Maps

When existing maps are not suitable, either because they are of too small a scale or lack sufficient detail, then topographic mapping of the project site must be done. Map making consists of the accurate location of the horizontal position of a number of points on the ground surface, the measurement of their elevation, and the interpolation of evenly spaced contours between the points. The number of points needed depends on (a) the contour interval needed or desired and (b) the typical ground slope in the mapping area. For flat terrain and a correspondingly large contour interval, only a few points are needed. For hilly terrain and a small contour interval, many points are needed.

### Direct Mapping Methods

Field measurement of elevations at specific horizontal positions is the most common method of developing contour, or topographic, maps. Survey mapping involves personnel traversing the ground surface, measuring distances and angles between points, and measuring differences in vertical elevation between points. Horizontal and vertical measurements may be made using (a) traditional surveying instruments, such as theodolites and tapes or distance measuring devices, or/and (b) portable Global Positioning System (GPS) equipment. The GPS uses an electronic measurement of the relative positions of at least four of the specific earth-orbiting satellites to determine a horizontal position on the ground surface. Vertical measurements, relative to a given starting point, are also possible.

In instances where a vertical precision of one meter (3 ft) or more is acceptable, a hand-held level and a range pole (a rod marked in 2.5- or 3-decimeter, or 1-foot, increments) can be a useful field expedient. While this is occasionally true, most projects will require the greater precision available through established surveying methods.

Some direct measurements can be made by amateur surveyors familiar with surveying equipment and methods. However, most states require that site development activities include a survey certified as accurate by a licensed surveyor. In the latter case, the services of a state-licensed land surveyor are needed.

There are several surveying plans commonly used to establish the locations of the large array of horizontal points at which elevations are determined. The three most commonly used plans are the grid (checkerboard) method, contour tracing, and control points.

**Checkerboard method.** The *grid, or checkerboard, method* consists of establishing a series of parallel lines on the ground in two mutually perpendicular directions. Then, with the locations of all grid points (nodes) known, the elevation of each grid point is determined using optical or laser leveling with a level rod moved from point to point. The line spacing is determined by the steepness of the terrain and by the desired or needed contour interval.

**Contour tracing.** *Contour tracing* is feasible when a convenient and rapid method of distance measurement and of communication are available. A specific elevation point is established. The level rod holder is then positioned at a number of points where the level operator measures the same elevation. The horizontal location of the rod at each point, relative to the instrument, is determined by distance measuring equipment or by stadia measurements in conjunction with a transit or theodolite for measuring angles from a known point. In this manner, each contour line is physically traced on the ground.

**Control points.** *Control point* mapping is a combination of checkerboarding and contour tracing and is best used when the topography consists of a number of well-defined topographic features. Using angles and radii (distances) from a known point, points on such features as ridge lines, gully lines, valley lines, edges of watercourses, and roadway center lines and intersections, can be located and the elevation of each determined. These spot elevations can then be used as an irregular grid and contours can be interpolated from the measurements. Or, controlling points can be used as an adjunct to checkerboard mapping or contour tracing to provide greater accuracy at important locations.

### Indirect Mapping Methods

Contour maps can also be produced economically from indirect measurements using photogrammetric methods. Aerial photos are taken as a stereo pair. Then, using visible, well-defined points established with ground control surveys, and using a stereo plotter (Kelsh Plotter), contours are drawn where chosen elevations come into focus. The scale and the minimum contour interval obtainable by this procedure depend on the height of the flight above the ground.

The USDA Natural Resources Conservation Service (Soil Conservation Service) Soil Survey maps (discussed above) are scaled in this manner to 1:20000. For contour intervals of 30 cm (1 ft), the flight must be 305 m (1000 ft) above the ground. A 1.5-meter (5-ft) contour interval requires a flying height of 1525 meters (5000 ft.). Aerial photo stereo pairs are normally obtained during winter months to avoid interference and confusion from existing foliage. While this method is less precise than direct measurement, it is considerably faster and less expensive. In some cases it may be sufficiently precise to fully support site design activities. Where greater precision is needed, additional ground control surveys are made to verify the accuracy of the photogrammetric methods.

## Geographic Information Systems

Geographic Information Systems (GIS) can provide a convenient and rapid method to assess the topography and conditions at a large number of sites. GIS has been used to identify wetland boundaries, classify wetlands, and even assess water quality in wetland systems. While GIS have many advantages, they are limited by the availability of electronic mapping data, the expense associated with obtaining the data, and the considerable time required to establish a working GIS even for a small project. However, as with many other technological advances, GIS are becoming more practical alternatives as their costs continue to decrease and the availability of GIS and their data continue to increase. Undoubtedly, GIS will become an essential tool of cost-effective site investigations in the near future.

# 2-3 Characterizing Existing Soils[1]

Surface and subsurface soils are critical wetland components. They provide a complex variety of services for wetland ecosystems such as (a) serving as a biological medium for plant growth, (b) acting as a biological interface to support macro- and micro-invertebrates and microbial populations, and (c) providing structural support for water retention structures. The soil profile characterization process measures the extent to which certain soil properties, important to the desired wetland functions, exist *before* the wetland restoration or creation design process starts. Thereby, the soils investigation provides a *baseline* for the designers to use in planning modifications to the site.

The objective of any subsurface soils investigation is to obtain the most complete and accurate estimate of the location and character of the near-surface soils that affect a project's design and construction that is possible within the monetary and time limits of the project. This chapter presents and discusses:

*a.* *Stages of soil investigations*. The three stages, or tiers, of the investigation of project soils are: (a) the initial screening of the estimated soil profile at candidate sites, (b) the baseline (plant-growth oriented) soil survey of selected sites, and (c) the detailed geotechnical investigation of structure locations.

*b.* *The soil profile.* A review of the characteristics of the mature soil profile and several soil profile terms that have definitions that differ between their biologic, pedologic, and engineering uses.

*c.* *Plant-growth attributes of wetland soils*. The attributes of the soil profile that significantly affect plant growth at a wetland restoration or creation site.

*d.* *Baseline soil surveys*. A strategy for the subsurface investigation to evaluate the existing wetland soil attributes.

*e.* *Soil classification systems*. Systems for describing, identifying, and classifying soils that are in common use by the various wetland-related disciplines and found in the professional literature.

*f.* *Soil exploration and sampling.* Methods and equipment that are suitable for subsurface exploration and for securing soil samples for wetland soils investigations.

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[1] By S. Joseph Spigolon and Donald F. Hayes

*g.* *Tests for wetland soil attributes*. Soil tests and observations appropriate for identifying plant-growth attributes and for soil classification.

*h.* *Detailed subsurface investigations for structures.* For subsurface investigations at specific structure locations, the significant soil properties and the exploration, sampling, and testing methods that differ somewhat from those used in the baseline, plant-growth oriented soils investigation.

## Stages of Soil Investigations

Investigations of the stratigraphy and wetland attributes of the soils at a wetland restoration or creation site will occur, as described in Chapter 2-1, in two or three stages, or tiers, although each stage may be repeated one or more times as the need for information about project soils develops. A site assessment flowchart for the substrate and geotechnical soil investigation part of a wetland project is shown in Figure 2-3.

**Reconnaissance survey of candidate sites.** In the first stage of any project, an initial site assessment is made to screen the near-surface soils at candidate sites for compatibility with the wetland project objectives. Topographic maps of the area are studied for factors significant to the soil survey. A study is made of all available prior (preexisting) information, including the geologic literature, the local county Soil (Natural Resource) Conservation Service soil survey, records of previous geological and geotechnical studies in the project area, and personal experiences of government agency and civilian personnel with soils in the project area. This is sometimes referred to as a *literature search* or a *desk study*. Then, a *field reconnaissance*, or personal site inspection, is made of the surface features of the site, including road cuts and the drainage patterns. The net result is an estimate of the character of the near-surface soil profile at each site. This information, combined with hydrologic and vegetation surveys, is used to screen the suitability of the candidate sites.

**Baseline soil investigation.** One or more candidate sites are selected for inclusion in the wetland restoration or creation project. Each selected site must have an intense, pre-design soils assessment, consisting of a *baseline subsurface exploration*. The purpose of the baseline soils investigation is to determine those soil properties of the near-surface soil profile that affect the plant-growth and hydrologic character of the site to such an extent that (a) an efficient design of the project can be made, and (b) the future effectiveness of the project can be measured.. The procedure for making a baseline soils investigation is discussed below.

**Detailed subsurface investigation**. During the baseline soil investigation, an intensive study will be made of the presence and character of soils suitable for the proposed substrate and its supporting subgrade. A detailed investigation is made of the existing soils to determine whether they can be developed into the needed substrate. If not, then a search is made for an alternate on-site source of suitable soils that can be moved on site. Failing this, then a search is made for an off-site source of substrate material.

If the project plan includes, or very likely will include, major structures (often involving excavation and/or fill placement), then a more specific *detailed geotechnical exploration* of the influenced areas will be made, with a more intense investigation of those geotechnical soil

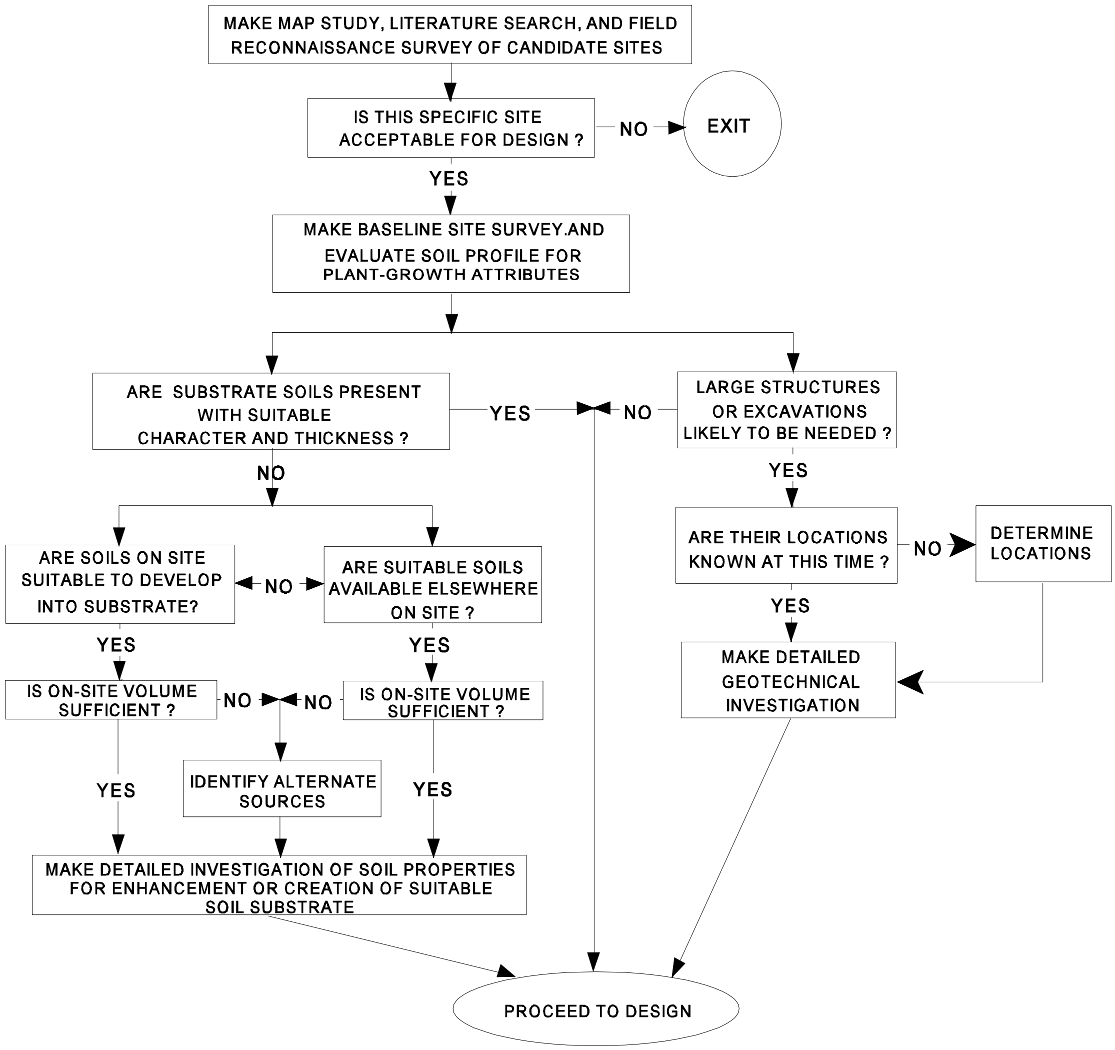


Figure 2-3. Site assessment flowchart for evaluating soils for substrate and earthwork suitability.

properties that will be of direct value for designing the structures. The soil properties and methods of geotechnical investigation are discussed below.

## The Soil Profile

The non-engineering and the engineering definitions of some soil-related terms are not always the same. The major difference lies in the primary concern of the discipline, whether *soil* is (a) a plant growth medium or (b) an earthwork or a structure-supporting medium. Soil-related documents, both the published literature and unpublished reports, about the project site are normally written using the terminology of the writer's professional specialty. Research of such literature by, or discussions between, project personnel from the various soil-related disciplines can lead to serious misunderstandings and, in the extreme, to legal complications if the differences in definitions are not recognized.

The following discussion contains terms relating to the soil profile that are used in the technical literature of the engineering and the soil science professions. The primary source used for civil engineering definitions was American Society for Testing and Materials Standard D 653, “Standard Terminology Relating to Soil, Rock, and Contained Fluids” (ASTM 1994) and the primary sources of soil science definitions were the U.S. Department of Agriculture Soil Conservation Service (SCS) *Soil Taxonomy* (Soil Survey Staff 1975) and the Soil Science Society of America *Glossary of Soil Science Terms* (Soil Science Society of America 1987). Starting in 1994, the SCS's name has been changed to Natural Resources Conservation Service. Throughout this discussion, the former name is used for all references prepared under the SCS designation.

## Soil Horizons

Soil scientists have recognized that plant-supporting soils formed under a given set of climatic conditions for a long time developed fairly uniform characteristics over wide areas. Mature, well-developed soils in moist climates generally exhibit a distinct *soil profile*, a vertical section of the soil, consisting of six horizons, O, A, E, B, C, and R, as defined by the Soil Science Society of America (1987). A simplified sketch of a mature soil profile is shown in Figure 2-4. Not all soil profiles have the mature profile described below and in Figure 2-4. Soil Taxonomy (Soil Survey Staff 1975) recognizes ten major soil orders, each having a unique solum development based on differing amounts and conditions of weathering.

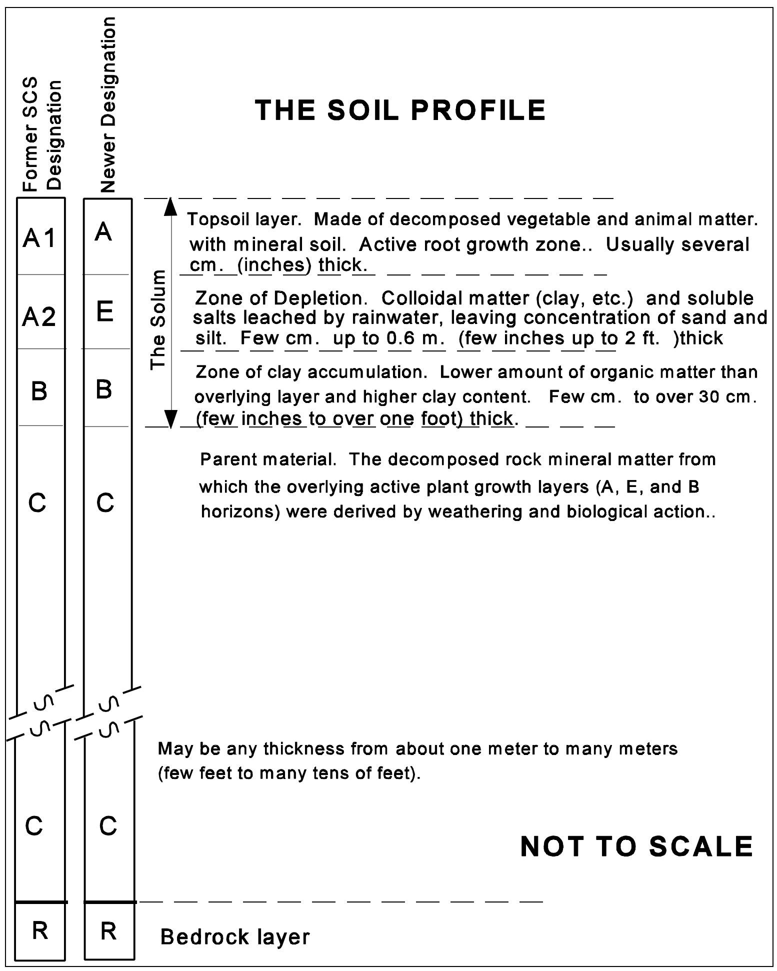


Figure 2-4. Soil horizons in a mature soil profile.

The soil horizons are approximately parallel to the land surface and indicate dominant kinds of departure from the parent (regolith) material. They differ in color, texture, and structure, may vary in thickness, and may even be absent in some soils. The six distinct horizons consist of the following:

**O horizon**. The O horizon consists of organic litter derived from plants and animals and deposited on the surface. This horizon is sometimes designated the A0 horizon, or the uppermost subdivision of the A horizon.

**A horizon.** The A horizon is the *topsoil*, the uppermost part of the mineral soil, which is the most favorable material for plant growth and which is formed at the surface or below an O horizon. It was formerly called the A1 horizon, a now obsolete term (Soil Science Society of America 1987). It is ordinarily rich in organic matter called *humus,* the dark colored material formed by the partial decomposition of vegetable or animal matter combined with mineral soil.

**E horizon.** The E horizon is formed below the A horizon. It was formerly called the A2 horizon, a now obsolete term (Soil Science Society of America 1987). It is, in moist climates, the zone of depletion in which much of very fine colloidal material (silicate clay, iron, and/or aluminum) and soluble mineral salts have been elutriated (washed downward) by percolating water, leaving a concentration of sand and silt size particles of quartz or other resistant materials. The thickness of the combined A and E horizons ranges from a few centimeters (few inches) to, in extreme cases, 0.6 meter (2 ft.).

**B horizon.** The B horizon is the zone of accumulation. In many soils, the colloidal matter washed from the O, A, or E horizon is deposited in the B horizon. Therefore, the B horizon tends to be clay rich. The thickness of the B horizon ranges from a few centimeters (few inches) to a meter (3 ft.), although in extreme cases, it may be two or more meters thick (several feet).

**C horizons.** The C horizons or layers are the little-altered *parent material*, consisting of weathered rock fragments (engineering *soil*), which has been little affected by pedogenic processes and from which the overlying A, E, and B horizons were developed. There may be several C horizons of parent material, each with its own solum (A, E, and B horizons), overlying each other, as the result of newer deposition of sediments over an older soil profile. The thickness ranges from a few meters (few feet) to many meters (many feet).

**R layer.** The R layer (formerly called the D horizon) is the underlying consolidated (hard) bedrock. It may or may not be the parent rock from which the overlying C horizon was derived.

**Transitional horizons.** Two forms of transitional horizons are defined by the Soil Science Society of America (1987) by the use of dual letters: (a) the kind where the properties of an overlying or underlying horizon are *superimposed* on the properties of the other (i.e., AB, BC, etc.), and (b) the kind in which distinct parts of one horizon enclose parts of a second horizon (i.e., E/B, B/E, or B/C).

### Soil horizon terminology

The difference in emphasis between the plant-growth-oriented soil scientists and biologists and the earthwork- and structures-oriented geotechnical (civil) engineers has resulted in professional-specialty-specific terms related to the soil profile. Some of the major soil horizon terms that differ significantly between the several professional groups are presented below. Other unique or dissimilar definitions, for soil physical and chemical properties, are given in those parts or appendices where the specific properties are discussed.

**Hydric soil.** A hydric soil is a soil that formed under conditions of saturation, flooding, or ponding long enough during the growing season to develop anaerobic conditions in the upper part (Federal Register, July 13, 1994).

**Pans.** As used in soil science, *pans* are horizons or layers in the near-surface soil profile that are dense, strongly compacted, indurated, or very high in clay content A *claypan* is a slowly permeable soil horizon that contains much more clay than the horizons above it. A claypan is commonly hard when dry and plastic or stiff when wet. *Hardpan* is any buried, hard, impervious layer in the A, B, or C horizon that does not become plastic when mixed with water and definitely limits the downward movement of water and roots. In many cases, *pans* are soils cemented by calcium carbonate or iron oxide. *Fragipan* (brittle pan) is a pan that occurs mainly in silty-clay soils leached of carbonates. A fragipan will usually start at 0.5 to 0.6 m (1.5 to 2 ft) depth and fade away at a depth of 1.2 to 1.5 m (4 or 5 ft) and is usually hard because of a high bulk density. Fragipans are very slowly permeable and may contribute to a locally high, or *perched*, water table (Spangler and Handy 1982).

**Saprolite**. A soil science term used to describe residual soils, those that have weathered in place and have not been transported by water, wind, ice, or mass movement. *Saprolite* is defined (Soil Survey Staff 1993) as: “Soft, friable, isovolumetrically weathered bedrock that retains the fabric and structure of the parent rock . . . .” Other definitions state that a saprolite is a soft, earthy, typically clay-rich, thoroughly decomposed rock, formed in place by chemical weathering of most types of parent rock (Bates and Jackson 1987).

**Solum**. The upper part of the soil profile, above the C horizon, in which the processes of *soil* formation are active. In the Soil Science Society of America (1987) definition: “The upper and most weathered part of the soil profile; the A, E, and B horizons.” Generally the characteristics of the materials in these horizons are unlike those of the underlying, parent material. The living roots of plants and animal activities are largely confined to the solum.

**Subgrade** (soil science and wetlands biology) That part of the near-surface soil profile that supports the *substrate* and its functions.

**Subgrade** (engineering). “Below the grade” or beneath the finished ground level of a project. It is the prepared earth surface on which a pavement is placed or on which the foundation of a structure is built.

**Subsoil** (soil science). Generally, the B horizon. The *subsoil* is also that part of the solum below plow depth.

**Subsoil** (engineering). The *subsoil* is: "(a) soil below the subgrade of fill, or (b) that part of a soil profile occurring below the "A" horizon." (ASTM D 653, 1994).

**Substrate.** As used in wetlands biology, the *substrate* is a term that refers to that part of the surface of the wetland soil profile that actively supports the growth of hydrophytic plant species. It is a functionally defined component rather than a specific soil material or a definite horizon within a naturally developed soil profile. It serves a function in the same sense as, for example, a pavement structure, consisting of a base course and wearing surface, resting on a natural or modified subgrade. The substrate may be naturally existing or may be designed, prepared, and placed for a specific wetland objective. It is supported by a *subgrade* that generally consists of the existing, natural soil "as is" although, in some instances, the subgrade may be modified by cutting and/or filling to provide the necessary supporting characteristics for the substrate. It generally corresponds to the solum in soil science terminology and to the topsoil in civil engineering terminology.

**Substratum** (soil science). "Any layer lying beneath the soil solum, either conforming or unconforming" (Soil Science Society of America 1987). *Webster's New Collegiate Dictionary* (Woolf 1980) defines the *substratum* as: " (a) used as a foundation: an underlying structure, layer, or part; (b) used as a subsoil or substrate: a layer of rock or earth below the surface soil."

**Subsurface layer** (soil science). As used by the SCS, the *subsurface layer* is, technically, the E (formerly the A2) horizon. This term generally refers to a leached horizon lighter in color and lower in content of organic matter than the overlying surface (A horizon) layer (USDA-SCS 1989).

**Topsoil** (soil science). "(1)The layer of soil moved in cultivation. (2) The A horizon. (3) Presumably fertile soil material used to topdress roadbanks, gardens, and lawns." (Soil Science Society of America 1987).

**Topsoil** (engineering). *Topsoil* is the "surface soil, usually containing organic matter." (ASTM D 653, 1994). Generally, the A horizon.

## Plant-Growth Attributes of Wetland Soils

Many of the physical, chemical, and biological properties of the near-surface soil profile must be known as a baseline and as input to design analyses. The hydrologic engineers must deal with subsurface drainage and with the erosion potential of the upper soil profile. Geotechnical properties (Section 6 of this handbook) of the C horizon affect the design of water control structures. For vegetation, the character of both the substrate and the upper part of the subgrade must be evaluated. Therefore, as a minimum, all or most of the following attributes should be determined in the initial subsurface investigation:

*a. Soil profile.* The thickness and character of the soil horizons.

*b. Texture.* Particle size analysis, including clay content; estimate of the shrink-swell potential of clayey soils.

c. *Structure.* Configuration of peds, including seven types, five sizes, and four grades (for details, see Appendix A, Soil Classification Systems).

d. *Consistence.* Plasticity and strength.

e. *Pans.* The vertical location and thickness of low permeability, high density, and/or high clay content layers.

f. *Water table location.* If it is below the ground surface.

g. *Moisture content.* For each of the horizons. Must distinguish between the total weight or the dry weight basis. In the solum, the available water capacity.

h. *Density.* The bulk, or mass, density of the undisturbed soil, particularly in the solum (A, E, and B horizons).

i. *Fertility.* The capacity of the soil to supply nutrients to growing plants from both the exchangeable and the moderately available forms.

j. *Nutrient content.* Concentrations of the various nutrient elements present and their exchangeability.

k. *pH.* The relative acidity or alkalinity of the soil.

l. *Salinity.* The presence and concentration of soluble salts, exchangeable sodium, or both.

m. *Organic content.* Relative weight of organic matter to the total weight of the soil.

## Baseline Soil Investigation

The depth of subsurface exploration for the initial site assessment is not expected to exceed 1.5 to 2 m. (5 to 7 ft.) below ground surface. Access to exploration sites may be hampered by the lack of suitable roads and may involve water-covered locations or even dredging sites. Therefore, it is desirable that simple, lightweight, and uncomplicated equipment be used.

This discussion is limited to soils (unconsolidated materials) and soft rock (lightly cemented soils). Where hard rock (indurated material) is encountered at a wetland site, either at the surface or below the solum, it is generally not necessary that it be identified by type, only by its presence, location, and possible influence on the project.

There are no standard requirements or methods for a baseline soil investigation. Each subsurface investigation must be adapted to the geomorphic environment, locally available equipment and personnel, personal experiences with local soils, and to time and budget constraints. The general sequence of events in a subsurface investigation is fairly well known and used by both soil scientists and geotechnical engineers. Therefore, it is important that experienced and professionally qualified individuals are employed to direct the investigation, interpret the resulting data, and present conclusions in a concise, consistent, usable form to the project planners.

## Procedure

The strategy (plan) for a typical initial subsurface investigation for a wetland project contains the following steps. These steps are valid whether applied to the *initial*, or *baseline*, site investigation or the second, more detailed investigation of *specific* construction-related locations.

1. Based on the information developed during the literature search and the field reconnaissance stage, an initial *estimate* of the overall subsurface profile of the project site is developed, including the types, configuration, and physical and pedologic behavior characteristics of the soils present in the soil profile. If the available information is sufficient for the project, the soils investigation is terminated at this point.

2. If the knowledge of the soil profile is not sufficient, then an intensive physical subsurface exploration plan is formulated. The number and location of sampling and testing sites are established tentatively, perhaps on a statistical sampling basis, with the option of changing the plan as information develops.

3. At each exploration site, specific depths and specific methods are selected for sampling and field testing the soils. Sampling depth may be reached by drilling holes or digging pits. Soil samples are then obtained for laboratory tests. Field soils tests are made when appropriate. Piezometers may be installed for groundwater observations. Using field expedient and visual-manual tests, an identifying description is made in the field for each sample. The descriptions are later confirmed in the laboratory or office by further examinations and tests. The previous estimate of the nature of the soils in the near-surface soil profile is reviewed for consistency with the new data and is accepted or revised as needed.

## Sources of pre-existing information

There are several sources of geological, geotechnical, and pedological information that pre-exist the current subsurface investigation. These should be consulted to form the initial estimate of the soil profile. They include:

a. *Geologic and Pedologic Data Sources*--Sources of geologic literature, maps, and related information for the project area include the U. S. Geological Survey, the U.S. Department of Agriculture Soil Conservation Service (renamed the Natural Resources Conservation Service in 1994), including the local area conservationists, the state geological survey, agricultural county agents, and well logs.

b. *Project Records*--Public, and sometimes private, records of construction projects in the wetlands project area may be available that contain a summary of the geologic and geotechnical information developed for use in the design of those projects.

c. *Remote Imaging*--Aerial and/or satellite photography, using either visible or non-visible light waves, and ground probing radar.

d. *General Sources*--Libraries, local and regional agencies, and knowledgeable local individuals.

## Scope of baseline soil exploration

If the vertical or horizontal character of the soil profile is expected, from a study of all pre-existing information, to be fairly uniform, then the depth of exploration and the number and location of borings or test pits can be reasonably established. However, if the soil profile is erratic or not very well known in advance, geophysical studies can provide valuable, money- and time-saving information useful for more efficient planning of the physical exploration.

Geophysical techniques applicable to a wetland soils and groundwater investigation include seismic refraction and electrical resistivity methods. Acoustic impedance may be of value if all or a portion of the site is covered by water. Seldom, however, can geophysical methods alone be used to establish reliable subsurface information (ASCE 1976). All geophysical data should be verified by correlation with “ground truth” boring or test pit data.

**Number and location of borings.** The investigator must establish, in consultation with other members of the wetland design team, the number and location of discrete attribute populations, i.e., individual areas in which *each of the attributes* described above tend to be relatively homogeneous, with only random variations. Significant changes in the parent material, water regime, slope, slope aspect, and similar factors should signal a systematic (population) change in one or more of the significant attributes. Each such plot or deposit should, of course, be treated separately.

The amount to be spent on the total subsurface investigation, which determines the total number of test borings or test pits, and the magnitude of the sampling and testing program, depends on the amount of monetary and other risk to the project if (a) all or part of the exploration is not done and there is a significant lack of vital information, or (b) unnecessary or meaningless information is obtained. The amount and impact of the risk is impossible to establish analytically because of the lack of input probabilistic information. However, practical sufficiency can be established intuitively by conference between the owner-developer of the wetland project (the source of funds) and the soil scientists, geotechnical engineers, and other professionals involved in the project design. Complete initial agreement by all parties should not be expected since the priorities and personal biases of each participant will vary from those of the others. The owner-developer must be informed by the professionals of the possible consequences, and level of risk, due to limitation of the investigation to any given level of funding.

Of the total number of borings or test pits that are to be made, apportionment should be made according to the relative uniformity of the character of each plot or deposit. Ideally, if a plot or deposit for a specific attribute were *entirely uniform*, then only one sample needs to be taken and tested to characterize the entire deposit. Some plots or deposits will have fairly uniform properties over a long horizontal distance. Others will have a dramatic change over a short horizontal distance.

Within each discrete plot or deposit a minimum of four and perhaps up to 10 borings or test pits should be used. Each boring or test pit should be located horizontally either (a) completely randomly or (b) in a pattern, as systematic sampling with a random start. Within each boring or pit, each soil horizon and pan should be identified by thickness, texture, and depth. If the thickness of any horizon exceeds the normal length of a sample, the vertical location(s) within each thickness should be established at random.

**Depth of exploration.** If the study of pre-existing information or the early borings and/or test pits indicate that only one or two types of parent material (C horizons) exist in the near-surface soil profile, then the initial soil explorations may need to extend only deep enough to confirm the depth and character of the C horizon(s), on the order of 1.5 to 2 meters (5 to 7 ft) (Soil Survey Staff 1993). One or more deeper borings may be needed for piezometer installations to monitor the depth, inclination, and seasonal variation of the free water surface, i.e., the water table.

## Soil Classification Systems

In soils technology, a distinction exists between the terms: identification, description, and classification. Unfortunately, these terms are sometimes used interchangeably and this may lead to misinterpretation.

*Soil identification* is the determination to which class a given soil specimen belongs using *factual information* derived from generally accepted test and observation methods. The specific *identification* tests and observations that are made on a soil are usually dictated by the requirements of the soil classification system to be used. The results of each test or observation are part of the identifying characteristics of the specific soil sample.

A *soil description* is a representation, using words, phrases, and numerical data, of the significant characteristics of a soil specimen. The descriptor terms are generally arranged into groups, or classes, defined according to the results of certain agreed upon observations and identification tests, *without consideration of a specific application*.

*Soil classification* is a systematic arrangement into groups, according to certain agreed upon rules or criteria, based on identification tests and observations, that provide a *rating* of soils with regard to a certain limited number of qualities and potential behavior characteristics that are considered to be significant and important in a particular field of soil-related work based on criteria established by interpretations of experience. Soil classification is *interpretive* information, whereas soil identification is *factual* information.

All soil classification systems provide definitions of the descriptor terms used. Therefore, it is usually necessary in a soil description to identify (directly or by implication) the classification system being used so that terms can be correctly defined.

There are three soil classification systems frequently used in the wetlands literature and in the sources of pre-existing information described above. They are (a) USDA Soil Taxonomy, (b) the Unified Soil Classification System (USCS), and (c) the AASHTO Highway Soil Classification System. Soil Taxonomy was developed for agricultural soil science. Each of the two other systems was developed to serve a special engineering- or construction-related purpose. The three systems are described in detail in Appendix A.

Table 2-3 contains a comparison of four textural or grain size classification systems, illustrating the fact that definitions of gravel, sand, silt, and clay vary slightly between the systems. The Wentworth system (Wentworth 1922) shown in Table 2-3 was originally developed for use by geologists, but is now used by a large number of scientists in other disciplines. The *Wentworth exponent,* $\phi$, (Krumbein 1936) was introduced in pre-computer time to facilitate calculation of the statistical moments (average, variance, skewness, and kurtosis) of the grain size frequency distribution.

### USDA Soil Taxonomy

The U. S. Department of Agriculture Soil Conservation Service (changed to Natural Resources Conservation Service in 1994), in its soil surveys, uses *Soil Taxonomy, A Basic System of Soil Classification for Making and Interpreting Soil Surveys* (Soil Survey Staff 1975). However, when describing the engineering behavior characteristics of soils in its county soil survey maps and publications, the USDA uses the USCS, one of the geotechnical engineering systems.

The basic agronomic soil mapping unit is the *soil series*, whose members have the same genesis and weathering profile. Series having similar but not identical characteristics are grouped into *families*. Similar families are grouped into *subgroups*, then into *great groups*, and then into *suborders*. The highest category of Soil Taxonomy is the *order*, of which ten have been defined.

Within each soil series, the *soil profile* is divided into soil horizons and layers within each horizon. The identifying characteristics of the soil of each horizon layer consist of: (a) texture, (b) structure, and (c) consistence. These correspond, roughly, to the soil’s engineering properties. Texture is a measure of material grain (grain size) properties, structure corresponds to the mass (density) properties, and consistence corresponds to the physical (strength) properties. These characteristics are described in Appendix A.

### Unified Soil Classification System

The Unified Soil Classification System (USCS) is used (a) primarily as a rating, or classification, of soils for use in a compacted airfield base course and for other forms of earthwork, and (b) for describing soil materials of gravel size and smaller. Soils whose dominant particle size is larger than 76 mm (3 inches) are not included. This excludes fragments of rock, shale, cemented soil, boulders, and cobbles. The USCS is the classification system of the geotechnical engineer, both because of formal training and because of required use within the geotechnical branches of the US Army Corps of Engineers and the Water and Power Resources Service. The USCS is described in Appendix A.

Soils are classified first according to grain size. Soils with more than 50 percent retained by weight on the U. S. Standard No. 200 screen (0.074 mm) are classified as coarse-grained: either

**Table 2-3**
**Grain-Size Limits of Textural Classification Systems**

| Group Name | Equivalent Spherical Diameter, mm (U. S. Standard Sieve Size) | | | | |
|---|---|---|---|---|---|
| | **Wentworth (1922)** | **ϕ[1]** | **USDA Soil Survey Staff (1975)[2,3]** | **USCS (ASTM 1994)** | **AASHTO (1988)** |
| Boulder | | | | | |
| Cobble | 256 (10 in.) | -8 | 250 (10 in.) | 300 (12 in.) | ----- |
| Coarse Gravel | 64 (2-1/2 in.) | -6 | 76 (3 in.) | 75 (3 in.) | 76 (3 in.) |
| Med. Gravel | 16 (5/8 in.) | -4 | ----- | ----- | ----- |
| Fine Gravel | 8 (5/16 in.) | -3 | ----- | 19 (3/4 in.) | ----- |
| Coarse Sand | 2 (No. 10) | -1 | 2.00 (No. 10)[3] | 4.76 (No. 4) | 2.00 (No. 10) |
| Medium Sand | 0.500 (No. 35) | +1 | 0.500 (No. 35) | 2.00 (No. 10) | 0.425 (No.40) |
| Fine Sand | 0.250 (No. 60) | +2 | 0.250 (No.60)[3] | 0.425 (No. 40) | ----- |
| Coarse Silt | 0.063(No. 230) | +4 | 0.050 (No. 270)[3] | 0.074 (No.200) | 0.074 (No.200) |
| Medium Silt | 0.031 | +5 | 0.020[3] | ----- | ----- |
| Fine Silt | 0.016 | +6 | ----- | ----- | ----- |
| Clay | 0.004 | +8 | 0.002 | (0.002)[4] | (0.002)[4] |

[1] Wentworth exponent: $\phi = -\log_2 D = -3.3219 \log_{10} D$ where D = grain diameter, mm.

[2] USDA does not use the term "boulders." Instead, the following definitions are used:

| | |
|---|---|
| Coarse Fragments | 2 to 250 mm (gravel and cobbles) |
| Stones (rounded) | 250 to 600 mm (10 to 24 in.) diameter |
| Stones (flat) | 150 to 380 mm (6 to 15 in.) length |
| Large Stones | > 75 mm (> 3 in.) |
| Small Stones | < 75 mm (> 3 in.) |

[3] USDA subdivides sand and silt sizes into seven categories:

| | |
|---|---|
| Very coarse sand | 2.0 - 1.0 mm |
| Coarse sand | 1.0 - 0.5 mm |
| Medium sand | 0.5 - 0.25 mm |
| Fine sand | 0.25 - 0.10 mm |
| Very fine sand | 0.10 - 0.05 mm |
| Coarse silt | 0.05 - 0.02 mm |
| Fine silt | 0.02 - 0.002 mm |

[4] Although not specified, this value is generally accepted among geotechnical engineers.

gravel or sand. Soils containing 50 percent or more fines (material passing the No. 200 screen) are fine-grained soils: either silt or clay. The fraction of a soil finer than the No. 40 screen is used for the plasticity tests: liquid limit (LL) and plastic limit (PL), and the plasticity index (PI) which is the numerical difference between the LL and the PL. Only two levels of plasticity are recognized: LL equal to 50 percent or less means low plasticity and LL greater than 50 percent is high plasticity.

### AASHTO Soil Classification System

The American Association of State Highway and Transportation Officials (AASHTO 1988) classification system for highway soils is also described in Appendix A. This is a rating system based on expected load-carrying capacity and serviceability of the soil when used in the construction of a highway base or subgrade. It is assumed in the classification that the soils will be suitably compacted in place. Because soils will be remolded prior to use, the system uses only soil material data (grain size and Atterberg limits) for classification. To a minor extent, it recognizes the relative difficulty of excavating, manipulating, and compacting each of the various soil groups. Granular soils are those having 35 percent or less finer than the No. 200 screen (0.074 mm). Among the silt-clay materials (more than 35 percent passing the No. 200), silty soils are those with a plasticity index of 10 or less; clayey soils have a plasticity index of 11 or more.

## Soil Exploration and Sampling for Baseline Investigation

Geophysical exploration is sometimes used to obtain a rapid overview of site variability or of water table depths. Samples of the soils are obtained from the surface, or from below the surface by means of borings or test pits. The properties of the soil material (grains, pore fluid, etc.) are determined by testing disturbed, or remolded, samples. Soil mass and physical behavior properties tests are made either on undisturbed samples in the laboratory or in the field using in situ test methods.

### Geophysical exploration methods

All geophysical exploration methods measure energy fields emanating from, or applied to, the soil profile. The resulting data can then be correlated with soil or rock stratification and certain physical properties of interest. Of the several techniques available, the induced field *seismic* and *electric resistivity* methods, conducted from the ground surface, have found the most practical application for geophysical studies on land (USACE 1984) and acoustic subbottom profiling is applicable for underwater explorations such as in dredging studies (Spigolon 1993).

There are several sources of professional literature available that discuss the application of geophysical methods to subsurface exploration. Two excellent resources, each with extensive references, are the Corps of Engineers' Engineer Manual EM 1110-1-1802, *Geophysical Exploration* (USACE 1979), and the AASHTO *Manual of Subsurface Investigations* (AASHTO 1988). Manufacturers of geophysical equipment are also sources of valuable information.

Geophysical methods are limited to measuring the *average* characteristics of large areas or volumes, whereas borings, test pits, or probings provide detailed information at an individual exploration point. Geophysical explorations are of greatest value when made early in the field exploration program, in combination with a limited number of borings for "ground truth" calibration. The cost of geophysical explorations is generally low compared with the cost of borings or test pits. The *limited* information about subsurface stratigraphy and lithology from the geophysical studies can then be applied to developing a more effective and efficient plan for establishing the locations of the more detailed borings.

## Soil sampling methods

Soil sampling methods feasible for use in a wetland subsurface investigation include devices for securing either (a) undisturbed or (b) disturbed, but representative samples. Several design variations of each of these are in common use for both soil science (plant-growth) and for geotechnical engineering purposes.

A truly *undisturbed* sample is one that maintains all of the in situ soil mass characteristics including shape, volume, pore structure and size, grain orientation and structure, and the in situ horizontal and vertical pressures. A *representative* sample, on the other hand, may be remolded slightly or completely, i.e., it contains all of the soil material, both solids and fluids, of its in situ state but does not maintain the structure, grain orientation, or in situ density.

Laboratory and/or field tests of the in situ soil's mass and physical behavior properties, i.e., density, permeability, and strength, require an *undisturbed* sample. Tests for material grain properties are made on a *disturbed* sample, but are dependent on the sample being fully *representative.* If all of the constituents of a sample are not present, then obviously any material identification tests of the sample will not represent the real character of the soil. There is no technical reason to select one representative sampling method over another provided the resulting sample is truly representative. Total sampling cost and possible coordination with a physical behavior testing method are the prime requirements.

Devices for obtaining *undisturbed* samples include (a) the thin-wall tube sampler, including piston samplers, used *only* for soft to stiff cohesive soils, and (b) the core barrel sampler, used *only* for very hard or cemented soils. Devices for securing *disturbed, but representative*, soil samples include (a) the thick-wall split-tube sampler, the best known of which is the Standard Penetration Test sampler, (b) the vibrating tube sampler, (c) the bucket auger sampler, and (d) the scoop sampler.

**Thin-wall tube samplers for cohesive soils.** A seamless metal circular tube, with a sharpened cutting edge and relatively thin wall thickness, may be forced into a soil to obtain an *undisturbed* sample. It is nearly impossible, using practical methods, to obtain a truly undisturbed tube sample of sands or other granular soils. The thickness of the sampler wall, the pushing force, and any sampling vibrations tend to cause volume changes in granular soils, disturbing their in situ structure and significantly changing their mass and behavior properties. Undisturbed thin-wall tube samples may only be obtained from soft to very stiff cohesive soils, primarily clays. Appreciable resistance to penetration by the tube in hard cohesive soils will cause the tubing to crumple.

Undisturbed sampling devices require careful technique for obtaining, sealing, shipping, unsealing, extruding, and testing. The sampling must be done from a stable platform and the tube must be inserted with a slow steady push without impact or vibration. A poorly sealed tube will allow drying of the sample in transit and in storage. Drying cracking may affect laboratory tests for permeability. Vibration or shock during transport can totally destroy the structure of loose silt samples. Care must also be exercised during sample extrusion and handling, particularly with soft or partially saturated samples.

**Core barrel samplers for hard soils.** Extremely hard soils are too hard for sampling by the direct insertion of a thin-wall metal tube. The *Denison sampler* (Hvorslev 1949) is similar to a double tube rock core barrel except that the inner, non-rotating tube projects beyond the outer, rotating tube. The amount of projection can be adjusted for the type of material being sampled. A similar device is the *Pitcher sampler* which differs from the Denison sampler only in that the pressure on the inner tube is spring controlled.

**Thick-wall split-tube drive sampler.** An impact driven, thick walled sampler is capable of penetrating and retaining a wide variety of soil types and strengths, and is usually used in a small diameter drilled hole. The resistance to penetration is used to indicate the shear strength of soils by rough correlation with the relative compactness of cohesionless soils or the relative consistency of cohesive soils. The best known of these devices is the split-tube drive sampler used in the Standard Penetration Test (SPT) as described in ASTM (1994) Method D 1586, shown in Figure 2-5.

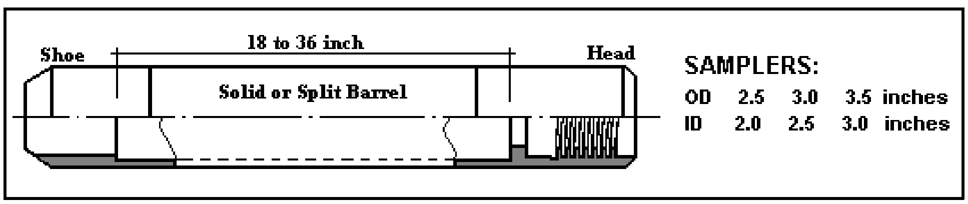

Figure 2-5. Cross-section of thick-wall tube sampler.

The sampler is typically fitted with a hardened steel drive shoe having the same outside diameter (OD) as the sampler, with an inside diameter (ID) 0.32 cm (0.125 in.) smaller than the barrel, or tube, ID. This permits the use of a thin metal sample liner inside the barrel, if desired. The maximum size of particle that can be sampled in a thick walled split barrel sampler is slightly smaller than the inside diameter of the drive shoe.

Although extremely useful as an exploration and sampling device, this sampler requires a stable drive platform, a heavy drop weight, and somewhat longer time to operate than several other sampler types. However, there is no requirement for a heavy (or any) weight as a reaction against pushing forces as in push-type penetrometers. Relatively untrained personnel can be taught to use the device in a short time.

**Vibrating tube samplers.** Vibrating tube corers (samplers) are capable of securing a sample without pre-boring or external casing. A continuous, lightweight metal tube is vibrated into the soil by an electrically operated vibrator situated at the top of the tube. No casing is needed for sampling below the water table or water surface.

The units are light enough to be manipulated by hand by one or two persons. The electric power unit is also lightweight, permitting the entire system to be operated from a small boat if needed. Tube lengths of 60 m (20 ft) and more are common. All soil types except very hard, dense, or cemented soils may be excavated and retrieved. These devices impart a sample disturbance to the soil whose magnitude depends on the type of soil, the effect of the vibration, the side friction in the tube, and the vertical stability of the tube during penetration. Although vibrating tube samplers are not capable of obtaining undisturbed samples, they do obtain a continuous representative sample.

There are several commercial manufacturers of vibrating tube sampling devices world wide. A typical vibrating tube sampler uses high frequency (7000 to 12000 vibrations per minute) and low amplitude vibrations applied to the drill string to shear the soils in the immediate vicinity of the cutting edge of the core barrel. This permits the typical device to enter unconsolidated granular and cohesive deposits at rates up to 1.5 m (5 ft) per minute. One commercial design uses lightweight equipment, having a 39-kg (85 lb) engine, an 11-kg (25 lb) drive head, and lightweight tubes of 85-mm and 135-mm (3.35- and 5.31-in.) diameter, and is portable and operable by a two-person crew.

**Bucket auger samplers.** A bucket auger consists of a fairly short metal tube, open at the top and connected to a drill rod. The partially closed bottom is provided with an open cutting edge for drilling and for retaining the excavated, highly disturbed sediment sample. The bucket is used both to advance the hole and to obtain a soil sample. The bucket is removed from the drill hole each time it is filled or if a sample is required.

Bucket sizes can vary from 5 cm to over 60 cm (2-3 in. to more than 24 in.) in diameter. A small diameter bucket auger, as shown in Figure 2-6, may be operated by hand; larger diameter buckets require machine rotation and handling in and out of the bore hole.

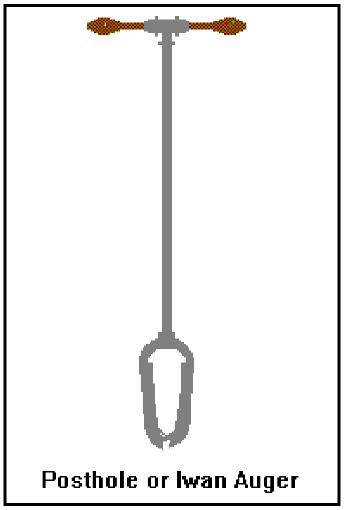


Figure 2-6. Hand-operated bucket auger.

Bucket sampling is applicable to all soil types. Large opening bucket samplers must be used when sampling soils containing cobbles or boulders or other large objects. Soils must be capable of being easily cut with the cutting edge of the bucket.

**Scoop samplers.** All samplers used in bore holes are limited in the size of particle that can be retrieved by the end opening of the sampler and the size of the bore hole. As a result, vegetation, debris, boulders, cobbles, coarse gravel, and rock fragments can sometimes only be sampled with a large-size, powered scoop sampler, or manually by a person, in a pit or trench. The simplest scoop is a manually operated shovel or a hand-held scooper such as a spoon or trowel. Powered scoop samplers are production-size, mechanical excavation (scooping or digging) machines such as (a) power shovel, (b) backhoe, (c) clamshell (grab). A small, tractor-mounted backhoe is the most available, popular, and useful of the powered scoops. Small backhoes can dig pits up to about 12-14 ft deep. Care must be taken to insure that the sides of the pit will not collapse on a person working at the bottom.

## Boring methods

Sampling of soils may be done at the soil surface or below the surface. If soil sampling is to be done below the surface, some method must be used to access, or reach, the sampling and/or testing depth. This may be accomplished by (a) excavating, or boring, a small diameter hole to the appropriate depth, or (b) digging an access pit.

Borings for sampling and/or field testing can be made without the use of heavy excavation equipment, although some boring methods require heavy, machine mounted equipment. Because of the shallow depths explored for the initial site exploration at wetland sites, virtually all borings are made by mechanical augering. A bucket auger or a continuous flight (spiral) auger is used to advance the hole and remove the cuttings. Small diameter units can usually be operated manually to depths of up to 30 or so feet. Larger diameter units, or deeper holes, or faster operations, require a drilling machine with a mast.

**Bucket auger.** A sampling bucket, Figure 2-6, with a cutting edge on the bottom, may be used to both advance the hole and obtain a soil sample. The bucket is attached to the bottom end of a drill rod and the system is rotated into the soil. The bucket is removed from the drill hole each time it is filled or if a sample is required. Bucket sizes are typically from 2 to 4 in. or even larger in diameter. Representative (disturbed) samples of the entire vertical reach of the boring are possible, even from under water, if the hole does not collapse. Sands sampled from under water may wash out of the bucket during removal. Casing may be required if the hole has a tendency to collapse, particularly for sands below the water table. The diameter of the bucket must be smaller than the inside of the casing.

A small diameter bucket auger may be operated by hand; larger diameter buckets require machine rotation and handling in and out of the bore hole. Boring depths are limited by the capability to handle the drill pipe into and out of the bore hole. Drill rod lengths up to 10 m (30 ft), with a small bucket, can be handled by a two-man crew, by hand, without a derrick. Bucket auger boring is applicable to all soil types except for those containing very coarse gravels, cobbles, or boulders. Soils must be capable of being easily cut with the cutting edge of the bucket, i.e., soft or loose soils.

**Continuous flight auger.** A continuous flight auger may be hand- or machine-rotated into the soil. The auger is withdrawn periodically for removal of cuttings or the cuttings will return to the surface on the auger flights without withdrawal. Samples taken from the auger flights after a very short insertion are similar to bucket auger samples and may be representative. Samples taken from the auger cuttings as they return to the surface tend to be segregated and non-representative. The auger must be withdrawn for sampling or in situ testing.

Continuous flight augers, Figure 2-7, are applicable to all soil types except for those containing very coarse gravels, cobbles, or boulders. Uncased holes in soft clays and clean granular materials below water tend to collapse on withdrawal of the auger because of groundwater pressure. Hole advancement is typically very fast when the auger is power driven, although hand-held power-driven units are portable and quite fast when operated by a two-person crew.

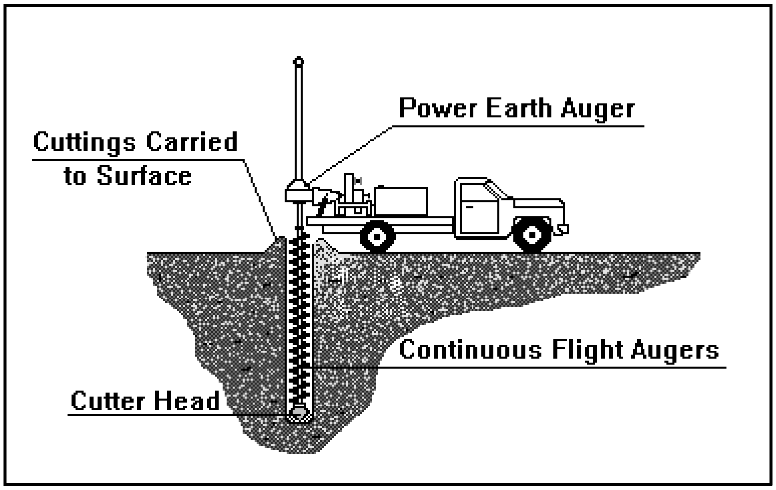


Figure 2-7. Truck-mounted continuous flight auger.

### Pits and trenches

A dug pit or trench is the most useful of all initial subsurface exploration methods. The entire soil profile can be exposed on the vertical side wall. This permits visual identification and thickness measurement of the soil horizons and of pans. Representative samples can be taken from the side walls at any desired level and of any reasonable size. Undisturbed samples can be obtained either as clods or as hand-trimmed samples from the side walls (USACE 1971). All samples should be sealed to prevent drying during transit to the laboratory.

Some sediments, such as coarse gravel, cobbles, boulders, shells, and debris, cannot be sampled effectively using the usual boring and sampling methods. When underwater sampling is required, without the ability to view the soil profile, a test pit or trench is then the only way of obtaining a representative sample of these materials.

Test pits and trenches are usually made with mechanical equipment such as clamshell (grab), dragline, or backhoe machines. The pit is dug to the sampling or testing depth. Sampling or testing is then done at the surface or sides of the pit. Because the excavation machinery disturbs the soil around its cutting edge and bucket sides, it is desirable that the last few centimeters (inches) of excavation be done by hand or by boring before undisturbed sampling or testing is done.

## Tests for Wetland Soil Attributes

Each of the wetland soil attributes described earlier in this chapter can be identified by means of a formal, well defined, test procedure. In many of the identification tests, the outcome of the test is directly affected by the specifics of the test procedure. For this reason, most of the test methods have been standardized. In field situations, where time and climate control do not permit laboratory-style tests, field expedient tests are available that give reasonable estimates of the results of the more formal tests. Mass properties tests must be done on undisturbed soil, either on an undisturbed sample or the undisturbed soil in the field, i.e., in situ. Summary descriptions of all appropriate soil tests, including definitions and test methods, are contained in Appendix B.

## Standard soil attribute tests

The primary source of standard soil-science test methods for USDA Soil Conservation Service is the *Soil Survey Laboratory Methods Manual* (Soil Survey Staff 1992). Other good sources of testing information, consisting of summaries of test methods, are contained in the USDA-SCS *National Soil Survey Handbook, Part 618* (Soil Survey Staff 1993) and in *Soil Sampling and Methods of Analysis*, a publication of the Canadian Society of Soil Science (1993). Other sources include various textbooks on the subject of soil testing for agronomy.

The main standardizing agency for engineering soil tests in the U. S., and in some of the rest of the world, is the American Society for Testing and Materials (ASTM 1994). Other, similar agencies exist in some European and Asiatic countries. The U. S. Army Corps of Engineers maintains a manual of soil test procedures (USACE 1970) that are similar in almost all respects to their ASTM counterparts.

## Field expedient soil identification tests

Because many of the formal laboratory tests require a laboratory environment, skilled technicians, and considerable time, a number of field-expedient visual-manual test methods have been developed to provide reasonably close, useful approximations to the results of the more formal tests. Both the USDA *Soil Taxonomy* and the USCS (ASTM D 2488, 1994; USACE 1971) describe field expedient tests that are made using visual-manual methods for determining the soil name and classification. The two systems, although using different names, use similar field expedient tests. The results of the field expedient tests are used to group similar samples and, thereby, to reduce the number of more expensive laboratory identification tests that should be made.

## Field tests of mass and behavior properties

The properties of the soil mass and the soil's potential behavior that may be determined by test during the baseline site investigation of a wetland include:

a. Density

b. Permeability

c. Suction (capillarity)

Procedures for making these tests in the laboratory and/or in the field are given in Appendix B. The field tests tend to be expensive in time and cost and are, therefore, often estimated by correlation with less expensive index properties tests.

## Correlations of soil properties

Soil properties will vary considerably over a fairly wide area. From mathematical statistics, it can be shown that any given property of a homogeneous soil deposit can be characterized by its average and variance. Furthermore, for estimates of the average and variance, a large number of low precision (high variance), inexpensive tests can be equivalent to a small number of highly precise, expensive tests. For that reason, simple indicator, or index properties, tests of soils have been used extensively to indicate the results of costly, time consuming, and complex tests. Many of the standard textbooks of soil science and of geotechnical engineering contain some correlation test relationships. The reader is referred to textbooks and other pertinent publications for specifics of the correlations. A highly useful reference source for pedologic soil behavior properties is the *National Soil Survey Handbook* (Soil Survey Staff 1993). Two excellent engineering reference sources are (a) U. S. Army Technical Manual TM 5-818-1, *Soils and Geology*, (USACE 1983), and (b) *Design Manual DM 7.1* (Department of the Navy 1982).

**Erodibility.** Erodibility is defined as the ease with which particles, or aggregations of particles, can be excavated, or removed, from their in situ position and condition with a fluid, water or air, flowing across (erosion by cavitation) or against (erosion by impingement) the surface. The surface erosion of a soil deposit depends on a number of interrelated factors whose properties are used in empirical methods for estimating the potential for water or wind erosion. These factors include: texture, organic matter content, stability of the soil aggregate, calcium carbonate reaction, rock fragments content, subsoil permeability, and depth to a pan.

**Permeability.** Fairly good correlations have been established between the permeability of granular soils and the results of grain size distribution tests. These are described in Design Manual DM 7.1 (Department of the Navy 1982). Several geotechnical engineering textbooks contain a tabulation, such as the one shown in Table 2-4, of typical permeability values for various soil types. These broad characterizations of permeability values are often sufficient for preliminary and even general design use.

**Shear strength.** Correlations have been published in textbooks and other literature for the strength properties of cohesive soils. These include correlations between (a) sensitivity and liquidity index, (b) shear strength of remolded clays and liquidity index, (c) the ratio of undrained shear strength to effective overburden pressure as a function of plasticity index or of liquidity index, and (d) angle of shearing resistance with plasticity index. The source references given above should be consulted for these correlations.

Correlations for the shear strength of granular soils have been published between (a) angle of shearing resistance and Standard Penetration Test blow count, (b) angle of shearing resistance and relative density, and (c) coefficient of earth pressure and angle of shearing resistance. The source references given above should be also consulted for these correlations. Other useful correlations, which have been established for local soil deposits, may exist only in local files.

**Compressibility.** Because of the lengthy time and high cost of laboratory consolidation tests of cohesive soils, a number of useful correlations have been established between the compression index and either liquid limit, initial void ratio, or initial water content. Correlations have been established between the coefficient of consolidation and the liquid limit. The settlement of granular soils under a footing load has been correlated with Standard Penetration Test results. The correlations may be found in geotechnical engineering textbooks.

**Table 2-4**
**Permeability Coefficients for Various Soils (after Peck, Hanson, and Thornburn 1974)**

| Soil Type | Permeability, k | | Drainage |
|---|---|---|---|
| | cm/sec | in/hr | |
| Clean gravels | $10^{2}$ | $1.42 \times 10^{5}$ | Good |
| | $10^{1}$ | $1.42 \times 10^{4}$ | |
| Clean sands | 1 | $1.42 \times 10^{3}$ | |
| | $10^{-1}$ | $1.42 \times 10^{2}$ | |
| Clean sand and gravel mixtures | $10^{-2}$ | $1.42 \times 10^{1}$ | |
| | $10^{-3}$ | 1.42 | |
| Very fine sands | $10^{-4}$ | $1.42 \times 10^{-1}$ | |
| Organic and inorganic silts, mixtures of sand, silt, and clay, glacial till, stratified clay deposits. | $10^{-5}$ | $1.42 \times 10^{-2}$ | Poor |
| | $10^{-6}$ | $1.42 \times 10^{-3}$ | |
| Impervious soils, for example, homogeneous clays below the zone of weathering. | $10^{-7}$ | $1.42 \times 10^{-4}$ | Practically impervious. |
| | $10^{-8}$ | $1.42 \times 10^{-5}$ | |
| | $10^{-9}$ | $1.42 \times 10^{-6}$ | |

# Detailed Subsurface Investigations

The remainder of this chapter discusses subsurface investigations for the structural and earthwork aspects of a wetland project. Included is guidance for selecting the number and depth of borings or pits. Although the principles remain the same as those for making the baseline subsurface investigation, the scope of a *detailed, or specific,* subsurface investigation for assessing the geotechnical engineering character of the soils requires sampling methods and soil tests more suited to earthwork problems, especially shear strength determinations.

## Significant soil properties

The emphasis in the detailed site investigation for earthwork is on the physical behavior properties of the soils rather than the plant-growth properties. Typical concerns in earthwork involve the physical behavior of excavation sites, the transport roadway, the compaction of soils in dikes or in subgrade sealing, and the depth to the water table.

The main soil characteristics to be determined in the detailed subsurface investigation of structure and earthwork sites are:

*a.* *Stratification.* For stratification, determine the elevation and thickness of the A-, E-, B-horizons, the nature of the C-horizon, and the depth of the water table. See Figure 2-4 for definitions of the soil profile horizons. Reasonably accurate volumes (area and thickness) of the various soil types to be moved are essential for planning cut and fill operations.

*b.* *Grain properties.* The soil material, or grain properties, of significance are texture (grain size distribution), Atterberg limits, organic content, and water content. The soil grain properties are useful for soil identification and as index properties, or indicators, for correlation with the physical behavior properties. They are used to reduce the need for the more complex and expensive physical behavior properties tests.

*c.* *Mass and behavior properties.* Density, permeability, relative consistency (cohesive soils only), relative density (clean granular soils only), compressibility, and erodibility are the mass and behavior properties of interest. Soil strength is a major factor in the diggability during excavation and of trafficability in the borrow area and the transport roadway. Compressibility of the foundation must be known for establishing constructed dike heights. The strength and permeability of compacted soil are needed for designing dikes and for subgrade sealing.

### Scope of detailed subsurface investigation

There are no standard requirements or methods for a subsurface investigation for borrow pits, roadways, or dike and levee sites. Each subsurface investigation must be adapted to the geomorphic environment, locally available equipment and personnel, personal experiences with local soils, and to time and budget constraints.

**Depth of investigation.** Earthwork will involve any or all of the areas at a wetland site that will be used for: (a) excavation, (b) soil transport roadway, or (c) deposition, either as areal fill or as a dike. The needed depth of exploration sampling and testing will vary with the type of site.

*a*. *Excavation sites.* The boring, test pit, or probing depth should extend at least one or more meters (few feet) below the maximum expected depth of excavation at each site. In addition to providing excavatability information, the borings may indicate the presence of a water table that can affect the excavation equipment.

*b.* *Roadways.* Trafficability studies are generally shallow unless a roadway is to be a permanent feature of the wetland and there is a need for road cuts or fill. Borings will rarely need to extend more than one or two meters (up to five feet or so).

*c.* *Deposition sites.* Unless an *areal fill* is more than a meter or so (a few feet) thick and the underlying strata are highly compressible, there is little need to extend the borings under such a wide fill more than one or two fill thicknesses. For *dikes or similar structural loads*, the rule of thumb is to extend borings to a depth where the net increase in soil stress under the weight of the structure is less than 10% of the average load of the structure. Since dikes generally have a triangular shape, the total cross-sectional load of a dike with reasonably expected side slopes can be converted to an equivalent rectangular, footing-like section of uniform loading. Then, using the 2:1 rule of thumb for a long footing, the depth of exploration should be about three times the equivalent uniformly loaded "footing" width of the dike. This will tend to equal about two times the actual base width of the dike.

**Number and location of borings.** AASHTO (1988), Sowers (1979), and Teng (1962) have provided guidelines for investigation site spacings for highway subgrade, earth dike or embankment, and borrow pit explorations, as shown in Table 2-5. These should be taken as initial guidance only, as a starting point for consideration, and then modified to fit the specific wetland project resources, priorities, and needs.

**Table 2-5**
**Guidance on Spacing of Borings for Earthwork**

| Specific Project | Horizontal Stratification | Suggested Spacing of Borings, meters (feet) | | |
|---|---|---|---|---|
| | | AASHTO (1988) | Sowers (1979) | Teng (1962) |
| Borrow pit (Excavation site) | Uniform | 60 (200) | 60-240 (200-800) | 150-300 (500-1000) |
| | Average | 30 (100) | 30-120 (100-400) | 60-150 (200-500) |
| | Erratic | --- | 15-60 (50-200) | 15-30 (50-100) |
| Highway subgrade (Construction roadway) | Uniform | 300 (1000) | 120-1200 (400-4000) | 300 (1000) |
| | Average | 60-90 (200-300) | 60-600 (200-2000) | 150 (500) |
| | Erratic | 30-60 (100-200) | 30-300 (100-1000) | 30 (100) |
| Embankment or Dike | Uniform | --- | 30-120 (100-400) | --- |
| | Average | 60 (200) | 15-60 (50-200) | --- |
| | Erratic | 30 (100) | 7.5-30 (25-100) | --- |

## Geotechnical exploration and test methods

Many of the exploration methods, sampling methods, and test procedures for determining the plant-growth characteristics of the near surface soils, described earlier in this chapter are also applicable to the needs of the detailed subsurface investigation for earthwork. Appendix C, Strength Tests of Soils, contains a discussion of those field strength testing methods and equipment that were *not included* in the earlier discussion and in Appendix B and that are particularly applicable to the soil handling and structure phase of a wetland project. The in situ shear strength of wetland soil affects the choice of excavation equipment, the energy needed for excavation of the material, and the stability of the foundation of a retaining dike. It is also a factor in determining trafficability in the borrow area and on the transport roadway.

Unlike structural foundation engineering, where soil strength must be accurately and precisely known, the strength of a soil to be excavated does not need to be determined with high precision. At the present state of the art, it is generally sufficient to categorize the strength of a soil in broad groups. It suffices, therefore, to define strength in terms of the relative compactness (loose to dense) of cohesionless soils, the consistency (very soft to very stiff) of clayey soils, and the relative hardness of cemented soils.

After the soil is removed from its original location, the in situ structure is disturbed and the original in situ strength is no longer available. The disturbed soil may then be used in a fill. The required shear strength of the compacted soil in a dike, which determines the placement method, water content, and compactive effort, is governed by the slopes used in the embankment (or vice-versa). Soil compaction is discussed in Section 7-8.

# Costs for Subsurface Investigation and Soil Testing

## Geotechnical subsurface investigation costs

The cost of a subsurface investigation can vary widely, depending on many factors. The equipment may be transported to any given exploration site, i.e., boring or pit, (a) on land-based equipment, either trucks or all-terrain vehicles, (b) on boats or small barges, and/or (c) hand carried or back-packed.

Drilling, sampling, and/or field testing on land can be very rapid if special machine-operated test drilling rigs are used. Wash boring or even hand auger boring is slower and the usual lack of an engine causes the use of slower hand labor. The cost of labor versus the cost of machines to do the same work, if time is not a factor, is usually the deciding factor. Commercial drill rigs and crews often must be mobilized from a central office at some distance from the project site at an hourly and mileage cost.

Test borings on water are more complicated than those made on land. If a drilling rig is to be used and the water surface is undulating, it may be necessary to use a spud barge with legs extending to the soft bottom of the pond, lake, or watercourse. Cone penetration in hard soils requires a heavy reaction load on the boat or barge. Vibrating tube corers have been successfully used to obtain samples by a two-person crew over the side of a small boat, but no strength information is obtained.

Table 2-6 has been assembled as an example for budgeting purposes, showing typical costs (1994 prices) for subsurface exploration services by a typical commercial drilling firm. Actual prices may vary somewhat from those shown, especially in various parts of the U.S. and if operating conditions are worse than anticipated in the pricing structure shown. Table 2-6 is intended only for budgeting purposes and does not represent a quotation or offer to do exploration work by the U. S. Army Corps of Engineers or by another person or firm associated with this handbook.

**Table 2-6**
**Typical Costs for Subsurface Exploration**

| Service | Typical Cost (1994 Prices) |
|---|---|
| Machine Drilling on Land | |
| Mobilization of drill rig, support vehicle, and person crew from office to project site and return. | $30 - 50 per hour + $0.47 - 0.78 per km. ($0.75 - 1.25 per mi.) |
| For drill rig and crew -- site preparation, long distance or delayed movement of drill rig on site, standby, and/or site cleanup. | $100 - 150 per hour. |
| Test borings, SPT at 0.75 m. (2.5 ft) intervals to 5 m. (15 ft). | $39 - 52 per meter ($12 -16 per foot). |
| Test borings, SPT at 1.5 m. (5 ft) intervals to 15 m. (50 ft). | $33 - 46 per meter ($10 -14 per foot). |
| Shelby tube (undisturbed samples), 7.6 cm. x 76 cm. (3 in. x 30 in.), as a substitute for an SPT sample | $12 - 15 each |
| Shelby tube (undisturbed samples), 7.6 cm. x 76 cm. (3 in. x 30 in.), in addition to an SPT sample. | $22 - 25 each |

## Costs for laboratory tests of soils

Many, if not all, soil samples taken in the initial site investigation will be tested for the wetland soil tests described in Appendix B. As an example of costs for use by the site investigation planners, the 1994 price range for some laboratory soil tests is given in Table 2-7. These prices are for test samples delivered to a private commercial soils (engineering and/or agricultural) testing laboratory and do not include the cost of securing the sample, transporting it to the laboratory, or temporary storage. Samples delivered to a commercial testing laboratory for soil testing are usually priced on a *per-test* basis. These costs will vary over the U.S. as the wages of the local testing technicians vary. Table 2-7 is intended only for budgeting purposes and does not represent a quotation or offer to do testing work by the U. S. Army Corps of Engineers or by another person or firm associated with this handbook.

**Table 2-7**
**Typical Costs for Laboratory Tests of Soils**

| Soil Property | Typical Cost (1994 Prices) |
|---|---|
| Cation exchange capacity (CEC) | \$15.00 to \$40.00 ea. |
| Elemental analyses -- B, Ca, Cu, Fe, Mg, Mn, Na, K, P, Zn | \$6.00 to \$12.00 ea. |
| Heavy metals -- Cd, Cr, Ni, Pb | \$15.00 to \$30.00 ea. |
| Linear extensibility (volume change) | \$50.00 to \$100.00 ea. |
| Moisture content (water content) | \$10.00 to \$15.00 ea. |
| Total Kjeldahl Nitrogen | \$20.00 to \$40.00 ea. |
| Organic matter | \$5.00 to \$15.00 ea. |
| Particle density (specific gravity of grains) | \$50.00 to \$75.00 ea. |
| Particle size (sieve analysis of coarse grains only) | \$40.00 to \$60.00 ea. |
| Particle size (silt and clay percent, using hydrometer). | \$80.00 to \$100.00 ea. |
| pH | \$5.00 to \$40.00 ea. |
| Plasticity (Atterberg limits, LL, PL) | \$75.00 to \$100.00 both |
| Total phosphorus | \$10.00 to \$20.00 ea. |
| Total sulfur | \$10.00 to \$20.00 ea. |

# 2-4 Determining Existing Hydrologic Conditions[1]

Existing hydrologic conditions must be carefully evaluated to determine if the site hydrology can support a functional wetland that satisfies the project objective and, if so, to support the development of a viable wetland design. If the site hydrology is not conducive to wetland development, the site should be eliminated from further design consideration unless it is specifically designated to become a wetland site. The hydrology of unsuitable areas can be augmented by importing water from nearby areas to support wetland establishment. Such methods are expensive and do not lend themselves to the long-term evolution of a wetland system. Thus, they are applicable to only a small number of projects.

A carefully planned and executed hydrologic assessment must be undertaken to quantify the temporal and spatial distribution of water at any site under consideration for wetland restoration or creation. The site assessment must consider surface water sources such as perennial streams, tidal influences, direct precipitation, rainfall runoff, and snowmelt and groundwater sources such as natural springs, interflow, and phreatic aquifers. Hydrologic site assessments must also consider potential losses of water such as infiltration, evaporation, transpiration, and seepage. Additionally, the site assessment must gather information on the watershed and its physical characteristics that may influence the impact flood flows, erosional forces (winds and waves), and water velocities on the wetland system.

This chapter describes the data that must be collected during the site assessment for specific design purposes and the available data collection methods. A brief description of the hydrologic cycle and water balances is provided for those unfamiliar with the terminology related to hydrologic investigations. The chapter discusses the requirements for initial hydrologic investigations and those for performing pre-design hydrologic analyses. Common sources and sinks of water in wetland systems are also discussed in this chapter.

## Hydrologic Cycle

The hydrologic cycle provides a convenient conceptual model (Figure 2-8) to identify the sources, sinks, storage, and exchange of water in the environment (Bedient and Huber 1992). Although this conceptual model is typically applied on a global or continental scale, it can be used productively in the planning and design of smaller scale projects such as a wetland site. The hydrological cycle for a wetland system consists primarily of precipitation, infiltration,

[1] By Lisa C. Roig

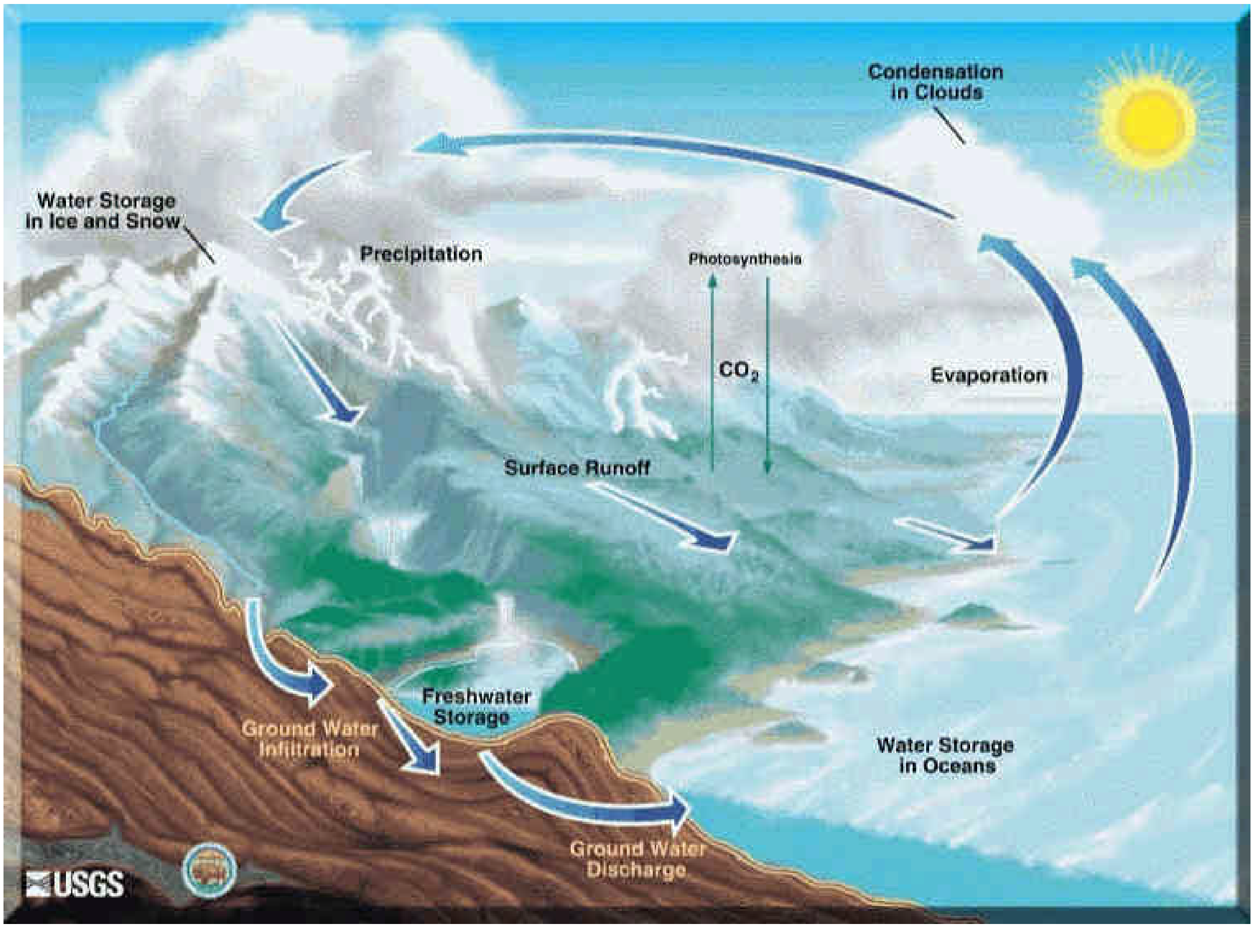


Figure 2-8. Conceptual depiction of the hydrologic cycle including water sources and sinks (United States Geological Survey).

evapotranspiration, groundwater flow, and surface runoff that occur within specified boundaries of the site.

*Precipitation* in the form of rain, snow, hail, sleet, fog, or dew deposits water on the wetland surface and throughout the watershed. Precipitation which falls directly on the wetland surface, commonly referred to as direct precipitation, contributes directly to the water storage in the wetland. Much of the precipitation which falls over the watershed may eventually make its way into the wetland, but will be subjected to various losses such as infiltration, evaporation, transpiration, and diversion prior to its arrival. Each of these factors represents potential losses and reduces the amount of water available to the wetland itself.

*Infiltration* is water that is exchanged between the surface and the subsurface. During a rain storm water seeps into the soil at a rate that is a function of the soil composition, the soil stratigraphy, the antecedent moisture conditions, and the rainfall rate. Infiltration is normally treated as a vertical process and therefore will not be a significant mechanism of water exchange through the lateral boundaries of the wetland. Infiltration does become significant when analyzing the dynamic distribution of water within the wetland. Empirical relationships to compute infiltration losses are available in the standard hydrology texts, and will be discussed later in this chapter. Seepage is related to infiltration, and it is used to mean the loss of water from a body of surface water to the groundwater. Seepage from lakes, reservoirs, and streams may be estimated when long-term streamflow records are available for the drainage basin. The seepage rate is calculated as the difference between the inflow and the outflow minus the change in storage and minus evapotranspiration and other losses.

*Groundwater discharge* (negative seepage) can also occur when the water table intersects the land surface. In these cases, groundwater can contribute significantly to the overall water budget for the wetland. In some cases, groundwater discharge may be the primary water source into the wetland.

Water is exchanged from the earth's surface to the atmosphere by means of *evaporation*. *Transpiration* is the process by which plants release water through their leaves to the atmosphere. Collectively these two exchange mechanisms are called *evapotranspiration* and are often lumped for the purpose of hydrologic analysis. Water that is evaporated or transpired from the earth's surface and from plant losses eventually condenses into clouds which may then develop into rain drops or snow flakes. Evapotranspiration is usually identified as a loss (or sink) of water from a wetland site, because it is unlikely that the water evaporated from the wetland site will be re-deposited on the same site. Evapotranspiration can be measured from field observations, calculated according to empirical formulas, or calculated by difference.

Water that is stored in the pores of subsurface geologic deposits (or strata) is called *groundwater*. Groundwater flows through the water bearing strata in the direction of decreasing pressure. When the water bearing deposit is near the surface and is not overlain by a less porous confining layer the aquifer is said to be unconfined. The interface between the saturated and the unsaturated zones of an unconfined aquifer is called the piezometric surface or water table. Wetlands frequently occur in areas where the water table intersects the land surface. In this case the entire soil column remains saturated and infiltration is inhibited. Groundwater may contribute to the surface flow by a reverse seepage process when the subsurface pressure gradient is favorable for flow into the wetland. Groundwater storage and transport must be accounted for in the wetland hydrologic analysis.

*Surface runoff* is the precipitation which is not lost to evaporation, transpiration, infiltration, or in depressions prior to reaching a stream channel or the wetland itself. Consequently, surface runoff is often referred to as excess precipitation. Surface runoff may reach the wetland as overland flow from surrounding areas or via a stream flowing directly into the wetland.

Tidal cycles can influence the hydrology of wetlands located in tidal zones dramatically. Incoming tides can provide a strong inflow of water into the wetland which is evacuated during the outgoing tide. These tidal cycles result in specific wetland characteristics associated with only tidal wetlands.

## Water Balances

One meaningful way to organize hydrologic data is by accounting for all water sources and sinks within a defined site. The process of accounting for these water sources and sinks is commonly referred to as a water balance or water budget. A water balance is a systematic method for quantifying the hydrologic components that influence a specified drainage unit. A water balance includes all of the major sources and sinks of water within the hydrologic boundaries of the system. The general water balance equation has been written in many forms, all of which are essentially the same. One such equation was presented by Fischenich et al. (1995):

$$\Delta S = (P + I_r + I_s + I_f + G_i + T_i + P_i) - (E + T + O_s + O_f + O_i + G_o + T_o + P_o) \tag{2-2}$$

where

$\Delta S$ = *change in water storage in the wetlands impoundment,* $m^3$
$P$ = *direct precipitation on the wetland impoundment,* $m^3$
$I_r$ = *runoff through overland flow into the wetland,* $m^3$
$I_s$ = *streamflow directly into the wetland,* $m^3$
$I_f$ = *inflow from adjacent stream flooding,* $m^3$
$G_i$ = *wetland inflow from groundwater,* $m^3$
$T_i$ = *tidal inflows,* $m^3$
$P_i$ = *inflow from pumping, diversions, or other artificial water source,* $m^3$
$E$ = *evaporation from the wetland surface,* $m^3$
$T$ = *transpiration,* $m^3$
$O_s$ = *outflow from streams leaving the wetland,* $m^3$
$O_f$ = *overland outflow due to wetland flooding,* $m^3$
$G_o$ = *groundwater percolation below the root zone,* $m^3$
$T_o$ = *tidal outflows,* $m^3$
$P_o$ = *outflows from pumping, diversions, or other artificial sinks,* $m^3$

A water balance is a useful tool for identifying water supply problems, identifying preliminary design opportunities, and assessing impacts of proposed engineering measures. A water balance can also be used to estimate the magnitude of unknown hydrologic components such as groundwater flow and infiltration losses. The Hydrologic Engineering Center (1980) has published a guide for the preparation of water balances.

Collecting all the data necessary to perform a complete water balance is not possible. Only the data necessary to support decisions that must be made at specific points in the design process must be available. Since these decisions become increasingly complex, investigations of the hydrologic conditions and analyses of the hydrologic data typically continue throughout the design phase. Representative data requirements for various types of hydrologic analyses are given in Table 5-2. It is very rare that all of the required data are available to perform the analyses. Thus, in some cases, values must be estimated or modeling techniques must be used to span data gaps resulting from incomplete records. The lack of appropriate data, however, increases the uncertainty associated with the hydrologic analysis. When there are not sufficient data to satisfy design requirements within an acceptable level of uncertainty, a pre-design monitoring program must be established to obtain the quality and amount of data necessary. Establishing such a monitoring program requires a substantial investment of time and effort and is seldom inexpensive.

## Conducting Hydrologic Investigations

An initial inventory of the site hydrology should be conducted during the initial site screening phase to determine if the site can potentially support a wetland system. This inventory can often be based upon a review of existing historic precipitation, streamflow, and groundwater data.

However, a site visit is necessary to verify existing conditions including sources and sinks of water. If the initial assessment suggests that the site could support a range of low cost, low impact designs, then the site likely warrants consideration beyond the initial site screening. However, if the hydrologic conditions are inadequate or elaborate engineering measures will be required to achieve desirable hydrologic conditions, the site should likely be eliminated in favor of other sites with more favorable hydrologic conditions.

The type of hydrologic information needed to support detailed design activities is a function of the dominant hydrology of wetlands (see Figure 2-9). Wetlands with a dominant or potentially dominant runoff component will require a careful analysis of the watershed and climatic conditions that influence rainfall and runoff patterns. In most cases, storm frequency and duration curves for the site will be necessary. Such curves can be developed from historical climate records or may be available from a local government agency. Historic streamflow records should be examined if available. Where no data exist, a pre-design monitoring program for surface water resources is recommended. A rainfall-runoff analysis for the existing site may be required to determine the runoff generation characteristics for a particular storm event.

**Detailed Hydrologic Site Analysis**

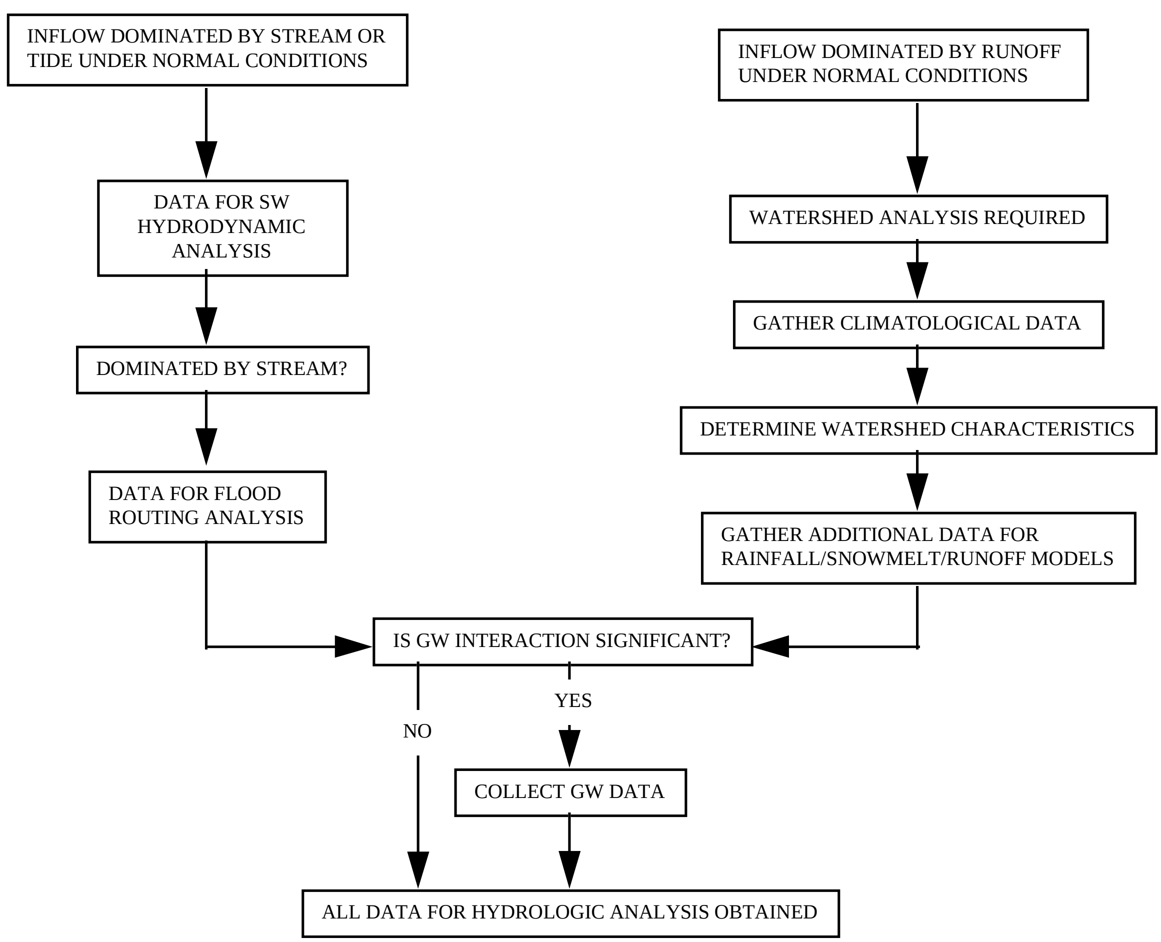


Figure 2-9. Data required to support various site analyses based upon site characteristics.

Wetlands dominated by streamflow or tidal flow will likely require a careful analysis of water flow patterns within the wetland itself to determine erosion potential and depositional patterns. Additionally, wetlands with a significant streamflow must consider the flooding potential from upstream flows and the impact of those floods on the wetland system.

Many design criteria for wetland restoration and creation relate specifically to the abundance and distribution of wetland surface flows. Such design criteria include the specification of the depth and the duration of inundation events, the specification of a minimum flood wave attenuation, or the specification of a maximum flushing period. Surface flows can be quantified by means of stream gauges, aerial surveys, and hydrometric surveys. Nonetheless, sufficient data are often not available to complete a thorough hydrologic analysis. A full year of stream gauge records both upstream and downstream of the wetland site is desirable for pre-design analysis. When such records are unavailable, several short-term hydrometric surveys must be conducted to characterize the surface water system. Hydrometric surveys should include discharge measurements at all inflow and outflow locations and an aerial survey of surface water resources including basin bathymetry and water surface elevations. The distribution of surface water in any wetland varies by season and by event. Therefore, a single hydrometric survey is insufficient to characterize the surface water resources of a proposed wetland site. Multiple surveys spanning at least a 1-year period are recommended over an annual period.

A thorough analysis of the existing hydrologic conditions at the site is needed for the design of flow control structures, water retaining structures, and other engineering works. A critical decision regarding the boundaries of the hydrologic analysis must be made early in the site investigation. Unfortunately, legal boundaries rarely coincide with the hydrologic boundaries of the drainage unit to which the proposed wetland belongs. Meaningful data about the sources, sinks, storage, and exchange of water are normally collected for the drainage unit or watershed as a whole. Consequently, it may be necessary to extend the analysis beyond the legal boundaries.

## Sources of Historic Hydrologic Data

Quantification of the water budget components is vital to any project involving water use or water planning. Thus, historic records of these components are maintained by a variety of local, state, and Federal agencies. Hydrologic records that are of value for wetland design include precipitation, wind, temperature, streamflows, lake levels, and river stages. Streamflow data are collected by various state and Federal agencies, including the USGS, Corps of Engineers, state water resources agencies, irrigation districts, and municipalities. The USGS serves as a clearinghouse for data from most of these sources, and the annual streamflow records for every station are published by state in *Surface Water Supply of the United States*, a USGS Water Supply Paper Series. Lake levels and river stages are often monitored by the Corps of Engineers or the U. S. Bureau of Reclamation (USBR) in the vicinity of Federally maintained dams, reservoirs, and levee systems. River stages are also monitored by state water resource agencies and municipalities that maintain any type of flood control project. Tide gauges are operated by the USGS, and by the National Oceanographic and Atmospheric Administration (NOAA) in coastal areas.

The quantity of precipitation, its temporal and spatial distribution can only be quantified by means of precipitation gauges. Precipitation data are collected by the National Weather Service, local weather bureaus, and state resource agencies. In most areas, these weather stations are nearby and maintain a substantial historical record of common climatological information such as precipitation, evaporation, wind speed. Precipitation rates can vary drastically over short distances in some areas, and the available records may not be sufficiently accurate for some projects. However, the long-term record at a regional station should be examined to determine the seasonal variation of precipitation and garner an understanding of regional precipitation patterns.

Collecting sufficiently accurate data to support design activities may require a precipitation gauge to be placed onsite to capture site-specific conditions during critical periods. At least one weather station should be set up at the site and operated for at least one year prior to construction. Gauges should be read daily during the wet season and at least weekly throughout the year. Additionally, winter snow surveys help determine the depth and water content of snow in the watershed. When site-specific monitoring is not implemented, the project design must be based upon regional rainfall data. The uncertainty of the analysis based on these data will be high and can result in high construction and materials costs when they result in an over-designed control structure or levee.

## Sources of Historic Subsurface Flow Records

Networks of monitoring wells are maintained by certain local, state and Federal agencies for special purposes. Irrigation districts often monitor aquifer levels to determine irrigation water supplies. Municipalities that rely on groundwater for domestic and industrial water supply also monitor the local aquifer levels. The USGS and USBR maintain monitoring networks in some regions for research purposes and for environmental impact assessment. Unfortunately, there is no central clearinghouse for groundwater data that encompasses all participating agencies. State departments of water resources are a good source of information about the extent and availability of existing groundwater data.

# 2-5 Characterizing Existing Vegetation and Site Conditions for Vegetation Establishment[1]

For the successful establishment and management of wetland vegetation, baseline site assessments will have to be developed. These assessments should include historic physical, chemical, and biological investigations. The following discussion is intended to first help interpret how baseline site conditions will affect vegetation requirements necessary to meet project restoration or establishment goals. Second, guidelines are given to help determine whether the vegetation onsite is adequate to meet project objectives and if desirable natural colonization is likely to occur.

## Restoration versus Creation

The first consideration for characterizing vegetation for a site assessment is dependent on whether the site is intended for wetland restoration or creation. Wetland creation means that a wetland will be located where wetlands have not previously existed. There will be no existing wetland vegetation onsite. Wetland vegetation will either colonize naturally from nearby wetlands, or plants will have to be introduced into the site. Facultative populations found in the adjacent uplands may also represent a propagule source. The site assessment should determine the potential for natural colonization or the need for a planting or seeding program. Although no existing wetland vegetation may be present, the existing vegetation can give clues as to underlying soil textures and chemistry, and past land use practices.

Wetland restoration, however, often entails management of existing wetland vegetation or the correction of past abuse. The desired vegetation may persist in the seedbank or as extant plants. Often the desired species are present, but the area is now weed infested and/or the architecture and structure of the community have been destroyed. The primary site assessment objective of wetland restoration is to describe the types and distribution of existing vegetation to determine whether, after correction of the abuse, the future vegetation development will meet project objectives. If adequate vegetation does not exist, the potential for natural colonization or the need for planting must be assessed.

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[1] By Mary M. Davis

**Table 2-8**
**Water Requirements for Various Vegetation Types**

| PLANT GROWTH FORM | AVERAGE WATER DEPTH (cm ) |
|---|---|
| Submergents ( e.g., water celery, elodea, pondweeds) | > 50 |
| Floating leaves (e.g., water lily, spatterdock, lotus) | 20-100 |
| Herbaceous emergents (e.g., duck potato, bullrushes, maidencane) | 0-50 |
| Shrubs (e.g. , buttonbush, wax myrtle) | 0-20 |
| Trees (e.g., cypress, green ash, red maple) | 0-50 |

# Physical Conditions for Plant Growth

Whether a site is intended for restoration or creation, the hydrology, soil, topography, and surrounding land uses must be assessed for their effects on plant growth. Conditions on restoration sites can often be directly assessed. If the restoration will entail a relatively minor landscape modification, such as the re-establishment of a floodplain hydrology of a diverted stream corridor, some existing site conditions may reflect conditions for plant growth. For example, the soil textures in a floodplain may not be significantly altered by the re-introduction of flood waters. Plant growth conditions for wetland establishment sites, however, will have to be estimated from existing conditions and planned developments.

## Water

The growth and distribution of wetlands vegetation at a site is dictated primarily by hydrology. Water limits diffusion of oxygen to buried seeds and root zones, which restricts germination and growth of most species. Wetland plants differ from upland terrestrial plants by having various morphologic and physiologic mechanisms for tolerating inundation of their roots. Different species tolerate longer periods of inundation than others. Young plants that are just developing from seeds or plant fragments do not have the same flood tolerance as mature plants of the same species. As such, young plants are more susceptible to loss via inundation. Too much water, especially during the growing season, will stress plants and limit growth and establishment. Outside the aquatics, complete inundation of most plant species, even wetland species, can be lethal. Therefore, a determination should be made to establish that the potential project site will have water at the appropriate depths, in the right places, at the right time of year to support the plant species targeted for the project. Table 2-8 summarizes one aspect of water requirements for various vegetation types

Hydrologic surveys should include estimates of water quantity and quality. The site's hydrologic regime should have seasonal water-level fluctuations similar to local natural wetlands to enable the placement of local wetland plant species in hydrologic conditions similar to where they are found growing naturally. When water management requirements do not permit a natural analog as a planning guide for species selection and placement, more general planting guidance must be used. Establishment success of trees, shrubs, and some emergents is often increased if water levels can be managed during the first one or two years to allow only short flooding periods and limited periods of soil saturation.

Water quality is a second factor that determines wetland plant distributions. Site evaluations of water quality usually include analysis of nutrients, pH, salinity, alkalinity, and turbidity, as well as toxins, where appropriate. The water chemistry parameters are important for defining site-specific conditions for which tolerant plant species must be selected. Because most rooted plants acquire their nutrients from the soil water, the chemistry of standing water is most important when considering submergent aquatic plants or potential eutrophication problems. Turbidity limits the depth of light penetration. Emergent plant species will grow in shallow turbid water; however, deep turbid water must be treated in order to support submerged aquatic vegetation. Section 2-4 addresses hydrologic site assessment.

## Soils

Several soil factors impact wetland vegetation. Assessment of site conditions for vegetation establishment and management must include a determination of whether or not the substrate will provide a stable rooting medium to an adequate depth for the target plant species. As described below, soil texture interacts with the hydrology and ground surface slope to determine the drainage capacities of the site and the period of saturation. The soils must also provide adequate nutrients for plant growth and maintenance. Excessively compacted soils, high bulk densities for the texture, will restrict plant establishment.

Soil stability is dependent upon soil texture, surface slope, eroding forces such as wind and water, and vegetation cover. Most of these factors affecting soil stability will be evaluated in concurrent activities conducted during the site investigation. Type and extent of vegetation cover should be characterized and management of existing vegetative cover should be included where practicable, if stability is likely to be a problem. Techniques for characterizing site vegetation are described later in this section and in Mueller-Dombois and Ellenberg (1974), Pielou (1974), and Bonham (1992).

Presence of a dense layer in the soil profile, such as rock, clay, or mineral deposits, needs to be closely examined because root penetration depths may be limited and drainage may be blocked. Root penetration depths differ with plant species. Generally, most fine roots that absorb nutrients occur in the top 30 cm of the soil. If an occluding layer is not within 30 cm of the surface, rooting depth is not usually a problem for herbs and shrubs. However, trees will require more rooting depth for increased stability against wind and currents. Limitation of drainage may be desirable to help maintain wetland conditions. If, however, an occluding layer is expected to create undesirable rooting conditions, either the layer needs to be broken up and amended to allow root penetration or plantings changed to reflect the soil conditions.

Little guidance is available about what nutrient concentrations are desirable for wetland vegetation. Soil analyses, particularly pH and cation exchange capacity (CEC), should be conducted and compared with tolerance ranges of target plant species, if available. Available soil nitrogen should also be characterized because nitrogen is the most common limiting nutrient for wetland plant growth. Some forms of nitrogen are highly soluble and rapidly lost from the site through drainage and percolation. In addition, nitrogen is rapidly transformed into gases by microorganisms and this nitrogen is largely lost to the atmosphere before being utilized by plants. Section 2-3 addresses site assessment with respect to soils.

## Topography

As discussed above, plant establishment and growth requires stable substrates for anchoring root systems and preserving propagules, such as seeds and plant fragments. Slope is a primary factor in determining substrate stability and should be adequately characterized during site assessment. Establishment of plants directly on or below eroding slopes is not possible for most species. In such instances, a site assessment would indicate that plant species capable of rapid spread and anchoring soils should be selected or bioengineering techniques should be used to aid the establishment of plant cover.

A thorough topographic assessment of the site is necessary because the ground surface slope interacts with the site hydrology to determine water depths for specific areas within the site. Depth and duration of inundation are principal factors in the zonation of wetland plant species. For example, a given change in water levels will expose a relatively small area on a steep slope in comparison with a much larger area exposed on a gradual or flat slope. Steep slopes often result in narrow planting zones for species tolerant of specific hydrologic conditions, whereas gradual slopes result in broader zones and enable the use of wider planting zones. In addition, soils on steep slopes generally drain more rapidly than those on gradual slopes. Thus, soils remain saturated longer on gradual slopes with falling water levels, and roots remain in anoxic conditions even after aerial plant parts are exposed. If soils on gradual slopes are classified fine textured, care will need to be taken that plant species to be selected for planting that are tolerant of saturation for longer periods of time than would be determined from surface water levels alone.

Site topography also affects maintenance of plant species diversity. Small irregularities in the ground surface (e.g., hummocks, depressions, logs, etc.) are common in natural systems. More species are found in wetlands with many microtopographic features than in wetlands without such features. Raised sites are particularly important because they allow plants that would otherwise die escape the physiological stress of prolonged inundation.

A second topographic feature that promotes increased species diversity in littoral wetlands is a convoluted shoreline. Littoral drift along a straight shoreline carries seeds and plant fragments along with sediments, with little opportunity for the propagules to be captured and become established. Concave portions of shorelines trap sediments and propagules enable more successful establishment and growth of more species. Consequently, the topographic assessment of the site should be adequate to reveal both large and subtle changes in elevation at the site. Section 2-2 addresses site assessment with respect to topography.

# A Decision Framework for Vegetation Assessments

The decision framework in Figure 2-10 is an aid in the initial assessment of onsite wetland vegetation to determine 1) whether or not it is adequate to meet project objectives and, if not, 2) if natural colonization of desirable vegetation is likely to occur, and 3) if site modifications will be necessary to enhance natural colonization and establishment processes. This framework is useful at several points in the wetland planning decision sequence: 1) during a site evaluation, 2) during development of design criteria, and 3) after the hydrologic and geotechnical features of the wetland restoration or establishment project are designed to determine vegetation requirements.

The level of detailed information required to effectively answer the questions in the vegetation requirements framework depends on the level of specificity in the project objectives. When possible, project objectives should be clearly formulated prior to determining the vegetation establishment requirements. Desired species composition, density, and areal coverage, and time to meet objectives should be specified to answer questions in the decision framework as accurately as possible.

The following sections discuss information relevant to questions in the vegetation requirement decisions framework (Figure 2-10).

## Do Desirable Plants Exist Onsite?

The objective of this question in the decision framework is to determine whether or not adequate wetland vegetation currently exists onsite to meet project objectives. The answer will not necessarily be a simple yes or no If a wetland is being established where a wetland has never been before, there will probably not be desirable vegetation present. If desirable vegetation is not present, then a determination will have to be made as to whether desirable vegetation will naturally colonize or will have to be planted or seeded. Wetland restoration projects, however, are likely to have relict wetland vegetation present. If a wetland requires restoration, the vegetative composition has probably been altered by any number of causes. As a consequence, undesirable species may be present with the potential to dominate and overwhelm the desirable species. Species richness may be low or the remnant vegetation may not have adequate areal coverage. Even though desirable vegetation may be present, management strategies may be required to enhance species richness or growth and meet project objectives. If management of site conditions alone cannot restore the vegetation onsite, alternative sources of vegetation such as colonization or planting may be required.

A basic approach to determining the plant species onsite is to catalog the areal coverage of dominant species observed during a site visit. This cataloguing of species may be all that is required for mature sites that have suffered only slight or short-term impacts and where the vegetation community is largely intact. Management may be required in these cases to remove unnatural disturbances (e.g., cattle grazing) or restore natural conditions (e.g., hydrology or fire). The objective of vegetation management in these restored wetlands may be the recovery of biomass, reduction of invasive species, or regained physical structure.

A species list and cover of extant plants in more highly disturbed wetlands, however, will not include a potentially vital component of the recovering vegetation: the seedbank. A more

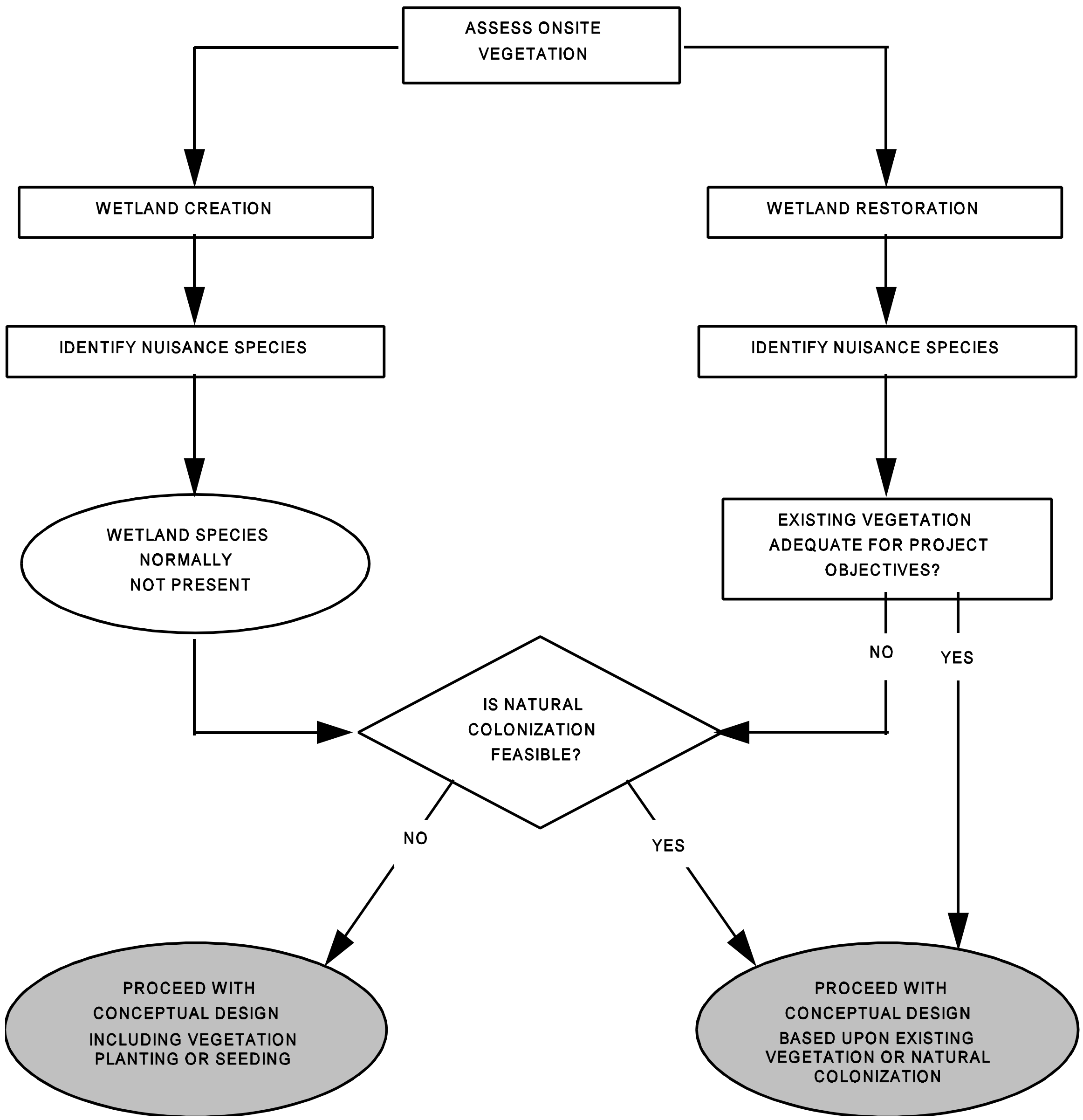


Figure 2-10. Decision process for onsite vegetation assessment.

involved approach to determining the plant species onsite is to determine the composition and abundance of the seedbank (see Appendix E, Seedbank Study Methods). Once the plant species onsite are identified to an acceptable level, then a determination must be made if a desirable complement of species is present onsite.

## Desirable Species

Determination of the desirability of plant species listed during the site visit and whether or not this determination is performed, from the seedbank study, depends primarily on the project objectives. Objectives that list specific target species allow a direct comparison of onsite vegetation with the target species. In another instance, project vegetation objectives may specify a suite of species similar to a reference wetland that is native to the area. In the latter case, the species lists from the project site evaluation can be compared with a list of species in the native community. Finally, project objectives may not provide target species, but may require the presence of species that will perform specific functions, such as shoreline stabilization or nutrient transformation.

The dominance of the species has to be considered in determining whether or not desirable species are present. For example, a species list for a marsh can include over 50 species. Not all of the species, however, can be specifically targeted in most wetland restoration or establishment projects. While diversity is a worthy objective of a wetland project, the strategy used in most projects is to ensure that the dominant plant species are established. The other species will become established with time. Therefore, for both dominance and diversity where species lists are compared for project objectives and onsite vegetation, the species should first be ranked by relative dominance or importance. Coverage and relative dominance of various wetland vegetation species are shown in Table 2-9.

**Calculation of Relative Dominance.** Relative dominance can be estimated from areal coverage, stem density, or seed density (if available), whichever seems to be the most appropriate for the type of vegetation. Relative dominance using the percent cover of each species in a fictional marsh (percent cover exceeds 100 percent due to overlapping of vegetation in layers) is calculated in the following manner:

$$Relative\ \ Dominance\ = \left( \frac{Species\ \ Coverage}{Total\ \ Vegetative\ \ Coverage} \right) * 100 \qquad (2\text{-}3)$$

The species should be listed in order of decreasing relative dominance. Determination of the dominant species requires a subjective cutoff point. Starting from the species with the highest relative dominance, sum the relative dominance values until the 50 percent threshold value is reached. Those species included in this sum are the dominant species. In the above example, Maiden cane and duck potato are the dominant species in the marsh. If the project objectives specify more diversity, the next most dominant species could be considered.

**Table 2-9**
**Coverage and Relative Dominance for Several Important Wetlands Species**

| SPECIES | % COVER | RELATIVE DOMINANCE |
|---|---|---|
| Maiden cane | 60 | 39 |
| Duck potato | 50 | 32 |
| Knotweed | 20 | 13 |
| Cattail | 20 | 13 |
| Sundew | 5 | 3 |
| TOTAL | 155 | 100 |

Once the species lists are ranked, the dominant species can be compared between the objectives and onsite vegetation. All of the target species do not necessarily have to occur in the onsite vegetation. The similarity of the species list can be determined somewhat subjectively by the percent of species in common, which is an adequate method for most cases. If several alternative sites are being evaluated as potential project sites, however, a more quantitative method may aid comparisons with the target species list. Similarity indices are commonly used to quantify the degree of commonality among different species lists. Several similarity indices are commonly used and can be found in texts about ecological methods (e.g., Mueller-Dombois and Ellenberg 1974, Pielou 1974). Sites with high similarity indices to the reference site can be prioritized for site selection based on existing vegetation.

The project biologists must determine whether or not the dominant vegetation will meet the project objectives. If target species do not occur onsite, the next step is to determine whether a natural source of plant propagules of the target species is available for natural colonization. If the onsite vegetation provides adequate desirable species, then a determination must be made as to whether or not they exist in adequate amounts, and whether there are potential nuisance plants present.

## Nuisance Plant Species

Nuisance plants are invasive, prolific, fast-growing, and often exotic species that are capable of rapidly colonizing and dominating the vegetation on a site. They usually are not able to become established in areas with healthy intact vegetation. For plants to become established, there must be a physical place for seedlings to become established and resources available for the continued growth and development of the new plants. Native vegetation that is well established can out-compete the invasive species. Nuisance plants may exist in low numbers or cover in the midst of established vegetation, but they become a problem as they spread. Often nuisance plants become dominant where vegetation has been altered by disturbances that expose bare soil (e.g., agriculture, erosion), altered nutrient inputs (e.g., agricultural runoff), or in altered wetlands hydrology (e.g., drainage, long periods of inundation). Once established, nuisance plant species can extend to nearly 100 percent cover of a site and reduce the natural diversity of the vegetation. Established nuisance species are typically very difficult to eradicate.

Several common wetland plant species are nuisance plants. Cattail is a very common wetland plant in many parts of the country that has traits common with many nuisance species. Cattails produce a tremendous amount of light-weight seeds that are carried by wind and water. They are deposited over a wide area surrounding the parent plants, but are most successful at becoming established on recently disturbed sites with bare soils. Wet roadside embankments and ditches are often rapidly invaded by cattail following soil exposure. For example, cattail are invading the sawgrass marshes of the Everglades in Florida from roadsides and dikes where they were able to become established. Exposure of soils during wetland project construction makes these areas susceptible to invasive species. Reinartz and Warne (1993) reported colonization of a newly created wetland in southeastern Wisconsin within the first year, increasing to 55-percent coverage in the three years following construction. Cattail plants are capable of rapidly expanding the area of coverage with rhizomes, even while inundated. Eradication methods must remove or kill as much of the whole plant as possible, including rhizomes and seedbank. Plant fragments or seeds that remain on a disturbed site are capable of recolonization, and eradication efforts will have been wasted.

If nuisance species are identified in the onsite vegetation and seedbanks, it is advisable to incorporate a management technique to control the undesirable vegetation prior to further vegetation management. Vegetation management techniques target different life history stages of the plants. If seeds of undesirable species are present in appreciable densities, management techniques should target seedling emergence. For example, a site can be lightly harrowed after seeds have been allowed to germinate to strip the seedlings from the soil. Multiple harrow treatments will deplete the seedbank and reduce the potential of nuisance species invasion from the seedbank, but do not turn the soil or you will expose additional seedbank. Alternatively, if seeds are intolerant of inundation, the site can be temporarily flooded until the seeds rot and viability is lost. Pre-emergent herbicides that are approved for aquatic systems can be applied to eliminate seedlings as they emerge. Vegetation management techniques can also target plant growth. Mowing and fire reduce plant biomass of existing nuisance plants. One of these treatments may be necessary to allow more desirable species to grow and become dominant. More extensive techniques are, however, usually required to control existing vegetation. Preferred vegetation management methods have as little impact on the desirable vegetation as practicable to minimize the need to plant the site later.

Additional information on common nuisance plants in wetlands and control methods is provided in Chapter 7-5.

## Adequate composition, density, and cover of desirable species

Wetland restoration and establishment project objectives should include an indication of desired vegetation, preferably a species list, and the density or percent of desired areal coverage within a specified time frame for the project to be considered successful. At this point in the project planning decision framework (Figure 2-10), a decision must be made as to whether or not adequate vegetation already exists onsite, if inadequate coverage of the desired vegetation will increase to adequate coverage within the project time frame, or if further management may be required.

The first aspect to consider is whether the composition of desired species that already exists on the site and in the seedbank (if a seedbank study was conducted) is adequate. If an adequate species complement is not already present, possibilities of natural colonization should be investigated, and barring colonization, selected species may have to be planted or seeded. If the species complement is adequate, potential coverage needs to be considered.

The potential for existing plants and seeds to grow and increase their coverage on the project site depends on several factors. The first is whether the designed conditions are optimal or marginal for plant growth. Rates of spread of healthy plant material can be estimated from the rate of spread of stock planted in optimal conditions. If hydrology, nutrients, competition, and herbivory are not limiting to plant growth, wetland projects for rhizomatous grasses, other herbs, and some shrubs planted to less than 5 percent coverage should reach 100 percent cover in less than 3 years, by spreading vegetatively. Non-rhizomatous species such as tufted grass and grasslike species planted as sprigs, however, spread more slowly. The radius of the tuft increases slowly as new culms are produced. In the case of single stem plants, like trees, growth is in height and crown radius. If, for example, 50 percent cover of a tree species is required within 10 years, to estimate whether adequate tree cover will be attained one needs to estimate 1) the canopy area required at the end of the project, 2) the density of trees onsite that are likely to survive at the end of the project time period, and 3) the likelihood that the trees will attain the required size. Assume the required tree coverage in the present example equals 5,000 $m^2$ (one half hectare) by year 10. If 110 trees/ha are onsite and 100 are expected to live 10 years, then the trees must average 50 $m^2$ cover at that time. This is a crown radius of 4 m (about 13 ft). The project biologist would have to estimate whether this coverage would be easily attained by the existing trees or whether additional trees should be established to ensure project objectives are met.

The second factor affecting potential growth of the plants onsite is their present state of health. Inspection of the plants should indicate whether they are capable of growth under present conditions. If the plants look weak (i.e., yellow or sparse leaves), severely damaged (i.e., excessive loss of leaves, branches, or roots), or suppressed (i.e., no indication of recent growth), there is little likelihood that the existing plants will recover and grow without some management intervention. Poor growth may reflect of poor site conditions. Onsite analyses should be made to determine the factors limiting growth of existing vegetation. Management such as exclusion of grazers, addition of fertilizer and/or pH amendments, erosion control, and altered hydrology are among the possible techniques (Fredrickson and Taylor 1982) that can be used to improve plant growth conditions on the wetland restoration or establishment project site.

Assessing the development of vegetative cover from seeds is more difficult and results are variable. For some wetland systems, reasonable agreement has been found between the species and numbers of plants that emerged from seedbank studies in greenhouses and from the respective natural sites (Leck 1989). Although many site factors such as erosion, inundation, and drying will affect emergence, results of the seedbank study can be used with caution to estimate the amount of vegetation that will emerge on the project site. Effects of the site-specific conditions on seed germination and seedling growth of the species of interest must be carefully evaluated.

## Colonization from Natural Sources of Seeds and Plant Propagules

If inadequate species and/or cover of desirable plants exist on the wetland restoration or establishment project site, natural colonization of the site by vegetation from nearby sources may be a viable method to vegetate the project site. The objective of this point in the planning decision framework (Figure 2-10) is to 1) determine whether sources of desirable vegetation capable of colonization are available, 2) identify barriers to migration, and 3) determine if site conditions are adequate for germination and establishment of colonizing species.

At a minimum, the following information will be required to assess the potential for natural colonization at a project site:

- At least one site visit will be required during a period of the year when onsite and surrounding vegetation can be identified to species. Plant species identification should always be made by a qualified expert familiar with local flora.

- The dispersal mechanisms and specific germination requirements of the desired species need to be determined. Germination requirements can be determined to different degrees of certainty using one of the methods discussed in the next section.

- Distance to seed/propagule sources and presence of barriers to dispersal should be assessed with maps, onsite evaluations, and, if water dispersal is necessary, hydrological records or evidence.

- Suitability of site conditions for germination and establishment of seeds and vegetative propagules can be determined from a comparison of potential colonizing species requirements and tolerances with site hydrology, soil conditions, and vegetation.

## Are Natural Sources of Desirable Vegetation Available?

Natural colonization of wetland restoration and establishment projects can be a highly successful method of revegetation if sources of seeds and plant propagules are nearby. Reinartz and Warne (1993) reported finding 142 species of vascular plants in naturally colonized created marshes of southeastern Wisconsin. They found that the diversity and richness of native wetland plants and the proportion of total plant cover that was comprised of native marsh plant species increased from 1-year to 3-year old wetlands. The diversity and richness of native wetland species increased with proximity to the nearest native marsh, with a marked decrease in species richness beyond 700 m to the nearest marsh.

Seeds of many woody species, however, have much shorter dispersal distances. Brown et al. (1992) evaluated a forested floodplain wetland as a source of windblown, bird-dispersed, and water-dispersed seeds to adjacent mined wetland areas. Windblown seeds decreased in densities as distance from forest edge increased. Densities ranged from 125/m$^2$ to 380/m$^2$ within the forest, 50/m$^2$ to 120/m$^2$ at the forest edge, and decreased exponentially as distance from the forest edge increased. Bird-dispersed seed densities at the base of constructed perches and tree “snags” ranged from 100/m$^2$ to more than 300/m$^2$, but decreased rapidly beyond several meters from the perch. Water-dispersed seeds trapped in a creek flowing out of the mined area ranged from 0/day to 200/day, whereas dispersal rates downstream of the forest floodplain ranged from 200/day to 5000/day. Water dispersal of seeds, however, is highly dependent on distance to seed source as well as hydrology. Extensive tracts of agricultural land in the Mississippi alluvial valley are being restored to bottomland hardwood forest. Planting efforts have concentrated on heavy-seeded tree species with the assumption that lighter seeded species would be blown onsite by the wind or carried in by water. Natural colonization by additional tree species has been disappointingly low, due in large part to the great distance to natural seed sources and competing vegetation.

Colonization of wetland vegetation from plant fragments is more limited than colonization from seeds, but can be an important form of colonization in some cases. Stem and root fragments of aquatic vegetation are capable of becoming established upon deposition. Hydrilla is a major aquatic nuisance species that is spread from stem fragments carried from one water body to another on boat propellers. Whole plants of wildcelery (*Vallisneria americana*) and sago pondweed (*Potamogeton pectinatus*) are ripped up by feeding migratory waterfowl in the upper Mississippi River. These fragments can settle and become established in shallow areas with low energy and adequate light penetration. Geese feed on two sterile species common in saltmarshes throughout the Arctic, *Puccinellia phryganodes* and *Carex subspathacea*, and in the process tear up thousands of plant fragments that are carried to new areas by water currents. Soft sediments that are exposed by the feeding geese are recolonized by these plant fragments (Chou et al. 1982). Although it is not commonly noted in the restoration literature, algae and bryophytes are also capable of colonizing new sites vegetatively.

Results of the studies described above indicate that sources of seeds of wetland species must be relatively close to the project site for dispersal of a diversity of species in adequate quantities to vegetate a site. The decision of whether adequate natural sources of seeds or vegetative propagules are available depends on the type of desired plants. For example, marshes containing desirable species that occur within 500-700 m (0.3-0.5 miles) of the project site are likely to be good seed sources of herbaceous plants, assuming the presence of dispersal vectors. Seed densities of wind-blown or animal dispersed tree species decline rapidly with distance from the forest edge. Wind-blown tree seeds will be carried only a couple of hundred meters. Densities of bird-dispersed seeds can be increased in localized areas with the provision of perches. Perches can be old remaining trees, shrub piles, “planted” snags, or any other structure that birds will land on. Water-dispersed seeds can be carried great distances, presumably for miles before they lose their buoyancy and sink. Sources of vegetative propagules and water-dispersed seeds must originate upstream of the project site.

## Barriers to Colonization

For natural colonization to occur, propagules (e.g., seeds, rhizomes, stolons) must be present at the site or must be able to disperse to the site. There are four primary agents of dispersal for wetland plants: wind, water, animals, or man. Propagules have numerous morphological adaptations that make them amenable to the various types of dispersal. Many of the common invader species that rapidly occupy a site are carried by wind (e.g., *Typha* and *Phragmites*). Currents, winds, and animal dispersal can account for some short range dispersal in riverine and fringe wetlands (Kadlec and Wentz 1974). A brief description of how each of the factors or conditions limit natural revegetation of a site is provided in the following sections.

*Topography:* Steep slopes may hinder the colonization of an area by a large number of species. The steep slopes increase runoff and may cause any seeds that have been dispersed to the site to wash off the slopes. A sudden and sharp increase in elevation between the site and its surroundings can present a physical barrier to dispersal of propagules to the site, particularly for those species that rely on wind dispersal. In riparian systems, floods occasionally carry seeds across land barriers (Kadlec and Wentz 1974).

*Currents and wave energy:* Colonization in riparian and fringe wetlands may be hindered by currents and waves that disrupt the establishment of seedlings and other propagules. Seeds and vegetative propagules must have stable sediments as roots develop to anchor the plant. Sources of energy that move soils or physically damage the plants will limit colonization.

*Dispersal rates:* On bare sites, such as sandbars, willow (*Salix* spp.) and aspens or cottonwoods (*Populus* spp.) frequently appear very rapidly because their wind disseminated seeds reach new sites quickly. Assuming the dispersal vectors are present, marsh and aquatic plants invade most new environments within a few growing seasons because their means of dispersal are remarkably efficient (Kadlec and Wentz 1974).

*Competition from existing vegetation:* Competition from existing indigenous and aggressive undesirable species affects migration, growth, and survival of propagules that may potentially colonize a site. The existing vegetation physically limits delivery of seeds to a site, contact of the seeds with soil, and access of the developing new vegetation to light, water, and nutrients. Natural colonization may be an ineffective or undesirable method for establishing vegetation at a site when one or a few aggressive species are present and can exclude all others. (Southern Tier Consulting 1987).

*Soil condition:* Disturbances in soils at a site may significantly alter the soil condition at the site and prevent the colonization of original assemblages of species on the site or of species from surrounding areas. For example, if an area has been clear cut and has potentially been subject to a high amount of rainfall, leaching of soil nutrients may have occurred if the site has been left in a disturbed condition. If an area has been degraded by off-road vehicle use, changes in soil conditions, particularly compaction, may preclude the colonization of desirable species at the site. See discussion above for other considerations of soil as a limiting factor.

*Modified hydrology:* A wetland site whose hydrology has been modified may require a review of the degree of hydrologic change prior to selecting natural colonization as the method of establishment. For example, a site that once supported an assemblage of forested wetland species that were tied to annual cycles of flooding and inundation throughout the growing season may not be able to support this same assemblage of species if the site timing, frequency, duration, and depth of inundation are greatly reduced at the site. A change in timing, frequency, duration, and depth of inundation can affect the survival of species in the seed bank. The ability of the species in the seed bank or propagules dispersed from adjacent locations to become established at a site will depend on the tolerances of the individual species to the new hydrologic regime and water budget.

*Time:* Natural colonization may require several years before the desired assemblage of species and cover is achieved. While many species may be established on a site without direct human intervention, the time required to achieve the desired assemblage at the desired coverages can be quite prolonged, especially sites where the natural conditions of the site have been disturbed, modified, or regraded.

*Ecotypes:* Ecotypes are genetically different individuals of a species that are adapted to a specific set of local or regional environmental conditions. Because ecotypes have developed adaptations to a specific set of environmental conditions, they often will not grow well under a different set of environmental conditions. Colonization in wet conditions of ecotypes that are adapted to upland conditions can result in high mortality of propagules. Examples of wetland species that may have different ecotypes within the same area, such as within a watershed, are green ash (*Fraxinus pennsylvanica*), black gum *(Nyssa sylvatica),* and red maple *(Acer rubrum).*

# Summary of Potential Site-Specific Conditions Limiting Wetland Vegetation

The following items can serve as a checklist for assessments of potential wetland project sites based on wetland vegetation.

1) Determine the physical limitations for dispersal of propagules onto the site and the establishment of plants on the site.

    a) What are the slope and soil characteristics of the site?

    b) Does the site have the potential for having poor drainage characteristics, i.e., for being either well drained or permanently flooded or inundated?

    c) What is the orientation of the slope with respect to the wind and the sun?

    d) Will this orientation have an effect on the potential success of establishment of natural vegetation?

    e) Are there any physical barriers to the natural dispersal of propagules to the site and if so what are these barriers?

    f) Can these barriers be removed easily and still meet the planned project goals?

    g) Are the soil conditions and characteristics adequate for the revegetation by local species?

    h) What is the soil condition including fertility and potential for productivity?

2) Evaluate the climatic limitations of the site. In which season will the site be ready for vegetation to be established?

3) Determine the biological limitations to natural revegetation.

    a) Is there an abundance of nuisance animals in the surrounding communities that often feed on seeds and young seedlings?

    b) What are the dispersal mechanisms of the native vegetation in the area?

    c) Is there a natural wetland complex near the site to provide a source of propagules?

    d) Are there sufficient numbers of desirable species at the site or adjacent to the site?

    e) How far away are the nearest sources of natural propagules and are the propagules likely to be dispersed to the site?

    f) What is the composition of the seed rain will reach the interior of the site?

    g) Is the seed bank a reliable source of a sufficient number of species?

h) Are the sources of propagules in good, healthy condition, stress-free, free of deleterious insect damage and signs of disease?

i) Are there any undesirable species at the site or near the site?

j) Are there any desirable species remaining on the site or adjacent to the site and what is the areal extent of the species?

4) Evaluate the site history and compare with current site conditions.

a) Hydrology - Has the natural hydrology of the site been significantly altered so that local species or species indigenous to the area would be precluded from the normal course of revegetation because the species and the site conditions are no longer compatible?

b) Soils - Have the soil characteristics of the site been significantly altered so that natural revegetation will be difficult without some site preparation or manipulation?

5) Identify any of the above problems that cannot be overcome.

6) Finally, determine if the site condition is compatible with the planned project goal if the site is not planted with transplants.

# Section 2
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# Wetlands Engineering Handbook

## Section 3

## Design Criteria and Site Selection

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# 3-1 Conceptual Design Criteria for Wetlands[1]

Many wetland restoration and establishment projects will have a preselected site or at least a designated area in which a wetland will be created or restored. The project design must incorporate the available resources, minimize radical re-engineering of the site, and fit within the confinements and constraints of the defined location. Despite these restrictions, various choices for the actual location of the wetland usually exist within the identified area. For other projects where sites or areas have not been specifically identified, site selection will be a significant part of the project. In most cases, site selection will be limited to a restricted locality, such as a particular watershed or specific land-use type. In either case, multiple design configurations and usually more than one prospective construction site should be considered. Figure 3-1 presents a logical process for site selection that applies to virtually any situation.

One of the most important considerations of site selection and evaluation is the amount of energy of natural processes (both potential and kinetic) acting on the site. Site energy is usually visible in the amount of erosion, transport, deposition, and other natural processes acting on the site. The energy inherent to the location should be a key factor of consideration during both site selection and the development of project concepts. If the wetland engineering concepts are not compatible with the local energy of the systems acting at the site, high energy (storms, floods, etc;) events are likely to destroy or redirect the project. The higher the site energy, the more unpredictable it becomes to achieve the goals of the wetland project. Consequently, high energy locations should be avoided whenever possible. At best, periodic maintenance will be required for the life of the project.

Section 2 described procedures for gathering site information to support an initial site screening, conducting baseline site surveys of target sites, and conducting a detailed site assessment of the final project site. Additional guidance on the kinds of geotechnical and hydrological information required for wetland projects is provided in the *Framework for Wetland Systems Management: Earth Resources Perspective* (Warne and Smith 1995). A thorough understanding of site conditions is necessary to accurately define design criteria and to develop conceptual designs. While this section focuses primarily on those projects for which site selection is a major component, most of the discussion applies equally to other projects targeted for a specific location.

[1] By Donald F. Hayes and Mary M. Davis

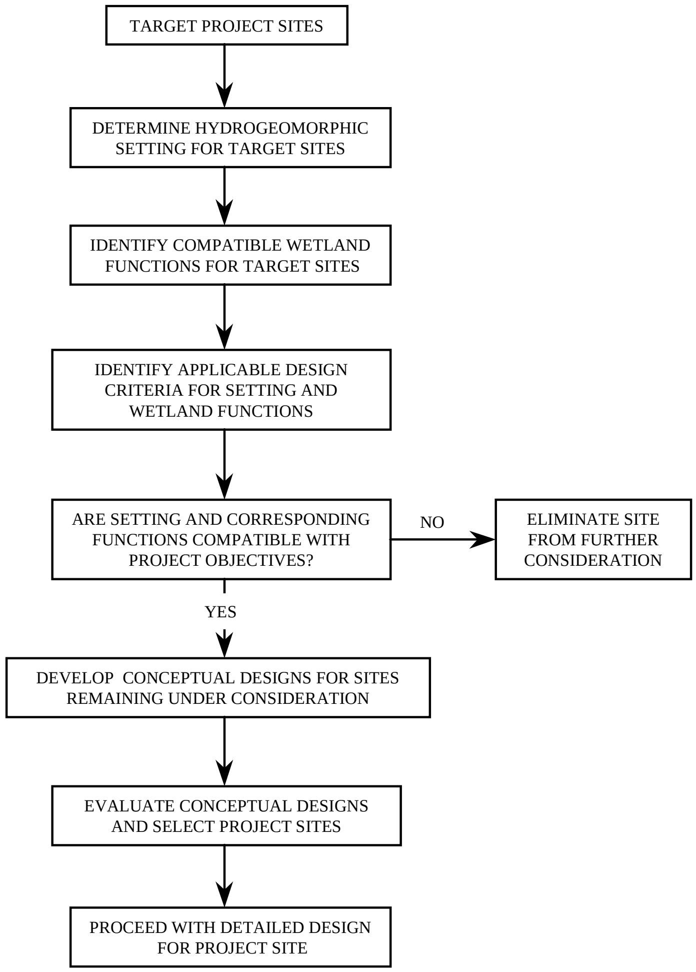


Figure 3-1. Decision flowchart for site selection and conceptual design development.

The remainder of this section discusses the key issues associated with wetland design. Chapter 3-2 presents the eleven accepted functions that wetlands may perform. These functions are essentially the goals of wetland restoration and establishment. In Chapter 3-3, the various types of wetlands, as classified by the “Hydrogeomorphic” procedure (Brinson 1993) are described. Conceptual hydrologic and geotechnical design criteria are presented in Chapters 3-4 and 3-5, respectively. Finally, in Chapter 3.6, a stepwise procedure for developing conceptual and specific designs for wetlands restoration and creation projects is outlined.

**Table 3-1**
**List of Wetland Functions Which Are Commonly Goals of Enhancement and Mitigation Programs**

| Function Categories | Wetland Functions |
|---|---|
| Hydrologic | Groundwater Recharge (GWR) |
| | Groundwater Discharge (GWD) |
| | Floodflow Alteration (FFA) |
| | Shoreline Stabilization (SS) |
| Water Quality | Sediment/Toxicant Retention (S/TR) |
| | Nutrient Removal/Transformation (NR/T) |
| Life Support | Production Export (PE) |
| | Aquatic Diversity/Abundance (AD/A) |
| | Wildlife Diversity/Abundance (WD/A) |

# Designing for Wetland Functions

Wetland functions are the positive contributions to the ecosystem that result from natural physical, chemical, and biological processes which occur either within the wetland system or result from the presence of the wetland system. Three general categories of wetland functions are presented in Table 3-1: hydrologic, water quality, and life support. Hydrologic functions include the reduction of peak discharges, increased groundwater recharge, and stabilized shorelines. The removal and transformation of water constituents such as nutrients, organic compounds, metals, and suspended sediment result from a complex combination of physical, chemical, and biological processes within the wetland. These removal and transformation processes are referred to as water quality functions. Wetlands also provide habitat for fish and fauna - the life support function of wetlands.

Most wetland projects are designed to provide a set of functions that support and enhance the local ecosystem. In general, the more functions a wetland can provide, the greater the potential benefit derived from the wetland. Wetland functions are not always separable. The same characteristics or criteria that provide one function may also support one or more additional functions. Additionally, not all functions are compatible and some functions cannot logically coexist within the same wetland system or within the same wetland at the same time. Table 3-2 summarizes the compatibility of specific wetland functions.

Since functions are the fundamental basis through which wetlands provide ecosystem benefits, it is important that project goals be translated carefully into a set of wetland functions. This is not always a straightforward process; it may well require tradeoffs between primary project objectives and secondary objectives.

**Table 3-2**
**Interactions of Wetland Functions in the Same Wetland (* = compatible, x = probable conflict, 0 = no significant interaction is known)***

| | Interaction with | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Function** | **GWR** | **GWD** | **FFA** | **SS** | **S/TR** | **NR/T** | **PE** | **AD/A** | **WD/A** |
| **GWR** | | 0 | * | 0 | X | * | 0 | 0 | 0 |
| **GWD** | 0 | | X | X | X | 0 | * | * | * |
| **FFA** | * | X | | * | * | * | * | 0 | 0 |
| **SS** | 0 | X | * | | * | * | 0 | X | X |
| **S/TR** | 0 | 0 | * | * | | * | 0 | X | X |
| **NR/T** | * | 0 | * | * | * | | X | 0 | 0 |
| **PE** | X | * | 0 | 0 | 0 | 0 | | * | 0 |
| **AD/A** | X | * | * | 0 | 0 | 0 | 0 | | * |
| **WD/A** | X | * | * | * | 0 | 0 | 0 | 0 | |

Modified from Adamus et al. (1991)

# Wetland Classification

Environmental conditions such as meteorology, hydrology, geology, morphology, and topography vary dramatically within the U.S. Certainly, coastal wetlands are dramatically different from prairie potholes in the great plains; both are also greatly different from bottomland hardwood wetlands. The challenge here is to describe design procedures that apply to all of these wetland types, yet recognize the variation in design requirements between these vastly different wetlands.

A number of wetland classification schemes exist and each has its advantages. However, the HGM method developed by Brinson (1993) is becoming the standard. This procedure classifies wetlands by geomorphic setting, water source, and hydrodynamics. Brinson identifies five hydrogeomorphic (HGM) wetland classes: riverine, fringe, depressional, slope, and extensive peatlands. This classification recognizes that the interrelationship between hydrology, geomorphology, and climate dictates the degree of wetland functions that are distinctive to geographic or physiographic regions. The hydrogeomorphic (HGM) approach is flexible enough to allow for the identification of all wetland subclasses within a region based upon factors such as water source, soils, and vegetation. Table 3-3 provides a breakdown of wetland classifications, including subclasses along with descriptions of important features of each subclass.

Simply classifying wetlands, however, does not support the purposes of this handbook. The purpose of this handbook is to facilitate the development of restoration or creation designs for specific sites. Determining the classification of the wetland that is the focus of the design project is an important first step in the design process. Understanding the characteristics commonly found among similar wetland types in the same hydrogeomorphic setting is crucial. Design criteria should reflect and mimic these traits if a successful wetland project is to be constructed.

## Types of Design Criteria

Useful conceptual designs require solid information upon which to base potential site modifications. In addition to existing site conditions, the actual design criteria which are to be achieved should be clearly understood. The term “design criteria” refers to quantitative measures of wetland components that provide the desired wetland functions. The purpose of this section is to describe the types of design criteria and how they relate to the design process.

Design criteria relate directly to the wetland characteristics necessary to provide specific functions. They can be divided into four categories - biologic, hydrologic, geotechnical, and engineering design - although there is considerable overlap between categories and related wetland functions. For convenience, the criteria may be characterized based upon their primary influence on the wetland system. Although brief discussions of these criteria are provided in this section, readers should consult other documents for a more extensive discussion of this subject.

## Biologic Criteria

Biologic design criteria include design requirements related to the biological aspects of wetlands systems. While these include design requirements for wildlife usage and fish spawning, the dominant focus is on the achievement of specific wetland vegetation communities considered optimum or at least desirable for achieving specific wetland functions. The focus on vegetation reflects the general premise that once the desired vegetative communities are achieved, many of the faunal characteristics will develop naturally, or at least be encouraged by wetland conditions.

Vegetation plays an important role in many aspects of the wetland ecosystem and is usually the most visible characteristic. Design requirements for submerged and emergent wetland vegetation include such aspects as water depths, inundation frequency, nutrient requirements, and shoreline slopes.

Unlike hydrologic and geotechnical design criteria, biologic design criteria are not discussed in detail in this section. Biologic criteria, especially vegetation, are best determined locally on a project-by-project basis. Fortunately, many documents and guidelines for plant selection for various uses in the United States, including wetlands establishment and restoration, already exist.

## Hydrologic Criteria

Wetland hydrology is fundamental to most wetland functions and is the lifeline of every wetland system. Unless the wetland hydrology is correct, a wetland will not exist at the site. In many cases where wetland restoration is desired, the wetland degradation resulted from a change in the hydrologic conditions. In some cases, dramatic changes resulted in a rapid decay of the wetland; in other cases, minor changes over a period of years eventually took their toll on the wetland system.

Considering the integral role of hydrology in a wetland system, the list of hydrologic design parameters is rather short. For convenience, hydraulic and hydrologic processes have been combined into the same hydrologic criteria category. The following nine fundamental hydrologic design criteria are discussed in Chapter 3-4:

*a.* hydrologic setting

*b.* flooding duration and timing

*c.* flooding depth

*d.* flow velocities

*e.* flow resistance

*f.* hydraulic retention time (HRT)

*g.* storage capacity

*h.* surface area

*i.* wind fetch

## Geotechnical Criteria

Geotechnical considerations heavily influence site location, design, and construction as well as the hydrology and biology of the system. The integration of a wetland project into the local landscape depends largely upon the composition, arrangement, and movement of Earth materials during site construction.

Seven specific geotechnical design criteria are identified including geologic setting, geomorphic setting, wetland form and size, soil composition and texture, hydrogeologic processes, geomorphic processes, and geomorphic trends.

# 3-2 Wetland Functions[1]

## Introduction

Wetland functions are the physical, chemical, and biological processes or attributes of wetlands. Functions, which are derived from the interaction of a particular set of geomorphic processes acting within a range of environmental conditions, are vital to the maintenance and enhancement of wetlands as well as the surrounding landscape ecosystems. Three categories of wetland functions can be distinguished: hydrologic, water quality, and life support (Table 3-1). Hydrologic functions include the capacity of wetlands to reduce and desynchronize peak flood discharge, influence baseflow, modify groundwater-surface water interactions, and stabilize shorelines (Preston and Bedford 1988). Water quality functions include the capacity of wetlands to remove or transform excess nutrients, organic compounds, trace metals, sediment, and other chemicals from water as it moves through the wetland system. Life support functions include the capacity of wetlands to furnish habitat and nutritional requirements to fauna that normally use wetlands.

In this chapter, functions that are commonly goals of wetland restoration and mitigation programs are briefly described (Table 3-1). Processes controlling different functions, particularly hydrologic processes, may be interrelated but are not necessarily compatible. Hence, a particular function may enhance certain other functions, but inhibit others (Table 3-2). Considerations of interaction among functions serve to highlight that no one geomorphic setting or wetland type will provide all functions.

Groundwater recharge and discharge, although essential components to most wetland water budgets, are not functions that are primary goals in wetland mitigation and restoration projects. Groundwater recharge and discharge, however, are critical to the other wetland functions, and therefore they are briefly reviewed. Recreation and uniqueness/heritage are two other commonly recognized wetland functions. They are not discussed in this handbook because there are no general design criteria applicable to these functions; they are enhancement and mitigation goals which require site-specific considerations (Marble 1992).

## Groundwater Recharge and Discharge

Groundwater recharge is the primary process in the hydrologic cycle for the movement of water downward from the surface to the subsurface. Porous underlying substrates allow water to pass to the groundwater system. Because wetlands are characterized by being shallow water

[1] By Lawson M. Smith and Sandy Pizalotto

bodies with relatively impermeable substrates in which water residence times are of sufficient duration to induce anaerobic conditions, wetlands are unlikely to significantly contribute to recharge of major aquifers, lakes, and rivers. Groundwater recharge, however, can be critical in controlling wetland water chemistry and residence times (the average time water remains in the wetland system). Groundwater recharge is especially important in wetlands with constricted or no surface outlet because the only other water outflow path is evapotranspiration (ET), which tends to concentrate dissolved solids. Groundwater recharge may be an important flushing mechanism for removal of salts and a source of dry season soil moisture during the dry season, especially in areas where evaporation exceeds ET.

Groundwater discharge is the primary process in the hydrologic cycle for the movement of water from the subsurface to the surface. This process is commonly referred to as base flow. Although groundwater discharge may only be a small portion of a wetland's overall water budget, discharge of nutrient-rich groundwater may be crucial to wetland water chemistry and thereby influence other wetland functions (Table 3-2). Moreover, groundwater discharge may be a vital water source during droughts. Excessive groundwater discharge, however, reduces residence times and inhibits anaerobiosis.

The movement of groundwater to or from a wetland depends primarily upon elevation of the wetland water surface relative to the water table (elevation head), the mass and pressure of the wetland water body relative to the surrounding groundwater system (pressure head), and physical characteristics and frictional resistance of. soils, sediments, and rocks underlying the wetland (hydraulic conductivity). Seepage into and out of wetlands tends to be concentrated in the near-shore areas (McBride and Pfannkuch 1975; Lee 1977). Groundwater recharge occurs where the wetland water surface is perched above the surrounding water table. Groundwater discharge is commonly induced by ET from the wetlands especially during the growing season. Both groundwater recharge and discharge are possible if the water table intersects the wetland water surface. Although wetlands that provide groundwater recharge and discharge simultaneously have been documented (Winter and Woo 1990), they are generally mutually exclusive (Adamus et al. 1991; Marble 1992). Fundamental hydrogeologic investigations are critical in the site-selection phase and are essential to achieving groundwater recharge or discharge in a wetland because of limits on the capacity to alter basic hydrogeologic conditions of sites.

## Flood Flow Alteration

Temporary storage of peak flow from runoff, channel flow, groundwater discharge (base flow), and precipitation in shallow depressions within a watershed delays downslope movement of potentially damaging flood waters. The stored water gradually contributes flow to streams and characteristically results in a broad but lower magnitude peak flow downstream. Landscapes contain a wide variety of shallow depressions, and all have the potential to temporarily store flood water and thereby play a positive role in flood control. Many of these depressions contain wetlands which, if not saturated, can contribute to flood flow alteration through temporary storage of overland and small stream flow.

The capacity of wetlands to significantly alter flood flow has been questioned, particularly because many wetlands are saturated (Adamus et al. 1991). Effectiveness of this function varies regionally and seasonally. Most agree that few wetlands are capable of significantly altering flood flows from severe (50- to 100-year) floods, which cause most property damage (Adamus et al. 1991).

Principal landscape factors which provide the opportunity for flood flow alteration include frequent storms, pronounced flood season, high proportion of impervious surfaces and impermeable soils, location in the upper portion of the watershed upstream of areas to be protected against flooding, and presence of numerous other depressions and wetlands in the watershed (Ogawa and Male 1986). Specific wetland features which promote this function include: constricted surface outlet, broad, flat shallow water areas, dense, broad-leaf, emergent vegetation, thick, porous wetland soils and substrates, and low groundwater discharge rates.

## Shoreline Stabilization

Shoreline stabilization is the binding of sediment at and near the coast and the physical dissipation of erosive energy caused by waves, currents, tides, storm surges, and ice (Marble 1992). Essential to sediment stabilization is the presence of dense, emergent vegetation which serves to bind and stabilize substrates with their root systems, and dissipate wave and current energy and trap sediments with their stems and leaves. Unstable shorelines generally occur along the fringes of major water bodies (oceans, seas, and lakes) or along rivers and streams, and many of these shorelines contain or are capable of sustaining wetlands.

Principal landscape factors which provide the opportunity for shoreline stabilization include: high-energy wave and current regime, high tidal range, location along a protected, non-protruding portion of the shoreline, and frequent storms. Principal factors which promote shoreline stabilization within wetlands include: low fetch, cohesive soils, dense, emergent vegetation, broad, rough shallow water areas, and toe of slope or bank which is high relative to mean storm high water. The effectiveness of shoreline vegetation largely depends upon physiological characteristics of the particular plant species involved (its flood tolerance and resistance to undermining).

## Sediment and Toxicant Retention

Water passing through wetlands undergoes appreciable chemical change. These changes are primarily the result of reduction in water velocity, decomposition of organic substances by microorganisms, metabolic activities of plants and animals, photosynthesis, and absorption of chemicals onto sediments. Of particular interest is the removal of pesticides, heavy metals, and other potentially toxic organics through chemical breakdown, temporary assimilation into plant tissue, and burial. Sedimentation rates can serve as an indicator of toxicant retention because many toxicants adhere to suspended or deposited sediment, especially clay minerals and organic matter.

Principal landscape factors which provide the opportunity for sediment/toxicant retention include: high proportion of urban and agricultural land use, high sediment yields, and frequent storms. Principal wetland features which promote this function include: high sedimentation and primary productivity rates, anaerobic conditions within the shallow substrate, large populations of organic decomposers, and constricted surface water outlets.

## Nutrient Removal and Transformation

This function involves the retention of nutrients, transformation of inorganic nutrients to their organic forms, and transformation of nitrogen to its gaseous form. Excessive quantities of nutrients, particularly phosphorus and nitrogen, degrade water quality through their promotion of algal blooms and population explosion of undesirable aquatic plants. Wetlands are more effective than uplands in removal and transformation of nutrients because anaerobic, organic-rich soils which typify wetland substrates are conducive to transformation processes.

Nitrogen transformations in wetlands involve several microbial processes (Mitsch and Gosselink 1986). Principal nitrogen transformation processes include: ammonification which is the biological alteration of organic to ammonium nitrogen ($NH_4$) during breakdown of organic matter. Nitrification is the oxidation of ammonium nitrogen by bacteria to form soluble nitrate ($N0_3$). Denitrification, which is carried out by microorganisms in anaerobic conditions, involves the conversion of air to gaseous nitrous oxide ($N_20$) and molecular nitrogen ($N_2$). Phosphorus is removed from the nutrient cycle by: precipitation of insoluble phosphates by combining with ferric iron, calcium, and aluminum under aerobic conditions; absorption onto clay minerals, vegetal matter, and ferric and aluminum oxides and hydroxides; and incorporation into living biomass.

Principal landscape features which provide the opportunity for nutrient removal and transformation include: high proportion of urban and agricultural land use, impermeable soils, high sediment yields, and frequent storms. Principal wetland features which promote nutrient removal and transformation include: prolonged residence times, high sedimentation rates, anaerobic conditions, large bacteria populations, broad, flat and shallow water areas, and constricted surface water outlets. It is of note that bacteria and other microorganisms are responsible for the transformation of most nutrients; whereas vascular plants play a relatively minor role. In general, freshwater wetlands are more effective for nutrient removal than estuarine and marine systems, largely because of higher carbon concentrations in freshwater wetlands. It is important to keep in mind that large or long-term nutrient loading cannot be assimilated without altering wetland vegetation, polluting downslope areas, or being associated with dispersal of toxicants in the food chain as the wetland reaches its capacity to assimilate nutrients.

## Production Export

Wetlands are commonly capable of producing large quantities of vegetal material which, at some time after the growing season, can be flushed out of the wetland downstream or to deeper water portions of the basin. This partially decomposed material then becomes part of the food chain and is eaten by primary consumers. Two principal attributes of a wetland which determine its ability for production export are plant productivity and capacity for physical dispersal of biomass. Organic detritus is most commonly transported from a wetland by tides or flood waters.

Principal landscape features which provide the opportunity for production export include: undeveloped watershed, seasonal flooding, high tidal ranges, and diverse ecosystems. Principal wetland features which promote this function include: discharge of nutrient-rich groundwater, high primary productivity, and good hydraulic connection with deeper water bodies. Production export is successful only if there are aquatic populations downslope to consume the exported biomass.

## Aquatic Diversity and Abundance

Nearly all freshwater and many saltwater fish species, at some stage in their life cycle, require shallow water areas. Because wetlands are commonly densely vegetated shallow water areas, they provide nutrition and habitat for abundant and diverse invertebrate and fish populations. Habitat encompasses those physical, chemical, and biological factors that are necessary to sustain larval, juvenile, and adult aquatic organisms. Habitat factors include food supply, salinity, temperature, substrate, types of shelter, current velocity, and dissolved oxygen (Adamus et al. 1991).

Principal landscape factors which provide the opportunity for aquatic diversity and abundance include: undeveloped land, diverse ecosystems, location in lower portion of watershed, and frequent storms. Principal wetland features which promote this function include: a broad range of vegetation types, water depths, water velocities and hydroperiods, high groundwater discharge rates, and abundant vegetation cover. Wetlands should be hydraulically linked by surface water inflows and outflows to deeper water areas. Diversity and abundance of wetland vegetation communities provide a variety of nutrients, protective cover, and temperature moderation by shading, and thereby promote success of aquatic populations. A portion of the wetland should contain standing water throughout the year.

## Wildlife Diversity and Abundance

Many birds, mammals, amphibians, and reptiles, including a significant proportion of threatened and endangered species, depend on wetlands for nutrition and habitat during all or part of their life cycle. To date, most of the work on wetland wildlife has focused on waterfowl and hence the discussion here is limited to wetland-dependent birds.

Principal landscape factors which provide the opportunity for wildlife diversity and abundance include: undeveloped and agricultural land, diverse ecosystems, presence of nearby wetlands, and location along migratory routes. Principal wetland features which promote this function include: a broad range of vegetation types, water depths, water velocities, hydroperiods, high groundwater discharge rates, and abundant vegetation cover. Diversity and abundance of wetland vegetation communities provide a variety of nutrients, protective cover and temperature moderation by shading, and thereby promote success of diverse wildlife populations. A portion of the wetland should contain standing water throughout the year.

Wildlife diversity and abundance are associated with three distinct waterfowl activities: breeding, migration, and wintering. Hydroperiods, water depths, density of vegetation cover, and other design considerations may be different for each of these three activities.

# 3-3 Hydrogeomorphic Classification for Wetland Design[1]

## Hydrogeomorphic Classification of Wetlands

The assessment used to group wetlands into a classification system useful for engineering design utilizes the "hydrogeomorphic" procedure developed by Brinson (1993). Wetlands are characterized by the geomorphic setting, water source, and hydrodynamics. Brinson identifies five hydrogeomorphic wetland classes as: riverine, fringe, depressional, slope, and extensive peatlands. This classification recognizes the interrelationship between hydrology and geomorphology, and climate dictates the degree of wetland functions that are distinctive to geographic or physiographic regions. The hydrogeomorphic (HGM) approach is flexible to allow identification of wetland subclasses within a region and can be evaluated in the landscape based on factors such as water source, soils, and vegetation.

Several categories presented in the HGM approach characterize the wetland setting on the basis of hydrodynamics in an inundated landscape. The hydrologic interactions between the geologic/geomorphic setting and the regional climatic regime have key elements of commonality. Important controls, such as landform morphology, basin relief, substrate type, geomorphic processes, and the length of the hydroperiod, were evaluated from wetland subclasses for similarity within the riparian, fringe, and depressional setting. Slope wetlands and extensive peatlands were excluded due to the difficulty of establishing and maintaining hydrology in large geographical areas such as the Florida Everglades or the Lake Agassiz peatlands. Slope wetlands and bogs present additional difficulties in creating ecological habitats that have evolved over time, or the hydrologic source (i.e., a groundwater seep) may be inadequate for the size of the wetland replacement.

The energy of moving water, particularly in the riparian and fringe settings, determines the magnitude and direction of water flow impacting the wetland as well as the hydroperiod. High gradient flows have lower residence times in the wetland because of a steep valley slope or high astronomical tides. Therefore, the distribution of water through time and space qualifies the energy regime for the riparian or fringe wetland setting. In the depressional wetland setting, the hydrodynamics, hydroperiod, and source of water are different. Water movement is vertical and bidirectional with residence times of water ranging from ephemeral to permanent in the depressional setting. The energy of moving water is considerably lower as water becomes modified through biogeochemical interactions of an enclosed watershed. The wetlands subclasses

[1] By Lawson M. Smith and Sandy Pizalotto

described in this chapter can be readily evaluated from existing sources, i.e. topographic maps, aerial photographs, field evaluations, and soil and plant surveys.

The various riverine, fringe, and depressional wetland settings in the United States were examined in terms of their fundamental HGM classification and divided into subclasses based on distinctive properties which have significance to wetland design, restoration, and establishment. The resulting classification yielded 31 wetland types. A systematic description of these 31 wetland types in terms of their regional setting, geomorphic occurrence, morphology, and hydrogeomorphic characteristics (hydrodynamics, hydroperiod, geomorphic features, substrate, and origin) is presented in Table 3-3. This list was further examined with respect to the likelihood of wetland engineering projects occurring in them in an effort to narrow the number of wetland environments that might require unique engineering solutions to a reasonable number.

Since wetlands perform functions by various levels of efficiency, the task of assessing diversity in the landscape should be focused on a particular wetland subclass most likely to perform a specific function. A group of 10 selected wetland subclasses, consisting of combinations of the subclasses in Table 3-3, were identified as having landscape features that control these functions and are likely to succeed as restoration or created sites. These 10 wetland types are described in the following paragraphs.

## Riverine Wetlands

Riverine wetlands are grouped into three major settings: High Energy Floodplain, Moderate Energy Floodplain, and Low Energy Floodplain. The riverine floodplain setting is characterized on the basis of unidirectional water distribution through the floodplain with the channel gradient, depositional distribution, and stream landform as key energy elements.

## High Energy Floodplain

High Energy Floodplains have steep valley gradients (>0.10 to <0.02) and very low to very high sediment transport channels. The High Energy Floodplain occurs in a confined channel of erosion and downcutting; typically, the valleys are V- to U-shaped with cascading step/pool or riffle dominated streams with a narrow wetland area restricted to the channel. These streams have relatively straight to slightly meandering channel morphologies corresponding to Rosgen Aa+, A, and B types. The streams generally have entrenched to moderately entrenched channels, low to moderate sinuosity, and low to moderate width/depth ratios. Also included in this group are braided streams (Rosgen D type) which have very wide floodplains with multiple, interspersing channels capable of wide lateral adjustments. Braided streams typically process unstable, eroding banks and transport very high sediment loads ranging from cobbles to sands. Braided streams have unstable sinuosity forms that are subjected to sudden temporal discharges or a very high sediment influx. The High Energy Floodplain typically displays a high gradient range in well-confined mountainous valleys (Aa+, A, and B stream types) or high discharge over a broad, unstable, braided floodplain (D stream type).

**Table 3-3. Wetland Hydrogeomorphic Classification[1]**

| Regional Setting[2] | Geomorphic Occurrences[3] | Riparian Morphology[3] | Wetland Hydrogeomorphic Characteristics |
|---|---|---|---|
| | | | **Riverine Wetlands[2,3,4]** |
| New England, Appalachian, Superior Upland, Colorado Plateau, Cascade-Sierra, other Provinces and Divisions | High-Gradient Valleys, Slope >10%, Aa+ Type, Figures 3-2, 3-3 **High Energy** | Very Steep, Deeply Entrenched, Narrow Floodplain associated with Waterfalls, Scour-Pools | **Hydrodynamics**: unidirectional, medium velocity flow; potential for debris flow; **Hydroperiod**: intermittent to low discharge perennial streams, short flood duration from snowmelt or storm; **Geomorphic Features**: low width-to-depth bankfull ratio, relatively straight channels in a highly confined, V-shaped valley; erosional bedrock or depositional features common; vertical step reaches with deep scour pools and waterfalls; negligible vegetation controlling influence on width/depth stability; **Substrate**: channel materials range from bedrock to silt/clay; **Origin**: down-cutting by differential erosion along geologic structures in response to regional uplift or isostatic compensation. |
| | High-Gradient Valleys Slope 4 -10% A Type, Figures 3-2, 3-3 **High Energy** | Steep, Entrenched, Narrow Floodplain associated with Cascading Step-Pools | **Hydrodynamics**: unidirectional, medium velocity flow, very high sediment transport of cobble/gravel/sand; **Hydroperiod**: intermittent to low discharge perennial streams, short flood duration from snowmelt or storm; low baseflow possibly maintained by groundwater discharge; **Geomorphic Features**: low width-to-depth bankfull ratio, relatively straight channels in a highly confined V-shaped valley; cascading step reaches with frequently spaced deep pools; negligible vegetation controlling influence on width/depth stability; **Substrate**: channel materials range from bedrock to silt/clay; stable channel/slopes with bedrock/boulder armor in most streams, alluvium generally lacking; very high streambank erosion in gravel/sand channels associated with colluvial deposits; **Origin**: downcutting by differential erosion along geologic structures in response to regional uplift or isostatic compensation. |
| New England, Appalachian, Superior Upland, Colorado Plateau, Cascade-Sierra, other Provinces and Divisions | Moderate Gradient Valleys, Slope 2 - 4%, B Type, Figures 3-2, 3-3 **High Energy** | Moderately Entrenched Riffle/Pool Floodplain associated with Rapids, Scour-Pools | **Hydrodynamics**: unidirectional, medium to high velocity flow; moderate sediment transport of gravel/sand/silt/clay; **Hydroperiod**: seasonal and climatic disparity of flow regimes resulting in temporarily flooded to intermittently exposed slopes; low base flow likely maintained by groundwater discharge; **Geomorphic Features**: moderate sinuosity and width-to-depth bankfull ratio, moderately to highly confined, riffle-dominated channel with common rapids and infrequently spaced pools in a narrow, uniformly-sloping U-shaped valley; stable channel morphology, steep, moderately-stable slopes and low terraces; moderate vegetation controlling influence on width/depth stability in cobble/gravel/sand/ silt/clay channels; **Substrate**: channel materials range from bedrock to silt/clay; colluvium and/or residual soils in small, scoured floodplain; **Origin**: Pleistocene glacial valleys with down-cutting differential erosion along geologic structures in response to regional uplift or isostatic compensation. |

[1] Brinson (1993)
[2] Bloom (1991)
[3] Rosgen (1994)
[4] Reineck and Singh (1986)

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**Table 3-3 (Continued)**

| Regional Setting[2] | Geomorphic Occurrences[3] | Riparian Morphology[3] | Wetland Hydrogeomorphic Characteristics |
|---|---|---|---|
| | | | **Riverine Wetlands[2,3,4,6]** |
| Central Lowlands, Great Plains, Coastal Plain, other Provinces and Divisions | Low Gradient Valleys, Slope < 2%, C Type, Figures 3-2, 3-3 **Moderate Energy** | Slightly Entrenched Meandering Floodplain associated with Point-Bars, Riffle/Pools | **Hydrodynamics**: unidirectional, medium to high velocity flow; very high sediment transport of sand; slow lateral shifting of channel; **Hydroperiod**: frequent overbank flooding with seasonal inundation of floodplain during most years, low base flow supplemented by groundwater discharge; **Geomorphic Features**: high sinuosity, moderate to high width-to-depth bankfull ratio, poorly to well confined, asymmetrical meandering channel with natural levees in a well-defined floodplain within a broad, terraced valley; very high vegetation controlling influence on width/depth stability in cobble/gravel/sand/silt/clay channels; floodplain features include oxbow lakes that are permanently inundated, sloughs of stagnant water that form in meander scrolls and along valley walls, backswamp areas are commonly found throughout the floodplain; **Substrate**: channel materials range from cobble to silt/clay; very high streambank erosion in gravel/sand channels; levees contain coarse sand/silt becoming more organic and clayey sloping into the backswamp areas; **Origin**: changes in the discharge magnitude to a lower base level yields new channel adjustments as a result of streambank instability; the channel response follows an increase in the width/depth ratio and a decrease in sinuosity. |
| Interior Plains, other Provinces and Divisions | Moderate to Low-Gradient Valleys, Slope <2 - 4%, D Type, Figures 3-2, 3-3 **High Energy** | Bar- and Island-Braided Floodplain associated with Alluvial/ Colluvial Fans | **Hydrodynamics**: unidirectional, multiple, low velocity flow; very high sediment transport of cobble/gravel/sand; excess bedload volume are the predominate characteristic;[5] **Hydroperiod**: seasonal stream discharge maintained upstream by moderate to high base flow; potential source for groundwater recharge; **Geomorphic Features**: rapid and continuous shifting position of channels that meet and re-divide as a bar-braided floodplain; unstable sinuosity, very high width-to-depth bankfull ratio, poorly incised, braided channels with longitudinal and transverse bars, very wide, poorly to moderately confined, asymmetrical valley; highly erodible, low slopes; alluvial and colluvial fans common in glacial outwash plains; moderate vegetation controlling influence on width/depth stability in all channels; **Substrate**: channel materials range from poorly-sorted cobble to silt/clay; **Origin:** braided rivers are controlled by the relationship of fluctuating, high discharge within a moderately steep channel slope; high sediment transport and unstable banks are contributing factors for this poorly-cohesive floodplain. |
| Intermontane Plateaus | Very Low Gradient Valleys, Slope < 0.5 %, DA Type, Figures 3-2, 3-3 **Low Energy** | Anastomosing Streams[5] associated with Stabilized Islands | **Hydrodynamics**: unidirectional, low to medium velocity flow; very low sediment transport of gravel/silt/clay; **Hydroperiod**: perennial, moderate to high base flows maintained during cool season; floodplain seasonally flooded; low base flow supplemented by groundwater discharge; **Geomorphic Features**: stable, but variable sinuosity, very high width-to-depth bankfull ratio, narrow, deep, multiple channels in a very wide floodplain in an unconfined valley, well-vegetated wetland floodplain with stable island bars, backswamps, and low terraces; very high vegetation controlling influence on width/depth stability in all channels; **Substrate**: stable gravel/sand channel materials bounded by very stable, unconsolidated, silt/clay banks; floodplain interspersed with vegetated bar islands composed of organic soils; **Origin:** fluvial response to climatic change and sediment transport mechanisms; aggrading reach is stabilized by extensive development of wetland vegetation and a low sediment bedload. |

[5] Smith and Smith (1980); [6] Mitsch and Gosselink (1986)

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**Table 3-3 (Continued)**

| Regional Setting[2] | Geomorphic Occurrences[3] | Riparian Morphology[3] | Wetland Hydrogeomorphic Characteristics |
|---|---|---|---|
| **Riverine Wetlands[2,3,4,6]** | | | |
| Interior, Coastal Plains, other Provinces and Divisions | Low Gradient Valleys, Slope < 2%, E Type, Figures 3-2, 3-3 **Low Energy** | Slightly Entrenched Alluvial Bottomland Floodplain associated with Tortuous Meandering, Riffle/Pools, and Island Divides | **Hydrodynamics**: unidirectional, medium to high velocity flow; moderate sediment transport of gravel/sand; slow lateral stream migration over floodplain; **Hydroperiod**: moderate to high base flows maintained throughout the year supplemented by groundwater discharge; seasonal, intermittent to temporary flooding of floodplain; **Geomorphic Features**: very high sinuosity, very low width-to-depth bankfull ratio; unstable gravel/sand bank slopes; narrow, shallow, stable channel in a very wide, unrestricted floodplain in an unconfined valley; variety of landforms controlled by fluvial processes include oxbow lakes, meander scrolls, point bars, natural levees, crevasse splays, sloughs and backwater areas with hydraulic connection to main channel; low rates of colluvium, alluvium deposition; **Substrate**: channel materials range from cobble to silt/clay; cohesive, silt/clay backswamp alluvium with a high organic content; very high vegetation controlling influence on width/depth stability in all channels; **Origin:** mature fluvial development subject to base level adjustment following climatic change that alters sediment transport mechanisms. |
| Interior, Coastal Plain, other Provinces and Divisions | Low Gradient Valleys, Slope < 2%, F Type, Figures 3-2, 3-3 **Moderate Energy** | Entrenched Meandering Non-alluvial Bottomland Floodplain associated with Riffle/Pools | **Hydrodynamics**: unidirectional, low to medium velocity flow; very high sediment transport of cobble/gravel/sand; **Hydroperiod**: very low slopes permanently flooded to intermittently exposed during drought; infrequently flooded terraces; base flows maintained by groundwater discharge throughout the year; **Geomorphic Features**: high sinuosity, moderate to high width-to-depth bankfull ratio; narrow, shallow, laterally unstable channel in a wide, restricted floodplain in a confined valley; moderate vegetation controlling influence on width/depth stability in cobble/gravel/sand/silt/clay channels; **Substrate**: channel materials range from cobble to silt/clay; highly weathered sediments, immature soils; organic-rich clay substrate predominates in backwater regions; **Origin**: Pleistocene development of entrenched stream valleys in response to Late Pleistocene sea-level low-stand around 18,000 years B.P.; Holocene fluvial development occurred after a reduction of discharge and sediment loads. |
| All Provinces and Divisions | Moderate Gradient Valleys, Slope 2 - 4%, G Type, Figures 3-2, 3-3 **Moderate Energy** | Entrenched Headwater Position Floodplain associated with Gully Step/Pools | **Hydrodynamics**: unidirectional, low to high velocity flow; very high sediment transport of cobble/gravel/sand; **Hydroperiod**: ephemeral or intermittent streams; soil saturation following a precipitation event produces overland flow which concentrates downslope into channelized flow; **Geomorphic Features**: moderate sinuosity, low width-to-depth ratio; deeply incised channel in a narrow valley associated with fans or deltas; unstable channel due to gradient and unstable banks; very high streambank erosion in cobble/gravel/sand channels; high vegetation controlling influence on width/depth ratio stability; **Substrate**: channel materials range from bedrock to silt/clay; derived from colluvium and alluvial materials; **Origin**: Recent physical and chemical weathering processes in response to accelerated erosion on erodible slopes. |

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**Table 3-3 (Continued)**

| Regional Setting[2] | Geomorphic Occurrences[3] | Riparian Morphology[3] | Wetland Hydrogeomorphic Characteristics |
|---|---|---|---|
| | | | **Riverine Wetlands[2,3,4]** |
| Coastal Plain | Valleys,<br>Slope < 2%,<br>E Type<br>Tributary Lake<br>**Low Energy** | Drowned Tributary Valley associated with Lateral Lakes[7] | **Hydrodynamics**: unidirectional, low to very low velocity flow; very high sediment transport of sand by main stream, low sediment transport of silt/clay by tributary of main stream; **Hydroperiod**: backwater flooding predominates when main channel is at high stages; regularly flooded to seasonally exposed; **Geomorphic Features**: levees deposited at the mouth of tributaries form backswamp deposits upstream of tributary; very high vegetation controlling influence on width/depth stability of tributary; reversed delta at lower end of tributary pointing upstream; **Substrate**: channel materials range from sands along levees to silt/clay, occasional organic soils in backswamp deposits; **Origin**: fluviatile lakes form when a river aggrades its reach faster than aggradation can occur within the lateral tributary valleys. |

[7] Hutchinson (1957)

| Regional Setting[2] | Geomorphic Occurrences | Fringe Morphology[4] | Wetland Hydrogeomorphic Characteristics |
|---|---|---|---|
| | | | **Fringe Wetlands[4,6]** |
| New England, Interior Low Plateaus, Coastal Plain, other Provinces and Divisions | Lacustrine<br>Freshwater/ Saltwater<br>**Inland Lakes and Reservoirs** | Seiche Lakes associated with Beach/Ridge Terraces and Prograding Deltas | **Hydrodynamics**: bidirectional flow maintained by wind-generated open water level fluctuations; wetland levels regulated by fluvial sediment inputs, winnowing, and export of materials; groundwater seepage and outflows dependent upon the wetland position in the landscape, vegetation, and climatic variability; **Hydroperiod**: temporarily flooded to seasonally flooded slopes during mean high water; annual mean lake level controlled by multiple year climatic cycles; **Geomorphic Features**: wave-cut terraces develop along the side of prevailing wind direction; truncated beach ridge lineaments or variable changes in the vertical sequence of deposition/erosion horizon corresponds to mean lake levels; **Substrate**: cobble to sand to shell beaches along shoreline, alluvium near basin inlets; a coarse clastic sediment overlain by peat indicates an interface between mean lake level and wetland organic deposition; **Origin**: Pleistocene to Holocene development of structural basin, glacial basin, mass-movement basin, shoreline basin or older geologic volcanic basin formation; climate controls the nature of weathering and soil development in the catchment area as well as the vegetation. |

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**Table 3-3 (Continued)**

| Regional Setting[2] | Geomorphic Occurrences[4] | Fringe Morphology[8] | Wetland Hydrogeomorphic Characteristics |
|---|---|---|---|
| | | | **Fringe Wetlands[6,9,10,11]** |
| New England & Atlantic Coastal Plain (Georgia), Pacific Border Provinces | High Energy, Marine Dominated Shoreline **Mesotidal** | Tidal Inlets and Coastal Embayments associated with Cliffs (Ria or Fjords) Figure 3-4 | **Hydrodynamics**: bidirectional flow by astronomical tides confined to a narrow foreshore zone adjacent to a steep slope; very little fluvial/groundwater discharge and high tidal flow producing homogenous salinities with no vertical gradient; **Hydroperiod**: mesotidal tidal range from 1.8 m to 3.65 m for New England and Georgia coasts, greater range during spring tides and cyclonic storms, semi-diurnal, nearly symmetrical tides with a period of 12 hr 25 min occur in the New England Province; semi-diurnal, asymmetrical tides of a range up to 2.5 m occur in the Pacific Border Province; flashy overland drainage and localized precipitation are the principal sources of freshwater; **Geomorphic Features**: shoreline barrier island development not present due to strong tidal currents; sloping foreshore with limited estuarine fringe having good drainage at low tide; **Substrate**: well-sorted sand along foreshore becoming poorly sorted mud along the backshore; intermittent gravel to boulders derived from adjacent cliffs; high marsh sediments consist of weathered silty alluvium mixed with a coarse organic fraction of root and rhizomes; **Origin**: regional coastal uplift and shoreline emergence with recent estuarine development associated with isostatic rebound; relict salt-marsh peat deposits range from 5,000 to 11,000 years B.P. |
| New England, Pacific Border Provinces, Atlantic Coastal Plain | Moderate to Low Energy Shoreline **Microtidal Marine** Type 1 | Tidal Inlets and Coastal Embayments associated with Spit Development Figure 3-4 | **Hydrodynamics**: bidirectional flow by astronomical tides in a mixed energy regime ranging from wave-dominated to tide-dominated, salinity varies by season and strength of tidal flushing; **Hydroperiod**: microtidal range < 1.8 m for Upper Atlantic, Pacific Border coasts, greater range during cyclonic storms; high marsh irregularly flooded between extreme low and high spring tides with a minimum of ten days of continuous exposure, low marsh flooded daily with a maximum of nine days of exposure; beach ridges not inundated except during exceptional storm surges; **Geomorphic Features**: long, straight barrier beaches with widely spaced inlets and well developed tidal deltas, foreshores have dunes above mean high water, backshores composed of intertidal mudflats and peaty marshes, sandbars form following periodic flooding as sediments become aligned to tidal currents and long-shore transport at the mouth of funnel-shaped embayments; tidal pools or pans in the backshore have lower accretion rates and may develop salt accumulations that inhibit vegetation growth; **Substrate**: salt marshes receive sediments from rivers, nearshore and offshore shelf deposits, beach ridges are composed of coarse sands, gravels and shell materials by the landward flow of bottom water across the continental shelf; spits are built from poorly sorted sands, silts, and clays deposited from rivers, landward of the spits and beach ridges, a sand substrate is overlain by peats forming the high marsh or mangroves, clean sand occurs near tidal inlets or on beach, tidal mudflats recently deposited lack vegetation; **Origin**: shoreline stabilization associated deceleration in sea level during the past 5,000 years where locals have an abundance of terrigenous sediments, other locals that are wave dominated have a landward flow of water and sediments across the continental shelf. |

[8] Fairbridge (1980); [9] Nixon (1982); [10] Josselyn et al. (1990); [11] Simenstad (1983)

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**Table 3-3 (Continued)**

| Regional Setting[2] | Geomorphic Occurrences[4] | Fringe Morphology | Wetland Hydrogeomorphic Characteristics |
|---|---|---|---|
| | | | **Fringe Wetlands[6]** |
| Atlantic Coastal Plain,<br>Pacific Border Provinces | High to Moderate Energy Shoreline<br>**Microtidal Marine**<br>Type 2 | Tidal Inlets and Coastal Embayments associated with Drowned River Valleys<br>Figure 3-4 | **Hydrodynamics**: bidirectional flow maintained by gradient between stream discharge, wind, and astronomical tides; salinity regulated by strong tidal flushing; **Hydroperiod**: irregularly flooded to irregularly exposed slopes inundated during regular semi-diurnal tidal oscillations, impoundment maybe constricted by local relief, resulting in amplification of tidal range between 0.5 to 2.0 meters along the tidal inlet attenuating inland; cyclical, semi-diurnal astronomic tides, low to moderate velocity tidal currents; high marsh inundated to a depth of 0.3 meter for up to 4 hours, low marsh inundated to 1.0 meter for 9-13 hours, and depressional areas have continuous standing water ranging from 0.3 to 1.5 m in depth; **Geomorphic Features**: tidal marsh elevation and proximity to over-bank flooding create zones between high and low marshes, typically, high marsh is older, more organic-rich and higher in elevation than the low marsh; depositional landforms include: distributary channels, natural levees and tidal mudflats; erosional landforms include funnel-shaped bays; **Substrate**: sediments ranging from clean sands, muddy sands, muds and organic materials; **Origin**: Late Pleistocene valley development and subsequent Holocene river drowning of river valleys and sedimentation that developed into palustrine tidal marshes. |
| Atlantic and Gulf Coastal Plains | Moderate to Low Energy Shoreline<br>**Microtidal Marine**<br>Type 3 | Tidal Inlets and Barrier Islands associated with Coastal Lagoons<br>Figure 3-5 | **Hydrodynamics**: bidirectional flow by astronomical tides in a mixed energy regime ranging from wave-dominated to tide-dominated; mixing of marine waters with continuous freshwater input results in variable salinities; tidal creeks that form in low marsh serve as conduits between the estuary and open water; occasional marine storm surges erode temporary channels within the foreshore; **Hydroperiod**: foreshore regularly inundated by daily microtidal tidal range <0.5 m for most of the Gulf of Mexico Coastal Plain; intertidal marsh irregularly exposed to irregularly inundated during spring tidal cycles; back-shore, pannes or restricted depressions, usually inundated during spring-tide high waters and storm surges; **Geomorphic Features**: beach ridges have a continuous linear dunes near the high water line with a sandy beach foreshore present with a trough-like hollow (runnel) landward of the ridge on the foreshore; occasional mangroves flats are found seaward of beach ridges; a broad area (ranging up to 8 to 11 km wide) of barrier island beaches, tidal inlets, tidal deltas, tidal channels, lagoonal basins, intertidal mudflats and salt marsh form a complex drainage system; upper part of the intertidal zone is developed as salt marsh with the lower intertidal zone as barren mudflats; shoreline progradation is a series of deposits built upon a sequence of alluvial, salt marsh deposits overlying lagoonal and coastal sand deposits extending over previous shelf muds; **Substrate**: foreshore fine to medium sand and shell debris with the backshore composed of fine sand; clean sand with occasional mud deposits comprise tidal deltas and inactive tidal channels; lagoonal substrates are muddy, organic deposits, strongly bioturbated and vegetated; intertidal substrate ranges from non-vegetated clean sand near tidal inlets to anoxic, mud deposits away from tidal inlets with bioturbation present; **Origin**: Pleistocene sediments deposited on shelf during sea level fall, shoreline stabilization began around 6,500 years B.P. |

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**Table 3-3 (Continued)**

| Regional Setting[2] | Geomorphic Occurrence[4] | Fringe Morphology[4] | Wetland Hydrogeomorphic Characteristics |
|---|---|---|---|
| | | | **Fringe Wetlands[6]** |
| Gulf Coastal Plain | Low Energy Shoreline **Microtidal Marine** Type 4 | Prograding Shoreline associated with Chenier Plains Figure 3-6 | **Hydrodynamics**: bidirectional flow generated by wind-driven and small astronomical tides in a mixed energy regime ranging from wave-dominated to tide-dominated; widely spaced, small tidal creeks drain the low marsh throughout the chenier plain; occasional marine storm surges erode temporary channels within the foreshore; **Hydroperiod**: Gulf Coastal Plain is microtidal, with a spring tide range < 2 m; foreshore regularly inundated by tidal range less than 0.5 m; backshore (upper beach) remains dry except under unusually high water conditions or storm surges; following polar frontal passages, tidal outlets within the intertidal marsh drain readily; **Geomorphic Features**: chenier plains have a series of long, narrow, wooded beach ridges parallel to the coast with a sandy beach foreshore present with a trough-like mudflat plain landward of the beach ridge; cheniers have well drained, sandy linear dunes well above the high-water level with a fine-grain foreshore and backshore; dimensions range up to 50 km in length, 6 m high, and 450 m wide, seaward side of chenier has regular, straight, steep slopes, landward side is irregular; both chenier and beach ridges have wash-over fans on top of the salt marsh; **Substrate**: cheniers consist of sand, shell and a minor amount of organic clay and silt resting upon peat or clay; chenier plain, both landward and seaward has fined-grained, organic sediments several meters in thickness capped by a several-centimeter-thick layer of muck; bay mouth deposits have well-sorted silt and oyster shell debris; **Origin**: at the close of the Pleistocene, Mississippi River delta sediments were eroded, transported westward and deposited; during the middle Holocene, around 3600 to 4000 yr ago, sea level rose to its present level, following a period of reduced deposition, winnowing away of the mud plain led to the formation of sandy beach ridges; cheniers that developed as beach ridges were further stabilized by vegetation with mudflat deposition occurring seaward of the chenier barriers; repetitive changes in the sediment supply associated with shifts in the position of the Mississippi delta is the process responsible for successive chenier formation. |
| Gulf Coastal Plain | Marine-Fluvially Dominated Delta and Estuaries Low Energy Shoreline **Microtidal Marine/Fluvial** | Prograding Delta (Mississippi River Delta) | **Hydrodynamics**: unidirectional flow of high suspended discharge entering a low tide, low wave energy, low longshore drift regime; mean annual discharge for the Mississippi River 15,360 $m^3$/s and average maximum and minimum 57,400 $m^3$/s and 2,830 $m^3$/s, respectively; annual sediment discharge averages 4.97 X $10^{11}$ kg (Wright, 1985); position of the freshwater-saltwater transition and the zone of maximum turbidity occurs within 5 km of the mouth entering the Gulf (Gibbs 1977); **Hydroperiod**: Gulf Coastal Plain is microtidal, with a spring tide range < 2 m; estuary regularly inundated by tidal range less than 0.5 m; **Geomorphic Features**: delta consists of elongate distributary mouth bar protrusions oriented normal to overall coastal trend; the sub-aerial delta, that portion of the delta plain above the low tide limit, consists of depositional surfaces adjacent and between the distributary channels and includes natural levees, overbank splays, and interdistributary channels; interdistributary areas commonly have shallow, open or enclosed bays which may become in-filled with salt marsh; **Substrate**: surface sediments consist of vegetation mats mixed with fine mucks to a depth of 10 to 35 cm and underlain by 1 to 5 m of black, low-shear-strength clay with an organic content generally exceeding 50% of the deposit; **Origin**: Result of the deposition of Mississippi River deposits onto the shallow Gulf Continental Shelf over the last 18,000 years. |

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**Table 3-3 (Continued)**

| Regional Setting[1] | Geomorphic Occurrences[6] | Depressional Morphology[6] | Wetland Hydrogeomorphic Characteristics |
|---|---|---|---|
| | | | **Depressional Wetlands[6]** |
| Interior Plains | Glaciated Regions | **Prairie Potholes**[12] associated with Ephemeral, Temporary, Seasonal, Semipermanent, Permanent, Alkali Lakes and Fen Ponds | **Hydrodynamics**: weak unidirectional flow to vertical flow supplied by precipitation, basin runoff and groundwater discharge; fresh, brackish to saline waters; dissolved solids obtained from seepage inflow or runoff are concentrated within the basin by evaporation; **Hydroperiod**: runoff from spring snowmelt to summer precipitation events sustain ephemeral, temporary, and seasonal ponds and lakes; groundwater discharge maintains semipermanent, permanent and alkali basins; fen ponds often lack open water but are maintained by alkaline groundwater seepage; basin hydrology subject to multiple year drought cycles; **Geomorphic Features**: basins are situated in an ill-defined, youthful glacial drainage area with enclosed, circular to oval, shallow depressions or near abandoned meltwater channels within the glacial drift and outwash terrain; potholes are usually less than 1 m, rarely over 2 m deep and have common perched water tables; permanently inundated potholes have wave-cut terraces with associated beach deposits; **Substrate**: organic-rich soils underlain by glacial till of various textures; occasional lenses of stratified silt/sand/gravel at shallow depths; glacial outwash ranges from boulders/cobbles to gravels/sands near fluvial meltwater sources of the end moraine; soils typically contain calcium carbonate or alkali (Na, Mg sulfate and chloride) salts; **Origin**: kettle terrain derived from Pleistocene ground and end moraines that resulted from ice stagnation; some basins created by deflation processes on a loess material deposited from outwash plains. |
| Southeastern Coastal Plain | Raised Marine Terraces and Hummocks | Hydric Hummocks[13] | **Hydrodynamics**: vertical and weak unidirectional flow in low relief interstream divides; broad, overland sheet flow following precipitation events; occasionally located in areas of groundwater discharge; **Hydroperiod**: precipitation is the principal source of water; limited flood duration from adjacent streams and seepage from sandy uplands; slopes intermittently flooded to regularly exposed; seasonal high water table from above soil surface to 0.3 m below for 2 to 6 months; **Geomorphic Features**: a slight rise in ground elevation on a former marine terrace to an isolated mound in a bottomland hardwood swamp, hummocks on coastal terraces range upwards to >40,000 ha and inland hummocks may be as small as 2 ha in area; occasional mangrove Hummocks found in the Florida Everglades that have a raised peat surface 5-10 cm above the surrounding landscape; **Substrate**: nearly level, poorly drained, low to moderate permeability; a thick organic horizon over non-alluvial, low to moderate organic content, sandy to loamy soils usually over limestone bedrock; soil pH slightly alkaline to slightly acidic; saline soils associated with mangrove hummocks; **Origin**: exposed Pleistocene marine terrace and coastal dunes that have become inundated during the Holocene sea-level rise which induced development into palustrine marshes. |

[12] Steward and Kantrud (1971); [13] Vince et al. (1989)

(Sheet 8 of 12)

**Table 3-3 (Continued)**

| Regional Setting[1] | Geomorphic Occurrences[6] | Depressional Morphology[6] | Wetland Hydrogeomorphic Characteristics |
|---|---|---|---|
| **Depressional Wetlands[6]** | | | |
| Interior Plains Appalachian Highlands | Extensive Peatlands | Ombrotrophic Bog[14] | **Hydrodynamics**: vertical flow through a perched water table in an area of negligible relief; surplus water impounded without significant surface inflow or outflow drainage; strongly acidic, organically-stained, nutrient-deficient freshwater supplied principally from precipitation; isolated from allochthonous sediment input and mineralized groundwater discharge; **Hydroperiod**: a high water table ranging from the surface to <0.5 m below the surface throughout the year in a climate where precipitation exceeds evapotranspiration; groundwater recharge maintained by bog infiltration, runoff and periodic groundwater discharge; **Geomorphic Features**: a raised, convex profile peat mound up to several meters in height in a topographically flat area formerly covered by a lake, river valley, or glacial depression; **Substrate**: a highly organic, deeply (>130 cm) stratified histosol, partially to well decomposed peat formed under saturated, anaerobic conditions; very poorly drained organic substrate with permeability decreasing with depth, organic substrate rests upon a water body or mineral (calcareous) substrate; bog substrate is composed of 90% organic material with a pH <4.5; bog acidity is due to sulfuric acid formed from the oxidation of sulfur compounds and humic acids; **Origin**: Holocene lake basins that became filled with peat derived moss vegetation under a cool moist climate; peat accumulation commonly extends beyond the original basin area; surface and groundwater hydrology became diverted around these organic obstructions which induced ombrotrophic vegetation succession. |
| Interior Plains Appalachian Highlands | Extensive Peatlands | Minerotrophic Fen[14] | **Hydrodynamics**: vertical and weak unidirectional flow in the same hydrologic setting as the ombrotrophic bog except a slightly greater hydraulic gradient is maintained between surface and groundwater flows; circum-neutral pH and nutrient-enriched water derived from groundwater passing through a mineral substrate; nutrients supplied to the minerotrophic fen by mineralized groundwater support a higher productivity than the ombrotrophic bog; **Hydroperiod**: permanent surface saturation maintained by groundwater and precipitation, long hydraulic retention time; **Geomorphic Features**: similar setting as the bog except there is a rudimentary surface drainage of anastomosing channels that drain low relief slopes of the basin; compaction of the lower layers of peat creates an impermeable horizon that forms a perched water table above a mineral soil; **Substrate**: poorly drained, slowly to moderately permeable, thick (>130 cm) histosols containing moss-sedge to woody peat; **Origin**: low relief, glaciated regions of undifferentiated till where peat accumulations have developed over several thousand years during the mid to late Holocene |

[14] Siegel (1988)

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**Table 3-3 (Continued)**

| Regional Setting[1] | Geomorphic Occurrences[6] | Depressional Morphology[6] | Wetland Hydrogeomorphic Characteristics |
|---|---|---|---|
| **Depressional Wetlands[6]** | | | |
| Mid-Atlantic Coastal Plain | Upland Interstream Divides | Pocosins[14,15] | **Hydrodynamics**: vertical and weak unidirectional flow; surface water inflow derived from overland sheet flow following precipitation events; acidic, ombrotrophic, organically-stained freshwater with available nutrients supplied by precipitation; occasional groundwater discharge areas at uphill edges of basin supplying minerotrophic freshwater; **Hydroperiod**: precipitation is the principal source of water; water table at or near the surface from 2 months to throughout the year; inundation during winter, spring flooding, slopes intermittently flooded to regularly exposed; **Geomorphic Features**: low relief, poorly-drained basins found in upland areas of inter-stream divides where the water table intersects the land surface; **Substrate**: very poorly-drained, slowly to moderately permeable, extremely acidic, organic mucks and peats ranging from 40 to >130 cm in thickness, well-decomposed organic to woody debris horizons; mineral soils typically are loamy sand with a shallow organic horizon (<40 cm) to very fine grey clay, poorly to moderately drained, moderately permeable; **Origin**: post-Pleistocene inter-stream divides that experienced a rising high water table from a decrease in stream capacity that initiated paludification upon the upland coastal plain; the expansion of water storage above the regional water table by peat consolidation permitted perched aquifer development; depression basins that do not fill completely are maintained by periodic drought and fire. |
| Mid-Atlantic Coastal Plain | Raised Marine Terraces | Carolina Bays[16,17] | **Hydrodynamics**: vertical flow and weak unidirectional flow maintained by precipitation and sheet runoff; groundwater discharge and recharge are minor hydrologic components; acidic to circum-neutral pH, ombrotrophic organically-stained freshwater; **Hydroperiod**: precipitation is the principal source of water; Carolina Bays are saturated during the winter and become dry during the summer; slopes intermittently flooded to regularly exposed; **Geomorphic Features**: an enclosed, shallow, remarkable oval shape basin, generally aligned in a northwest to southeast direction with the large end oriented toward the northwest, generally lacking natural surface inlets or outlets; many basins have a wide, elevated gravel to sand rim (>1 m in height and 18 m in width) enclosing the depression, especially along SE and NE ends; **Substrate**: acidic soils ranging from loamy along the basin periphery to silty toward the center of the depression and are slowly to moderately permeable; below the surficial horizon, a buried soil surface ranging from 30 cm to several meters in thickness is composed of sandy loams changing to a silt-clay hardpan or to well-decomposed rock (saprolite); outer rims of the depressions are permeable clean sands or gravels underlain by a sandy loam hardpan to alluvial sediments of clay and sand; **Origin**: various hypotheses of origin have been postulated to include deflation, groundwater solution, Pleistocene ice movement, and the impact of a comet. |

[14] Scharitz and Gibbons (1982); [15] Daniel (1981); [16] Savage (1982); [17] Bliley and Burney (1988)

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**Table 3-3 (Continued)**

| Regional Setting[1] | Geomorphic Occurrences[6] | Depressional Morphology[6] | Wetland Hydrogeomorphic Characteristics |
|---|---|---|---|
| | | | **Depressional Wetlands[6]** |
| Appalachian Highlands, Interior Highlands, Coastal Plain, Interior Plains | **Karst Region** | **Dolines**[3] associated with Solution, Collapse, Subsidence, Subjacent, and Cockpit Sinkholes Figure 3-7 | **Hydrodynamics**: vertical flow and weak horizontal flow maintained by precipitation and sheet runoff; unidirectional flow may terminate in a buried alluvial karst; localized areas characterized by groundwater functions; **Hydroperiod**: brief to long-term inundation following precipitation; slopes intermittently flooded to regularly exposed, impervious substrate subject to instability resulting in periodic draining and flooding; **Geomorphic Features**: enclosed, circular to oval shaped, gently to steeply overhanging slopes, lacking surface inlets or outlets; clay plug in a subterranean passage is a common feature; **Substrate**: very poorly drained to well drained, usually permeable to occasionally impermeable; substrate ranging from cobble rubble, alluvium or loess soil underlain by soluble limestone; **Origin**: a natural parting in a limestone formation without apparent displaced faulting (jointing) is the most common cause for collapse sinks; other origins occur when localized subsidence is induced by groundwater and precipitation infiltration of limestone, a process of dissolution which leads to sinkhole formation. |
| Appalachian Highlands, Interior Highlands, Coastal Plain/Interior Plains | **Karst Region** | **Uvalas**[3] associated with Compound Sinkholes, Karst Windows and Blind Valleys | **Hydrodynamics**: vertical to weakly horizontal overland flow; runoff collects in small, surface channels and that flows into depressions as a groundwater recharge site; alkaline pH, carbonate enriched freshwater; **Hydroperiod**: regularly exposed to intermittently saturated depressions; **Geomorphic Features**: a network of interconnected dolines with relict fluvial channels but lacking surface stream flow (blind valley); karst window is an unroofed underground stream channel that forms a surface valley and continues underground downslope; uvalas range from hundreds of meters to a few kilometers with an irregular surface and scalloped boundaries from earlier dolines; **Substrate**: areas of flat-lying, inter-bedded limestone, shale, and sandstone containing alluvium overlain by weathered soil or peat deposits; **Origin**: similar geological processes as dolines except a higher degree of maturity; several dolines merge and develop into a complex of uvalas; uvalas merge into larger complexes known as poljes. |
| Pacific Border Province | Raised Marine Terraces or Interbasin Divides | Vernal Pools[18] | **Hydrodynamics**: weak horizontal to vertical flow where evaporation exceeds precipitation (Mediterranean-type climate); water is fresh to brackish acidic to circum-neutral freshwater; **Hydroperiod**: ephemeral inundation during winter-spring seasons when precipitation sustains semipermanent ponding, basins are dry from summer to fall; seasonally perched water table sustained by precipitation and minor runoff; water movement by evaporation and groundwater functioning; **Geomorphic Features**: shallow, circular to elongated, shallow basins on level surfaces of incised coastal terraces, low elevation coastal mountains, remnant basalt flows, and broad alluvial valleys; a poorly developed drainage system characterized by a localized relief; surface has an undulating, hummocky (gilgai) topography of micro-basins and mircro-knolls; **Substrate**: organic-rich loamy surface soils, ranging from gravel/cobble, sandy alluvium to clay loam to sandy clay loam underlain by swell-shrink clay substrate to a clay or cemented iron-silica sand or cobble hardpan; well-developed soil horizons with surface cracking of the basin floor upon desiccation and bioturbation; **Origin**: Of various origins, many probably the result of wind deflation during less humid periods. |

[19] Zedler (1987)

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**Table 3-3 (Concluded)**

| Regional Setting[1] | Geomorphic Occurrences | Depressional Morphology | Wetland Hydrogeomorphic Characteristics |
|---|---|---|---|
| | | | **Depressional Wetlands** |
| Interior Plains | **Aeolian Basins** | **Playas**[19] | **Hydrodynamics**: weak horizontal to vertical flow where evaporation exceeds precipitation annually; alkaline to saline water, dissolved solids derived from seepage inflow or runoff concentrated by evaporation; **Hydroperiod**: ephemeral inundation principally during late spring to early fall when precipitation sustains a perched water table and semipermanent ponding; basins are dry from late winter to early spring; surface water depth <1m accumulating for short durations before evaporation; **Geomorphic Features**: alluvial fan coalescing in desert basins, broad, flat expanses of polygonal-cracked mud or saltpan remain for the remainder of the year; subsidence caused by compaction, oxidation, piping, and eluviation processes that result in basin development expansion eolian transport of silts and fine sands may further modify basin morphology; **Substrate**: clay and silt sediments underlain by leached sands and impermeable, carbonate cemented (caliche) hardpans; carbonate dissolution and translocation of silts/clays occurs by the downward movement of percolating water that enhances the permeability and porosity of underlying beds; **Origin**: Originally lakes during more humid climatic regimes, playas are typically the result of regional structural depression between mountainous areas. |
| Coastal Plain, Great Plains, Basin and Range Province | **Aeolian Basins** | **Deflational Basins**[7] | **Hydrodynamics**: vertical flow where annual evaporation exceeds total precipitation; fresh to alkaline water, rarely saline; **Hydroperiod**: ephemeral inundation principally during late spring to early fall when precipitation sustains a perched water table and semipermanent ponding; **Geomorphic Features**: linear basins are situated between well-oriented, parallel dunes built up as curved sand mounds along the lee shore of the depression; drainage is poorly defined with occasional interconnection between basins, the basin complex is shallow, < 1 m deep, <500 m in width, and up to 6 km in length; **Substrate**: basins are underlain by clay and bounded by sandy shores and in places low ridges are marked with calcareous materials; **Origin**: basins developed by wind-driven deflation processes originating during the early Pleistocene possibly modified by large animal activity; solution and subsidence processes have been suggested, but have not been substantiated. |
| Columbia Plateau, other Provinces and Divisions | Volcanic Basins | Caldera Lakes | **Hydrodynamics**: strong horizontal and some vertical flow ; **Hydroperiod**: usually remain relatively constant with most hydrologic input during winter months; **Geomorphic Features**: steep shorelines with occasional small cinder cones; **Substrate**: rocky, with thin silty/clayey coatings; **Origin**: basins that developed from various volcanic formations ranging from collapsed lava flows (Yellowstone Lake, WY), in calderas of inactive volcanoes (Crater Lake, OR; Medicine Lake, CA). |
| Coastal Plain, other Provinces and Divisions | Tectonic Basin | Newland Lakes, Sag Ponds and Lakes | **Hydrodynamics**: strong horizontal and moderate vertical; **Hydroperiod**: annual fluctuations due to moisture surpluses and deficits; **Geomorphic Features**: irregular to regular wind and wave-modified shorelines interrupted by small deltas of tributary streams; **Substrate**: typically sandy; **Origin**: newland lakes form due to isostatic adjustment of former Pleistocene marine surfaces on which there were irregularities due to uneven sedimentation (Lake Okeechobee, FL); basins created by tectonic movement creating grabens between faults (Pyramid Lake, NV), tilted fault block basins (Abert Lake, OR), and earthquake-induced subsidence (Reelfoot Lake, TN). |
| Sierra Nevada | High Elevation Glacial Lakes | Cirques | **Hydrodynamics**: strong horizontal, some vertical; **Hydroperiod**: relatively uniform due to high altitude; frequently freeze during winter; **Geomorphic Features**: rocky but regular shorelines of glacial deposits; **Substrate**: relatively coarse gravelly, cobbly sediments; **Origin**: Cirques are the product of glacial growth and downslope progradation with resulting depressional erosion by basal and longitudinal scour by ice. |

[19] Osterkamp and Wood (1987)

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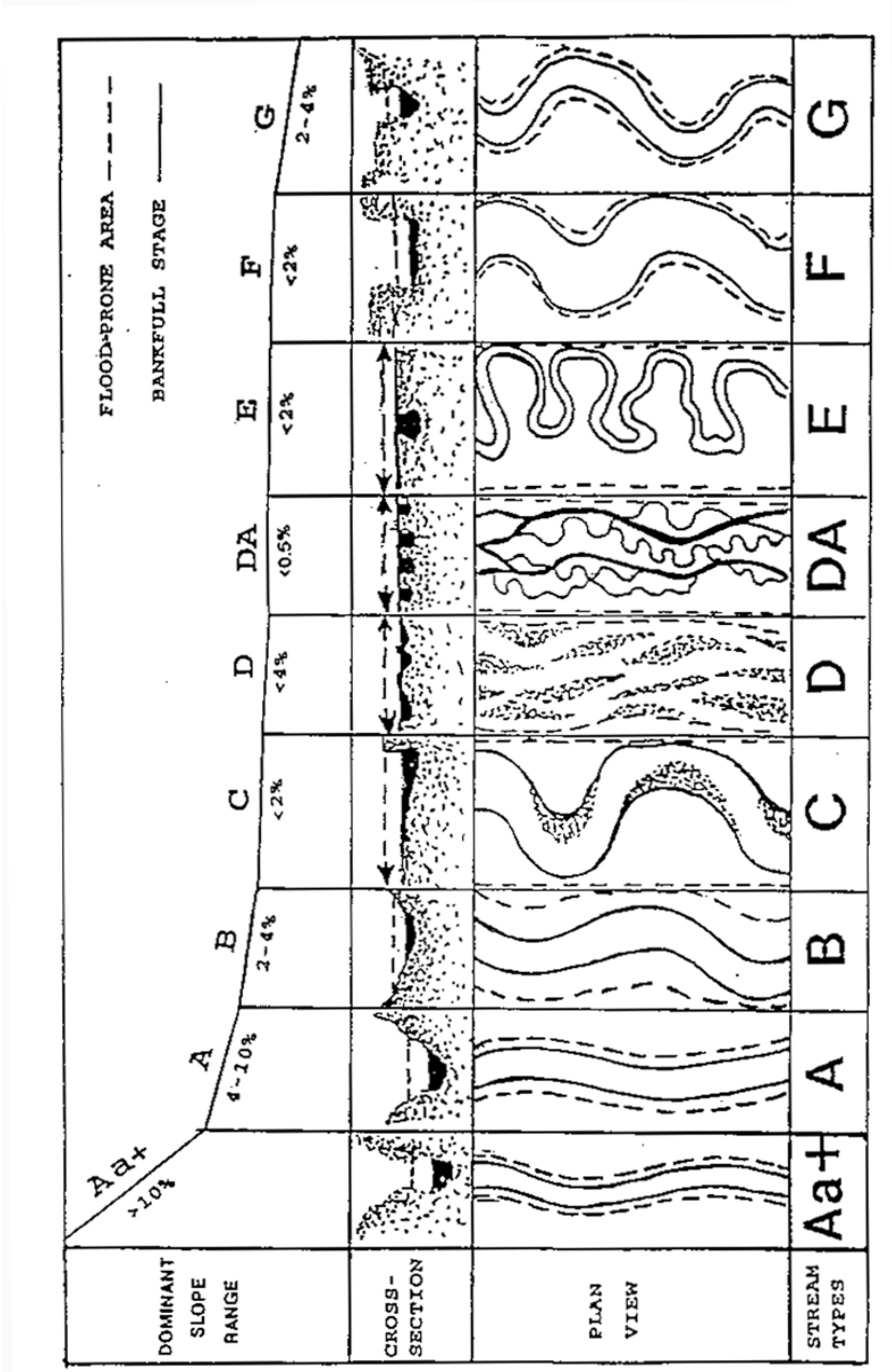



Figure 3-2. Valley gradient, cross-section and plan views of the major stream types (after Rosgen 1994).

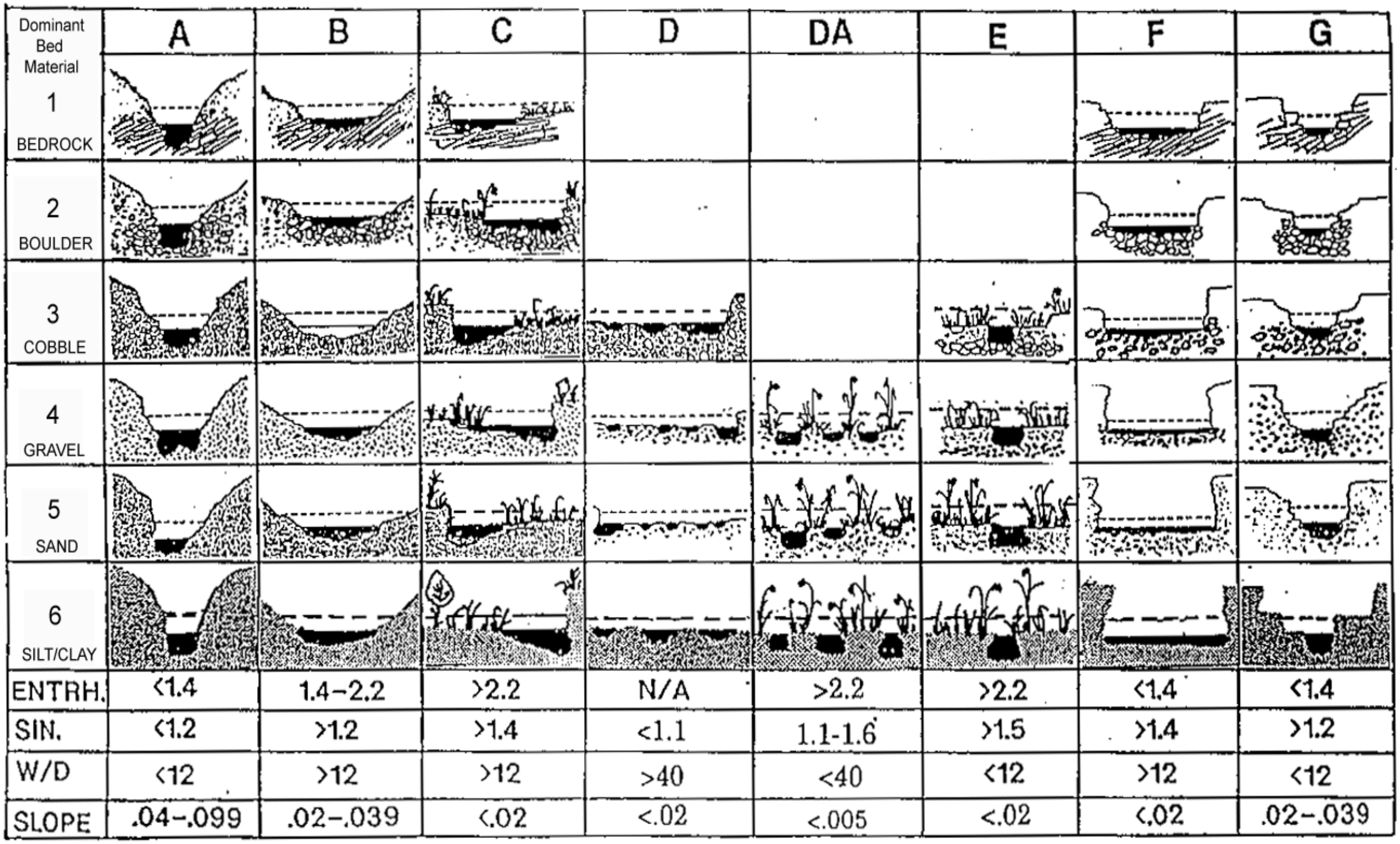



Figure 3-3. Cross-sectional plan view of the major components (entrenchment, sinuosity, width/depth ratios, and slope), substrate, and floodplain delineation of major stream types (after Rosgen 1994).

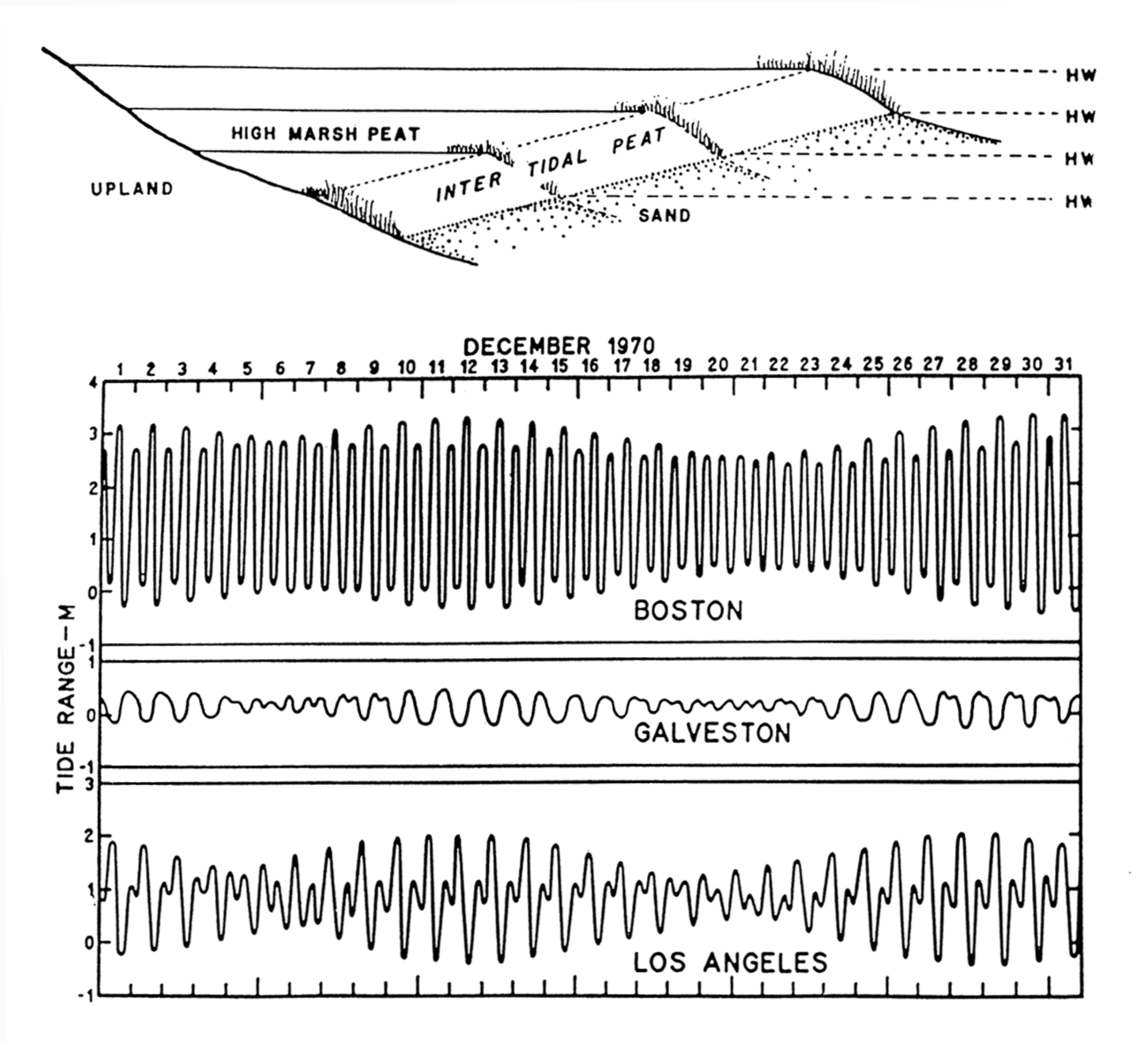



Figure 3-4. Tidal marsh models (top) and tide range regimes (bottom) (from Nixon 1982).

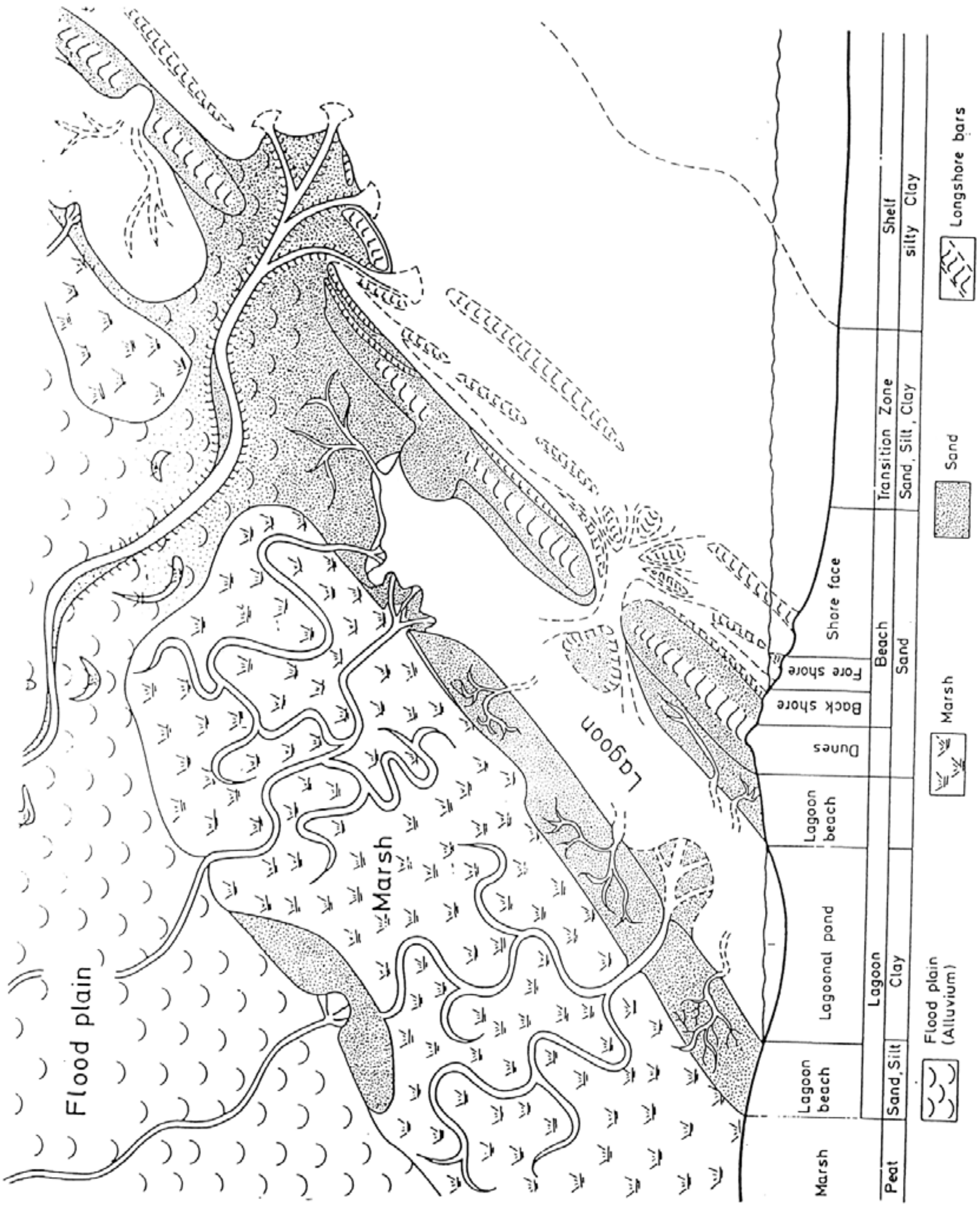



Figure 3-5. Cross-section and plan view of the major geomorphic features of barrier islands and associated lagoons characterizing the estuarine margin (after Reineck and Singh 1986).

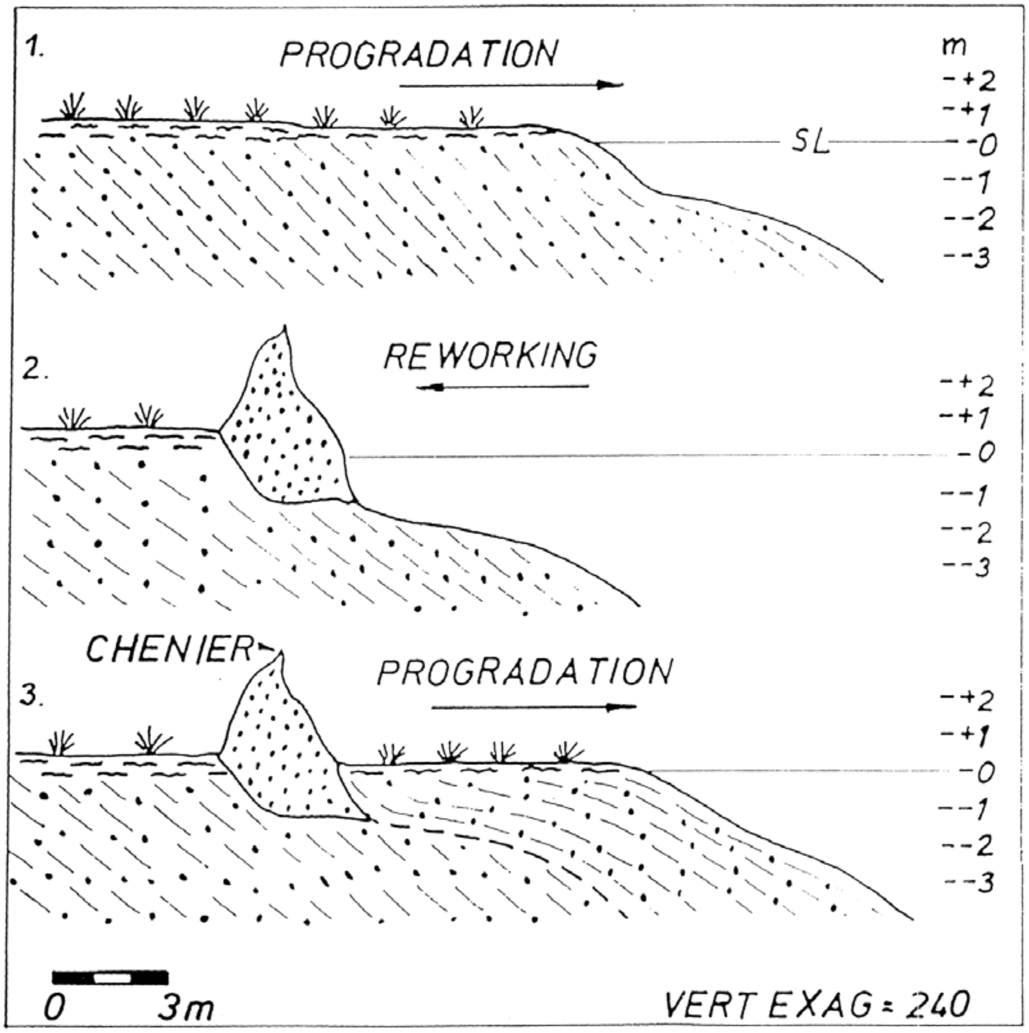



Figure 3-6. Chenier model (from Reineck and Singh 1986).

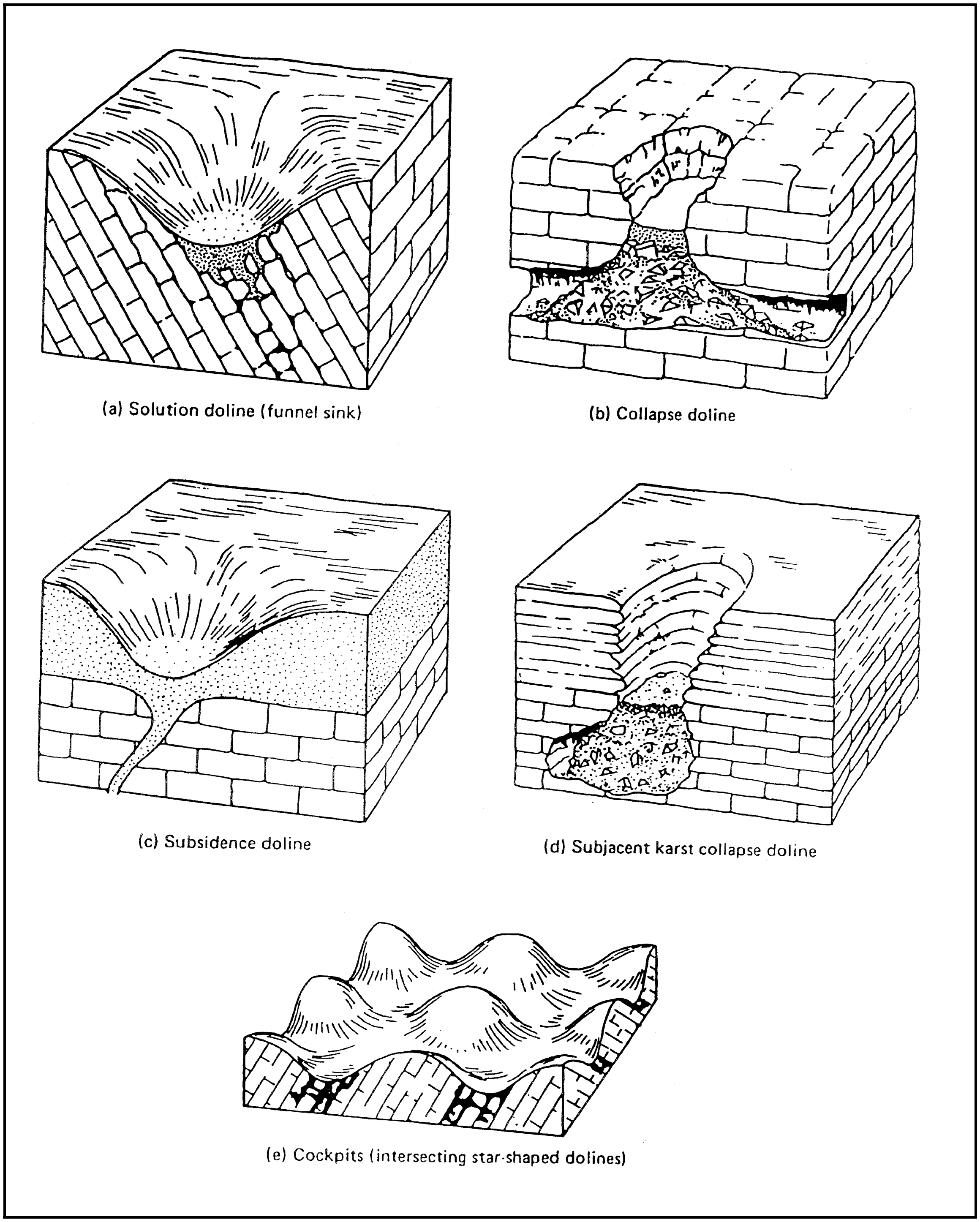



Figure 3-7. Block diagram of karst features associated with the five types of dolines (after Jennings 1985).

## Moderate Energy Floodplain

Moderate Energy Floodplains have valley gradients between 0.039 and <0.001 and very low to very high sediment transport channels. The Moderate Energy Floodplain commonly displays meandering, point-bar, riffle/pool channel morphology within a well-defined, broad alluvial floodplain. The floodplain is associated with asymmetrical (Rosgen stream type C) to symmetrical channels (Rosgen stream type F) and upland terraces. A variety of riverine wetlands whose channel morphology corresponds to the C stream type include: oxbow lakes, abandoned channels or sloughs, crevasse splays, natural levees, meander scrolls, and backswamp areas. This stream type has a slightly entrenched, high sinuosity, and moderate to high width/depth ratio channel that has developed in a mature floodplain. The Rosgen F stream type is quite similar to the C stream type except the channel has a well-entrenched channel profile and steep, laterally unstable banks. The Rosgen G stream type has an entrenched gully form, commonly found in narrow valleys, or deeply incised in alluvial landforms, such as fans, deltas, or well-developed floodplains. The Moderate Energy Floodplain has a moderate gradient range in a meandering, broad alluvial valley capable of distributing well-weathered alluvium of various sediment particle sizes to different alluvial environments. Their channels, particularly stream types F and G, are generally unstable with grade control difficulties and excessive bank erosion.

## Low Energy Floodplain

Low Energy Floodplains have valley gradients between 0.039 and <0.005 and very low to moderate sediment transport channels. The Low Energy Floodplain has a variety of stable, well-vegetated wetlands consisting of anastomosing, very high width/depth ratio (Rosgen Stream Type DA) channels and highly meandering, but very low width/depth ratio (Rosgen Stream Type E) channels. These slightly entrenched to well entrenched streams exist in broad, low gradient, unconfined, alluvial valleys whose channel beds are absent in bedrock or boulder substrates. The Low Energy Floodplain is capable of dissipating overbank floodflows readily due to its high vegetation controlling influence. The anastomosing stream (DA stream type) has interstream divides or stabilized islands that are laterally stable and provide the geologic control for a broad wetland floodplain. The tortuous meandering (E stream type) has a riffle-pool morphology that is efficient and stable at bank-full stages but has a very high potential for disturbance should the stream flow and/or sediment transport regime increase. Lateral lakes are extensions of the E stream type where tributaries entering the main trunk of the stream are periodically inundated by backwater flooding during high stages. The resulting siltation decreases the slope at the mouth of the tributaries, resulting in the formation upstream of palustrine marshes or bottomland hardwood swamps.

## Fringe Wetlands

Fringe wetlands were grouped into four major settings: Inland Lakes and Reservoirs, Mesotidal Marine, Microtidal Marine, and Microtidal Marine/Fluvial. The fringe wetland settings are grouped on the basis of bidirectional movement of a deep water environment controlled either by astronomical tides or wind-driven seiche. The tidal range is the key energy element difference between the mesotidal and microtidal environments. Another important distinction in the fringe setting is the relative salinity impacting the estuarine environment. There are several landforms in the microtidal environment (Types 1-4) where the influence of tidal energy and salinity must be evaluated for any site characterization.

## Inland Lakes and Reservoirs

Inland Lakes and Reservoirs have a deepwater environment greater than 2 meters in depth at low water and are situated in a topographic basin or dammed river channel having an area greater than 8 hectares. Water levels can be artificially regulated as in reservoirs and can transmit water by inlet or outlet or are hydrologically isolated. Lacustrine waters may be fresh to saline, but the salinity is not derived from oceanic waters. The principal water movement, by wind-driven seiche, is indicated by a wave-dominated shoreline that may be modified by the geomorphic setting.

## Mesotidal Marine

Mesotidal marine wetlands have a tidal range greater than 2 meters in depth and border a deepwater environment of marine origin. The mesotidal fringe setting is in a high energy regime that is wave to tidally influenced. Typically, mesotidal wetlands have a narrow foreshore adjacent to a steep slope and lack barrier island development. Other fringe settings in this environment may include coastal embayments and tidal inlets produced by drowning or submergence of the lower part of a river valley or estuary.

## Microtidal Marine

Microtidal Marine wetlands have a tidal range less than 2 meters in depth and consist of four types of shorelines influenced by high to low energy regimes. The shorelines range from wave- to tide-dominated with a variety of estuarine landforms influenced by fluvial systems. Salinity in these estuarine wetlands varies by season and the strength of the tidal flushing. Sediments supplied by longshore or fluvial transport to the estuarine marshes are dependent upon the position, elevation, and proximity of the wetland to the depositional source. Moderate to Low Energy Shorelines (Type 1) have barrier beaches with widely spaced inlets and tidal deltas typical of spit development by longshore transport. High to Moderate Energy Shorelines (Type 2) have tidal inlets and coast embayments associated with drowned river valleys that are generally tide-dominated and strongly influenced by longshore transport. Another Moderate to Low Energy Shoreline (Type 3) has tidal inlets and barrier islands associated with coastal lagoons that range from tide- and wave-dominated barrier beaches to wind-driven-tidal and fluvial dominated estuaries. Low Energy Shorelines (Type 4) are dominated by wind-driven tides along chenier plains, a barrier beach with an extensive backshore area drained by widely spaced tidal creeks. These four microtidal marine wetland types contain many geomorphic features but are largely controlled by the degree of tidal flushing and the relative position of the estuary.

## Microtidal Marine/Fluvial

The microtidal marine/fluvial wetland is a low energy shoreline strongly influenced by large prograding deltas (principally the Mississippi Delta in the United States) having a prominent freshwater and sediment input. Inter-distributary areas of the deltas commonly form salt marshes in relatively short time periods due to a high suspended sediment discharge entering a low wave and low longshore transport regime. This type of wetland is one of the most dynamic in terms of geomorphic evolution. Consequently, the ability of microtidal marine/fluvial wetlands to provide specific functions at specific locations may change substantially over time (tens of years).

## Depressional Wetlands

Depressional wetlands are grouped into three settings that have the greatest potential for creation or possess the best opportunity for restoration and enhancement. These wetlands include prairie potholes, karst, and Aeolian Basins. Other depressional wetlands listed in Table 3-3 which were not included in this discussion are hydric hummocks, ombrotrophic bogs, minerotrophic fens, pocosins, Carolina bays, vernal pools, caldera lakes, newland lakes and sag ponds, and glacial cirques. These wetlands are somewhat limited in geographic extent and occurrence. Depressional wetlands are influenced by the vertical, bidirectional water distribution in a hydrologically isolated region that imparts to wetlands a distinctive water chemistry. Characterization of shallow-water settings utilizes the geologic and geomorphic setting for predicting the function that a depressional wetland can perform.

## Prairie Potholes

Prairie Potholes are small basins that have formed in glacial terrain whose principal hydrologic input is from precipitation and groundwater. The hydroperiod of these small watersheds is controlled by the geologic substrate and climatic trends that determine the length of inundation ranging from ephemeral to permanent water levels. The pothole basins are situated in youthful drainage areas of various substrates ranging from permeable glacial outwash deposits to slowly permeable glacial till. The type of substrate and the interaction of groundwater characterize the water chemistry that influences the wetland vegetation found between various basins in a given region. Prairie Potholes have been identified as a setting that can be readily recreated in an important aquatic and wildlife habitat area as well as provide opportunities for groundwater recharge, sediment stabilization, and nutrient transformation in many natural basins.

## Karst Wetlands

Karst Regions are a type of topography characterized by sinkholes, caves, and underground drainage where dissolution of limestone, dolomite, or gypsum substrate occurs. In the HGM based classification, “dolines” and “Uvalas” are subsets of karst wetlands. These closed depressions range from simple sinkholes with steep contours to basins interconnected to one another, but are hydrologically isolated from riparian or fringe settings. Precipitation is the principal water source for these wetlands, becoming intermittent ponds and lakes during periods of heavy rainfall that percolate readily into water table aquifers. Karst Regions provide many opportunities for enhancing groundwater recharge and habitat/diversity although difficulty may be encountered in actual sinkhole creation due to problems regulating the hydroperiod. In many areas in the country where there is suitable surface limestone formations, small basins can provide opportunities for enhancement projects.

# Aeolian Basins

Aeolian Basins consist of two types of basins that originate wherever water can collect in surface depressions, principally, playas of the Southern High Plains (Texas and New Mexico) and deflational basins in the Sandhills of Nebraska. These basins have dissimilar forms and originate from different geomorphic processes. Playa basins originate as surficial lineaments from geologic structures that form as a result of dissolution and the downward movement of carbonates in the soil. Upon drying and exposure of the playa floor, wind erosion causes further expansion of the basin. Deflation basins, formed under previous arid conditions of the past, have basins enclosed by well-oriented, parallel rows of sand dunes created by wind deposition. The deflation basins evolved as small wetlands between the dunes following a change to a moist climate regime. The rise in the regional water table fostered vegetation that created an impermeable substrate. As with the Karst Regions, creation projects would be difficult to regulate a predictable hydroperiod, but many opportunities exist for functional restoration at many sites.

# 3-4 Hydrologic Design Criteria[1]

## Introduction

In wetlands engineering, hydrology is often used as a very broad term that encompasses all hydrologic and hydraulic processes related to wetlands. There are many hydrologic and hydraulic considerations important to wetland restoration and construction. The hydrology of the wetland is critical to the achievement of any and all of the functions described in this handbook. Although there are many functions and wetland types which require very different hydrologic and hydraulic conditions, the list of hydrologic design considerations (criteria) is actually quite short when boiled down to the most basic elements. The important hydrologic design criteria are hydrologic setting, flood duration and timing, flooding depth, flow velocities, flow resistance, hydraulic retention time (HRT), storage capacity, surface area, and fetch.

While some of these hydrologic criteria are purely hydrologic considerations some contain other characteristics, such as the importance of wind direction in the fetch criteria. In addition, these hydrologic design criteria are not completely independent of one another. For instance, surface area, storage capacity and HRT are interrelated by the geometry of the hydrologic features of the wetland. In that regard, the breakdown of hydrologic criteria is somewhat ambiguous and overlapping, which is always the case when trying to reduce a complex system into smaller digestible parts.

The essential hydrologic criteria for each of the different wetland functions are listed in Table 3-3. Although all of the above criteria may be important for each of the functions, certain criteria are essential to the attainment of some functions. In general, criteria in the table are listed in order of relative importance, with the most important variables coming first. However, for many functions the criteria may play an equal role, or the importance of each may vary between wetland types and individual wetlands of the same type. Each of these design considerations is briefly discussed below.

## Hydrologic Setting

The hydrologic setting of the wetland is used here to describe the location of the wetland in relation to other water bodies. These water bodies could consist of small streams, rivers, lakes, estuaries, groundwater or other wetlands. The hydrogeomorphic classification partially, but not completely, describes the hydrologic setting of the wetlands. The hydrologic setting is important

[1] By Charles W. Downer and Lawson M. Smith

to all wetland functions but is of particular importance to groundwater recharge/discharge, sediment retention, flood-flow alteration, and production export.

The hydrologic setting is particularly important to the functions of groundwater recharge and discharge. The topographic elevation of the wetland relative to the water table will determine which, if either, of these hydrologic functions the wetland may fill. The hydrologic setting is also a critical consideration for flood-flow alteration, as the position of the wetland in relation to the stream will play a large role in how the wetland affects the flood hydrograph. For production export to occur, the wetland must be located upstream of and be hydraulically connected by surface channel flow to the water bodies that are to be enriched.

The hydrologic setting is also of particular importance to the aquatic diversity of the wetlands. Fringe and riparian wetlands are tied to larger bodies of waters, such as streams, rivers, lakes, and estuaries and are often used by the aquatic species of the larger water bodies as feeding areas, nurseries, etc. The use of wetlands by aquatic species of other water bodies will depend, in large, on the wetland's flooding timing, depth and duration.

## Flooding Duration and Timing

In wetlands, the duration and timing of flooding is often referred to as the hydroperiod. The proper hydroperiod is essential to the attainment of almost every wetland function. The duration and timing of flooding will significantly influence which plant species are viable for the wetland, what birds and animals will visit and use the wetland, recreational opportunities, and groundwater recharge and discharge. The timing and duration of flood flows are also important design criteria for sediment and toxicant retention, sediment stabilization, and biological production/export.

## Water Depth

In addition to flooding timing and duration, flooding depth is also important to many wetland functions. The importance of water depth is frequently tied to the timing and duration of flooding. For example, deep flooding of a wetland for a very short period may not be as important to wetland functions as sustained low level flooding. The depth and turbidity of water has a profound effect on vegetation. In concert with the timing and duration of flooding, water depth and turbidity strongly influence which types of vegetation may grow in the wetland. In general, there is a transition from emergent to submergent vegetation at a depth of 0.5 to 1.0 m, and a transition of submergent to floating vegetation at depths greater than 1.0 m (Hammer 1991). These direct effects on vegetation have indirect effects on flood-flow alteration, sediment stabilization, sediment/toxicant retention, nutrient removal/transformation, production export, and wildlife and aquatic species usage.

The depth of water also has direct effects on groundwater recharge and discharge. The depth of water in the wetland provides the downward driving force for water. Deeper water produces stronger piezometric gradients. encourages groundwater recharge and discourages groundwater discharge.

The depth of water can also be important in the sediment/toxicant retention and sediment stabilization functions because the depth of water affects the flow velocity and shear stresses which affect erosion and sediment accretion. For a given flow, greater water depth will result in lower flow velocities and less shear stress on bottom sediments. Reduced shear stresses will result in less erosion of bottom sediments and deposition of suspended sediments. Wildlife abundance and diversity and aquatic abundance and diversity are also directly affected by the available water depth.

The flooding duration, timing and depth are determined by the wetland water balance. The water balance of a wetland is a basic accounting of water that enters or leaves the wetlands. Water balances are typically constructed on a monthly basis but may be of any length of time needed to adequately define the water regime. The water balance should be one of the first considerations of any wetland project design and would preferably be determined along with the site selection process. Defining the water balance incorporates a host of design criteria related to water levels, hydroperiods, and other hydrologic conditions. Things to consider in computing the water balance are: surface flows, precipitation, evapotranspiration, and groundwater discharge and recharge. The storage capacity of the wetlands includes surface water storage and water retained as soil moisture.

## Flow Velocity

The velocity and related stresses of flowing water are important to several wetland functions. Flow velocity has a critical impact on sediment and toxicant retention and sediment stabilization. As discussed below, flow velocity is a key condition of both erosion and settling of soil and organic particles. Flow velocity provides energy for the erosion of soil and organic material and the turbulence and lift to keep materials in suspension. Flow velocity will also affect the production/export function in it and will determine how much organic matter in the wetland will be exported downstream. Flow velocity also affects the hydraulic retention time (HRT), which in turn affects water quality enhancement characteristics. Higher flow velocities result in reduced HRTs. This reduction in HRT can cause a reduction in treatment efficiencies of suspended sediments and other pollutants. Additionally, flow velocity has a major effect on aquatic organisms as a critical environmental characteristic of their habitat.

## Flow Resistance

The depth and velocity of the flow in the wetland is dependent on flow resistance. For surface flows, flow resistance is the frictional drag of the wetland bottom and vegetation. Densely vegetated wetlands produce a great deal of resistance to surface flows. The roughness coefficient for equations such as the useful Manning estimation of flow velocity may be greatly increased by dense vegetation (Chow 1959, Kadlec 1990). Manning's roughness coefficients for natural channels may vary from 0.035 for a slightly meandering channel with clean gravel bottom to 0.150 for an irregular channel cluttered with trees, stumps and rocks. Manning's roughness coefficients as high as 0.55 have been measured in subtropical marshes (Shih and Rahi 1982). An increase in the Manning's n equates to an increase in frictional resistance to flow. As the resistance to flow increases, flow velocity decreases and flow depth increases. It is important to note that the Manning equation may not be applicable in densely vegetated wetlands because the vegetation changes the flow regime and redistributes the frictional resistance along the water column (Downer 1993).

Aquatic vegetation can cause a reduction in flow because energy is required to overcome the additional resistance to flow. The exact effect of an increase in frictional resistance depends on other channel parameters. Flow resistance can be important for several functions, including flood attenuation, sediment/toxicant retention, and sediment stabilization.

## Hydraulic Retention Time (HRT)

The HRT is defined as the average amount of time that a parcel of water stays within the wetland before exiting. The HRT is the key design criteria for water quality enhancement functions such as sediment/toxicant removal and nutrient removal/transformation. Wetlands essentially function as biological treatment systems and have a variety of mechanisms to treat, transform and remove pollutants in water. The mechanisms consist of physical, chemical, and biological processes, each requiring some minimal HRT to remove pollutants. Flowing waters must remain in the wetland long enough for these processes to occur if treatment is to be effective. However, excessive HRT in the wetland may cause wetland water quality problems such as low dissolved oxygen and production of sulfide and methane gases.

In general, the HRTs necessary to remove particulate matter are less than those required to remove dissolved constituents. The minimum HRT of the wetland is that required to achieve the level of treatment desired for the most persistent constituent. Hydraulic retention time is affected by the hydrologic setting, water depth, flow velocity, vegetation, and various other design criteria.

## Storage Capacity

Storage capacity is most important in the flood-flow alteration function because the amount of available storage in the wetland determines how much of the available stream flow can be routed into or through the wetlands The wetland's storage also affects the HRT, though the HRT is considered the design parameter, not the storage. The storage capacity may also affect groundwater recharge/discharge and aquatic abundance/diversity, in that larger wetlands will have more potential for groundwater recharge and may support more aquatic organisms. Wetland storage capacity, in relation to flood-flow alteration, is further discussed in the Flood-flow Alteration Section, Section 2.

## Surface Area

The wetland surface area is important for groundwater recharge and discharge. The groundwater recharge will be a function of the surface area, water depth, permeability of underlying soils and location of the water table. The amount of water recharged is often directly proportional to the surface area of the wetlands The surface area of the wetland also affects evapotranspiration which can be important for groundwater discharge and water quality functions.

# Fetch

Fetch is the length of open water available for wind-induced waves. Fetch is an important hydraulic consideration in wetlands because they are usually shallow water bodies which can be easily affected by wave action. The fetch of the wetland is especially important in sediment stabilization and sediment and toxicant retention. Long fetches will produce erosion of the downwind shoreline. Long fetches will also cause the resuspension of sediments and associated toxic chemicals and nutrients. Once these constituents are re-suspended they may have deleterious effects on organisms that live in or visit the wetland. Sediments may also be transported downstream by flowing water, losing any water quality benefits derived earlier by the settling of suspended particles.

Fetch is also important to water quality concerns because the greater the fetch the better the reaeration, the reintroduction of oxygen to oxygen-depleted waters. In addition, wave action may also induce the volatilization of constituents in solution. These effects may be important for both nutrient and toxicant transformations.

# 3-5 Geotechnical Design Criteria[1]

## Introduction

A major goal of wetland creation and restoration is to produce an environment that provides desired functions and, at the same time, exists as a landform which is in equilibrium with the surrounding landscape. To accomplish this, it is essential to consider the composition, arrangement, and movement of earth materials in the landscape. Geotechnical considerations tend to be primary decision-making guides for wetland site location, design, and construction because earth material composition and transformations they undergo profoundly influence the hydrology and biology of a landscape.

To create wetlands that provide desired functions and are in equilibrium with the landscape, a number of geotechnical characteristics of a wetland site must be considered. These include: geologic setting, geomorphic setting, wetland form and size, soil composition and texture, hydrogeologic processes, geomorphic processes, and geomorphic trends. In this chapter, these seven geotechnical characteristics are described. This discussion, however, is not a detailed guide to geologic and geomorphic analysis of landscapes, but does reference materials where such information is available.

## Geologic Setting

By offering variable resistance to geomorphic processes acting upon them, the distribution of rocks and sediments of varying composition has a profound effect on groundwater flow, topography, drainage patterns, and other landscape features and processes. Detailed geologic analysis of an area involves classifying rock and sediment types present (composition), determination of their stratigraphy (geometry), and evaluating their structural features (orientation). Each of these procedures is discussed below.

### Rock and sediment composition

Rocks are cohesive aggregates of grains of one or more mineral types. Sediments are any number of materials deposited at the earth's surface by physical, chemical, or biological agents. Minerals are naturally occurring, solid, inorganic elements or compounds, with a definite composition or range of compositions, usually possessing a regular internal crystalline structure. Geologic material is either igneous, metamorphic, or sedimentary in origin. Igneous rocks are

[1] By Lawson M. Smith and Sandy Pizalotto

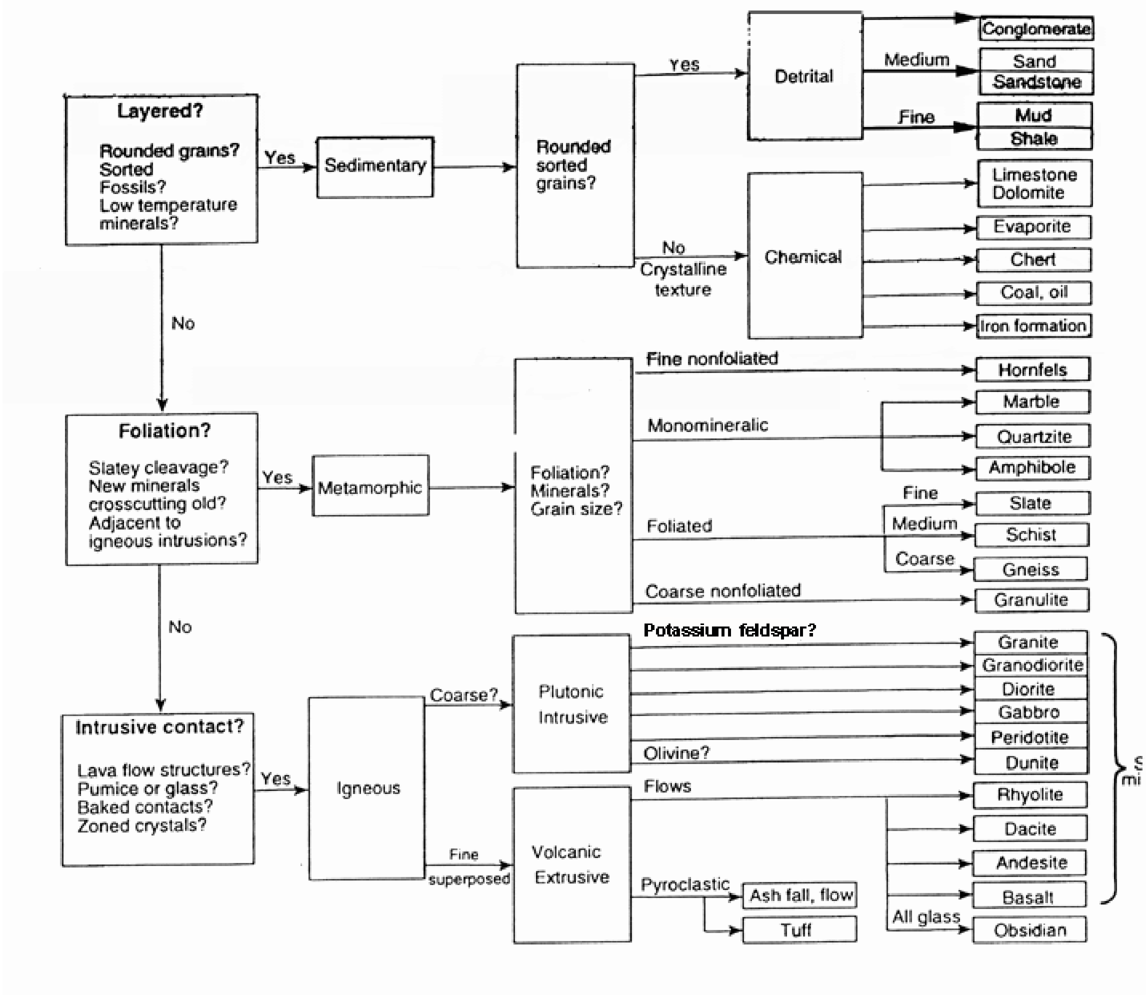



Figure 3-8. Rock identification chart. Gravel, sand, and mud (indicated by asterisk) are sediments; conglomerate, sandstone, and shale are their rock equivalents (after Press and Sevier 1986).

derived from molten rock or magma and are intruded into preexisting rocks below the earth's surface where they slowly cool, or are extruded onto the earth's surface where they quickly cool. Metamorphic rocks are preexisting igneous, metamorphic, and sedimentary rocks which have undergone recrystallization and changes in texture deep in the earth by coming into contact with molten rock, undergoing extreme pressures, or hydrothermal alteration. Sediments and sedimentary rocks are detrital material that was transported and deposited by fluids such as air and water, or are skeletal material (mostly shell) which may have been transported or may have accumulated in place. A basic classification of rocks and sediments and their fundamental characteristics is presented in Figure 3-8. An introduction to rocks and minerals can be found in Dietrich and Skinner (1979). The texture (size, shape, and arrangement of their components) of rocks and sediments is discussed in the hydrogeology section of this chapter.

Igneous and metamorphic rocks tend to be highly crystallized (have very low porosities) and indurated. Igneous and metamorphic rocks form at temperatures and pressures far greater than earth surface conditions which results in mineral constituents that are unstable (vulnerable to weathering) at or near the earth's surface, particularly in the presence of water. There is the general relationship that the higher the temperature and pressure conditions are under which minerals and rocks are created, the more unstable they are at the earth's surface and the more easily they react with water to dissolve and (or) form minerals (mostly clays) that are stable under low P-T conditions. In general, the higher proportion of the mineral quartz ($SiO_2$) a rock contains, the more resistant it is to weathering and erosion. Carbonate rocks (limestone and dolostone) dissolve in the presence of water and form distinctive karst topography.

Sediments are either consolidated or unconsolidated, that is minerals are either bound together by mineral cement or not. Sediment consolidation typically involves deep burial and solution re-precipitation of certain mineral components by groundwater which markedly decreases the permeability of sediments and increases their resistance to erosion. Unconsolidated sediments are known simply as sediments, or perhaps soils to engineers (see discussion of the term soil in the Soil Texture and Composition section of this chapter). Consolidated sediments are known as sedimentary rocks.

An essential component of site characterization is a geologic map which is sufficiently detailed to evaluate rock and sediment distribution in the watershed. Such maps may be available from state geologists, nearby academic geology departments, and local environmental or engineering firms. Detailed geologic maps provide information regarding the surface distribution of sediments and rocks. Additionally, by using symbols that indicate orientation of rock layers, these maps provide information regarding the subsurface distribution of earth materials important in wetland design and evaluation.

## Stratigraphy

Wetlands are commonly lowland features situated in areas of active sediment deposition and thus are underlain by unconsolidated sediment. Sediments typically occur in layered form. These layers reflect changes in sediment composition and grain size that result from modifications of the physical environment from which the sediment is derived as well as the environment of deposition itself. Layered sedimentary units are referred to as strata, and stratigraphy is the geologic study of both the physical (composition, form, arrangement, geographic distribution) and temporal (chronologic succession, and correlation) attributes of strata. Stratigraphic analysis not only provides information regarding the physical and temporal characteristics of sediments, it provides vital information regarding groundwater flow (i.e. geometry and distribution of water-bearing units).

Stratigraphic analysis typically involves field mapping and (or) acquisition of a series of sediment cores. Stratigraphic units at each field site and boring are then differentiated based upon distinctive physical attributes such as composition, grain size, and color. Stratigraphic successions from different areas or borings are then correlated. Attempts to correlate stratigraphic units based solely on physical attributes may lead to spurious conclusions because, like extant sedimentary environments, strata are not continuous. Correlations may be strengthened using additional indicators of stratigraphic similarity. Once areas and cores are correlated, a series of cross-sections are constructed which accurately portray the area's stratigraphy. The cross-sections can be used to decipher the geologic and geomorphic history of a landscape, and to determine its hydrogeology. Schoch (1989) provides a more thorough review of stratigraphic concepts and methods.

### Structure

After emplacement or deposition of rocks, they may be subject to deformation by gravitational and tectonic forces. Structural geology describes the disposition, attitude, and arrangement of deformed rock units. Four principal types of geologic structures can be distinguished: folds, faults, joints, and intrusions. A fold is bent or warped rock layers, which were originally horizontal and subsequently deformed. Folding of rock layers (strata) enhances fracturing and, in effect, turns strata of variable resistance on end so that the overriding controls on topography become the distribution of strata and their relative resistance (Figure 3-8). In areas of folded strata, watersheds tend to be elongate with the long axis parallel to regional strike. Heterogeneities in the subsurface caused by folding result in complex groundwater flow systems.

A fault is a surface zone of rock fracture. along which there has been material displacement. Faulting can disrupt groundwater flow systems by offsetting aquifers, and altering porosity and permeability along the fault plane. Faulting can exert control on the topography and surface hydrology of a watershed by juxtaposing rocks and strata of variable resistance, altering the course of rivers and streams (Figure 3-9).

One of the most common features in rocks are joints, which are partings in rocks without actual displacement. By markedly increasing the capacity of water to infiltrate rock, joints exert a strong control on weathering and erosion on a variety of scales, from microcracks to regional lineaments. Joints form as pressure is released on once deeply buried rocks which have been brought to the surface and in response to regional tectonic stresses. Joints that result from regional tectonic stresses tend to have preferred orientations. Such features exert a strong influence on groundwater flow in any rock type and produce distinctive surface expressions such as soil change, alignment of vegetative patterns, straight stream segments and valleys, aligned depressions and gaps in ridges. These linear features are commonly recognizable on aerial photographs and other remote sensing imagery. Lineament analysis can be an important component of geomorphic and hydrogeologic surveys (Fetter 1988).

### Intrusions

Igneous rocks that are formed by intrusion of magma into preexisting rock may disrupt otherwise continuous groundwater flow systems or, if brought to the earth's surface by uplift and erosion, may alter terrain development. The size of igneous intrusions varies widely from a few centimeters to hundreds of kilometers in circumference. There are two fundamental forms of intrusive igneous rocks: those that were created by injection of magma along bedding planes, and those that were created by injection discordant to bedding planes (Figure 3-10).

## Geomorphic Setting

Wetlands are inextricably linked to the other elements of the landscape and their landscape-forming processes. Consequently, such parameters as watershed size, position of the wetland in the watershed, shape and form of the watershed, and local climate influence the capacity of wetlands to provide specific functions. Analysis of landscape setting may be regional in perspective (Figure 3-11), in which long-term climatic and regional geologic parameters are

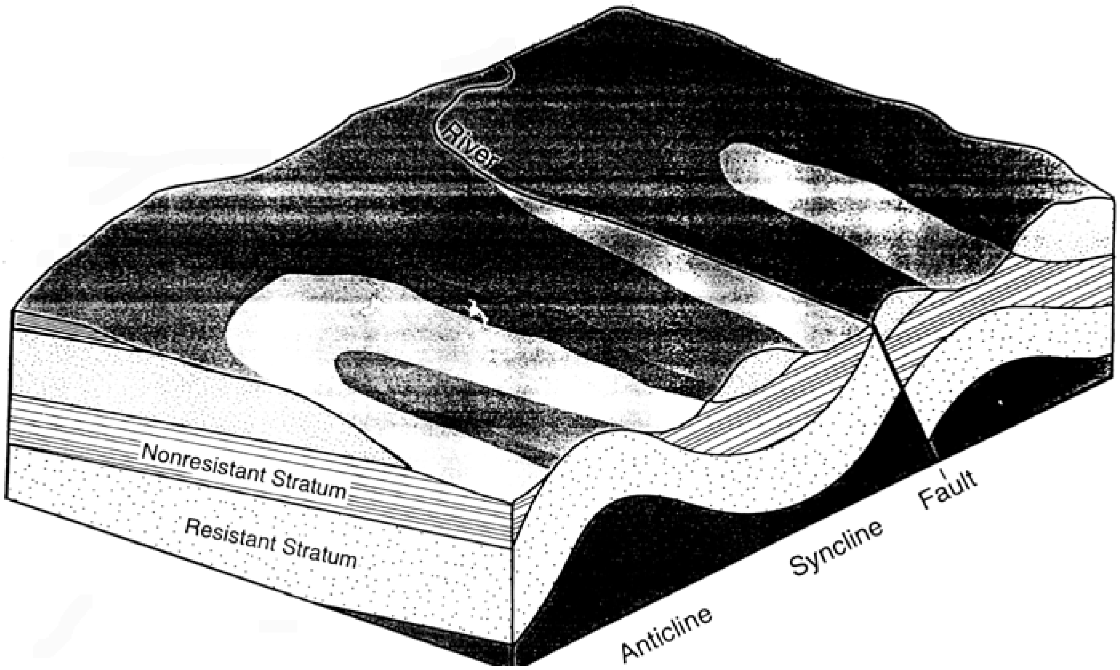



Figure 3-9. Block diagram showing general relationships between geologic structures and topography. Topographic highs may be associated with the cores of either synclines or anticlines. In the diagram, the axes of the synclines and anticlines are inclined (plunging) to the north. Note that the fault disrupts the sinuous surface expression of the plunging folds, and alters the course of the river.

significant. Analysis of landscape setting may also be more site specific in which short-term atmospheric (storms) and hydrologic (floods) processes and local stratigraphy play a critical role in flow of energy and material though the system. Both perspectives are important when evaluating a landscape for wetland engineering considerations.

The amount of area that drains into a wetland can influence the hydroperiod. Wetlands in small watersheds or in the upper portions of larger watersheds have less area draining into them, but are subject to intense runoff events associated with local storms. Under such conditions there is a tendency for wetlands to have variable water levels and irregular hydroperiods. On the other hand, wetlands situated in the lower portions of moderate and large watersheds are less influenced by individual rainfall/runoff events and therefore tend to have more regular hydroperiods. The size of the watersheds also influences sediment yield. Primarily because of the number of within-basin storage areas in larger watersheds, sediment yield per unit area tends to increase with decreasing watershed size (Ritter 1986).

The morphometry of a watershed strongly influences .hydrology and biology of a landscape, and many quantitative methods have been formulated to relate watershed form and function. Measurement of watershed physiography may be linear, areal, and elevational. Evaluation of linear aspects of a basin is concerned with stream channels. If attention is paid to inter-connections of stream channels, it is possible to devise a scheme of stream ordering. A first order stream is one which does not possess any tributaries, a second order stream is formed by the junction of two first order streams, a third order stream by the junction of two second order

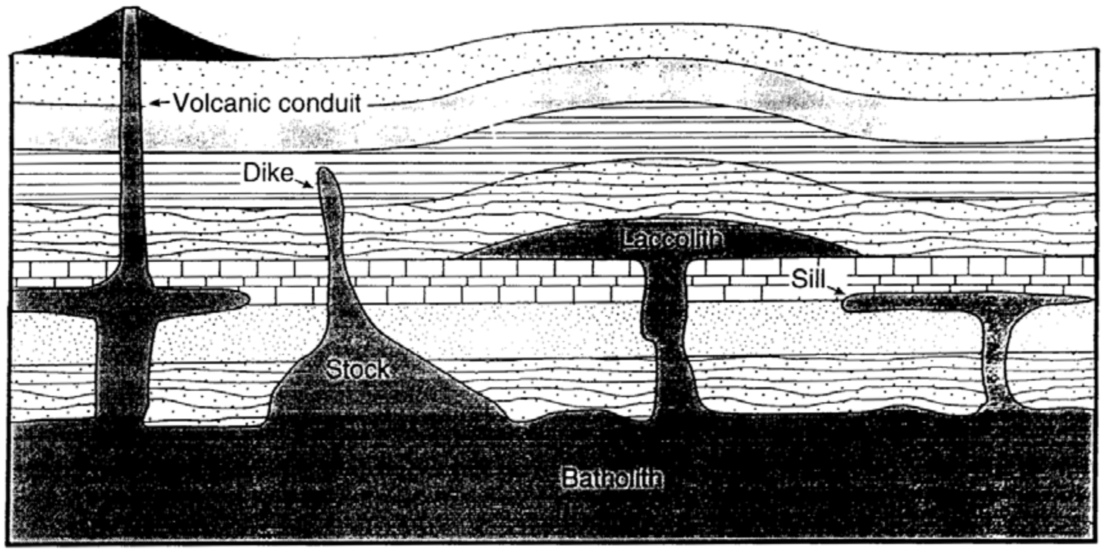
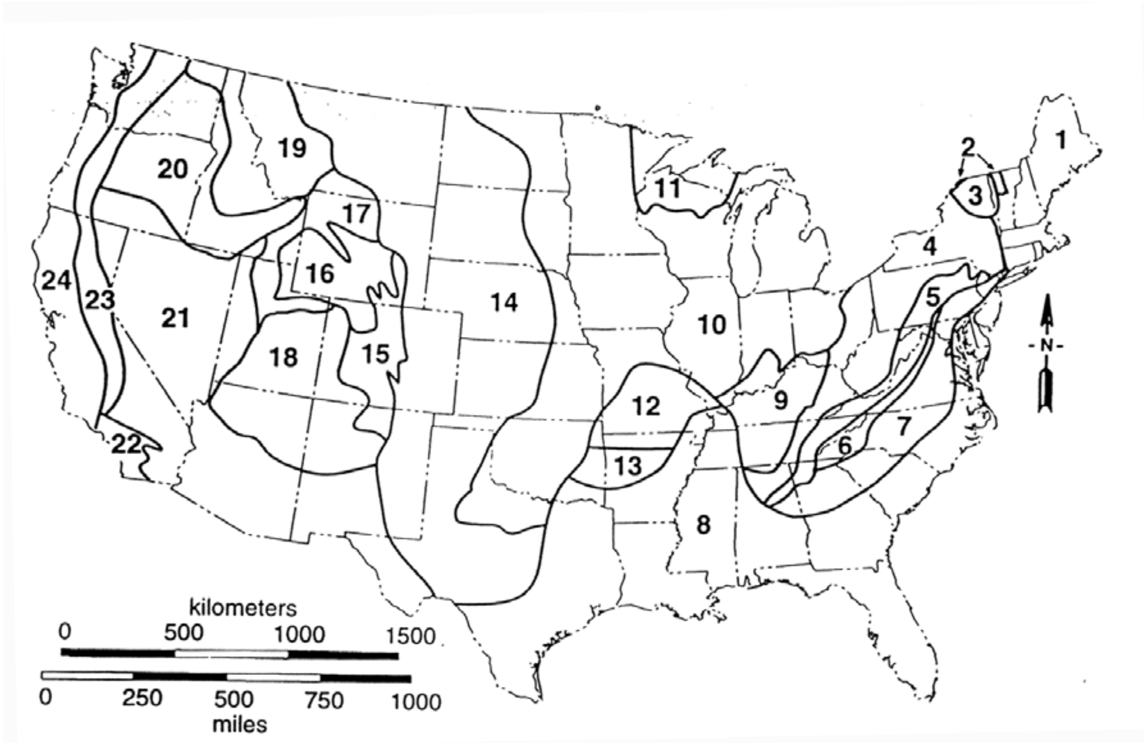



Figure 3-10. Types of igneous instrusions.

segments, and so on. The bifurcation ratio is the ratio of the number of streams within a watershed of a given order divided by the number of steams of the next highest order. Drainage basins with high bifurcation ratios contain a larger number of tributaries so that a landscape is capable of rapidly carrying off rainfall, resulting in pronounced discharge peaks.

Areal evaluation of a landscape includes calculation of drainage densities which highlights the antithetical relationship between overland flow and infiltration. Drainage density is measured by dividing the total length of stream channels by the total watershed area. Drainage density, to some extent, is a measure of the evolutionary stage of a landscape such that lower ratio values imply that a watershed is in early stages of geomorphic development and can be expected to change over time. Basins of high relief tend to be dominated by overland flow as opposed to infiltration and subsurface flow and develop high drainage network densities relative to lower relief terrains with similar surface conditions. Drainage densities tend to increase from humid to semiarid environments (Patton 1988).

Another areal measure of a landscape is the overall basin shape which can be evaluated with an elongation ratio which is measured by dividing the diameter of a circle having the same area as the drainage basin by the longest axis of the watershed (Schumm and Lichty 1965). Basins with high bifurcation ratios tend to have high flood peaks because surface water travel times to the base of the watershed are nearly equal across the basin. Whereas watersheds with low bifurcation ratios tend to have unequal stream path lengths which produce lower flood peaks but sustained flow because travel times to the base of the watershed vary across the basin (Strahler 1964). Not only does the elongation ratio provide information about basin hydrology, it also furnishes insight into the degree of structural control on basin morphometry because watersheds whose form is controlled by structural features such as lineaments, faults, and folds tend to have low elongation ratios.




| | |
|---|---|
| 1. New England province | 13. Ouachita province |
| 2. St. Lawrence Valley | 14. Great Plains |
| 3. Adirondack province | 15. Southern Rocky Mountains |
| 4. Appalachian Plateaus | 16. Wyoming Basin |
| 5. Valley and Ridge province | 17. Middle Rocky Mountains |
| 6. Blue Ridge province | 18. Colorado Plateaus |
| 7. Piedmont province | 19. Northern Rocky Mountains |
| 8. Coastal Plain | 20. Columbia Plateaus |
| 9. Interior Low Plateaus | 21. Basin and Range province |
| 10. Central Lowland | 22. Lower California province |
| 11. Superior Upland | 23. Cascade - Sierra Mountains |
| 12. Ozark Plateaus | 24. Pacific Border province |

Figure 3-11. Physiographic provinces of the conterminous United States (adapted from Bloom 1991).

The importance of basin relief as a hydrologic parameter has long been recognized. With increasing relief, steeper hill-slopes and higher stream gradients, the ratio of runoff to infiltration increases and time of concentration of runoff decreases, thereby increasing flood peaks. Two useful methods of evaluating the importance of relief in producing flood conditions are the relief ratio and the ruggedness number (Patton 1988). The relief ratio is the basin relief divided by the long axis of the basin. Generally speaking, drainage basins with high relief ratios are more prone to flooding. The ruggedness number is the product of drainage density and relief. Basins with - high ruggedness numbers tend to have high peak flows. It is of note that highly dissected basins of low relief can have ruggedness values similar to moderately dissected basins of high relief. Strahler (1964) and Stephenson et al. (1979) provide a variety of methods for quantitatively evaluating the relationship between basin form and process.

## Wetland Form and Size

Just as watershed form and size influence the capacity of wetlands to provide wetland functions, the size and morphometry of wetlands determine their capacity to furnish specific functions. Morphometric features which influence the capacity of wetlands to furnish functions include: form and depth of wetland bottom, size and shape of inlets and outlets, and shoreline length.

Wetland size, particularly relative to the watershed, may have significant influence on rate of flow of water and materials through the watershed, wetland water residence times, and hydroperiods. Moreover, the wetland size also influences the suitability and diversity of habitats for wetland flora and fauna (Adamus et al. 1991).

Broad, flat, rough shallow-water areas tend to slow water velocities and dampen waves and thereby tend to increase water residence times and decrease turbulence and potential for erosion. A variety of water depths promotes diversification of aquatic and wildlife habitats. The size and shape of inlets and outlets control the degree of communication with deeper water areas, hydrological residence times, hydroperiods, and the relative importance of surface flow in the wetland water budget. The ratio of shoreline length to wetland water volume influences the relative importance of groundwater in the hydrologic water budget (McBride and Pfannkuch 1975) and the diversity of habitats for wetland flora and fauna.

## Soil Texture and Composition

Soils are the dynamic interface between geology and climate, whose development is controlled by parent material, climate, organisms, slope, and time. Soils are thin veneers within complex three-dimensional systems that are active in space and time (Daniels and Hammer 1992).

Soils consist of a matrix of inorganic and organic particles with interconnected voids. Depending upon local conditions, these voids may be filled with varying amounts of water and gas. The meaning of the term “soil” is not necessarily the same to geologists, engineers, and soil scientists. Geologists commonly use the term “soil” to refer to the surficial layer of altered rock or sediment. Thus, for geologists soil might include all or part of the regolith. Regolith is the general term for the entire layer of loose, incoherent, and unconsolidated rock fragments, whether transported or the product of weathering, that nearly everywhere covers the more coherent bedrock. Civil engineers use the term "soil" to refer to that part of the regolith removed in excavation, used for fill materials, or to provide foundations to structures. Thus, to engineers soil generally includes the whole of the regolith. To soil scientists, "soil" refers to well stratified earth material, commonly one to two meters thick, that supports or is capable of supporting plants, and has formed through the interaction of climate, biological activity, and the rock fragments and mineral grains in the upper part of the regolith (U.S. Geological Survey 1977). A guide for comparing the soil textural classification systems used by soil scientists and engineers is presented in Figure 3-12.

Many soil properties obtain a steady-state condition over time. The time necessary to reach a steady state varies with the soil property, parent material, erosion or deposition rates, and, because different horizons develop at different rates, the soil horizon. Because a soil profile is the sum of many properties, a profile reaches steady state only when the majority of its diagnostic properties have attained equilibrium (Birkeland 1984).

### Soil texture

The size, shape, and arrangement of detrital material controls many soil properties and processes. Laboratory analysis may be used to determine the textural class of soils, but simple field tests by qualified personnel are often adequate (Costa and Baker 1981).

Soil porosity and permeability are directly related to soil texture. Coarser grained soils tend to be more porous and permeable, and well sorted (graded) soils tend to enhance groundwater flow. However, some clays and organic-rich clay soils can have high porosities because of the irregular shapes of organic materials and because the electrostatic charge on clay mineral surfaces repels other clay particles. Chemical activity of soils is related to soil texture. Because surface area per unit volume increases markedly as particle size decreases, smaller particles have greater potential for chemical exchange with groundwater. Moreover, smaller particles tend to be clay minerals which are more chemically active than other inorganic detrital material.

### Soil composition

Soil material is composed of varying amounts of organic and inorganic material. The composition of organic material ranges from undecomposed plant and animal material to humus. Humus is a complex, rather resistant brown to dark brown amorphous and colloidal material modified from the original tissue or synthesized by various organisms. Humus commonly makes up the bulk of soil organic matter, although in many wetlands, anaerobic conditions retard the decomposition of plant and animal tissue and peat may predominate.

Wetland soils can be generally classified as either mineral or organic types. Nearly all soils contain organic matter, but soils with less than 20% (dry weight) are considered a mineral soil. Organic soils are also known as peat soil and histosols. Two important characteristics of organic soils are the botanical content and degree of decomposition (Mitsch and Gosselink 1986). Organic material can be derived from mosses, herbaceous material, and wood and leaf litter. As plant material decomposes, bulk density increases, and hydraulic conductivity and

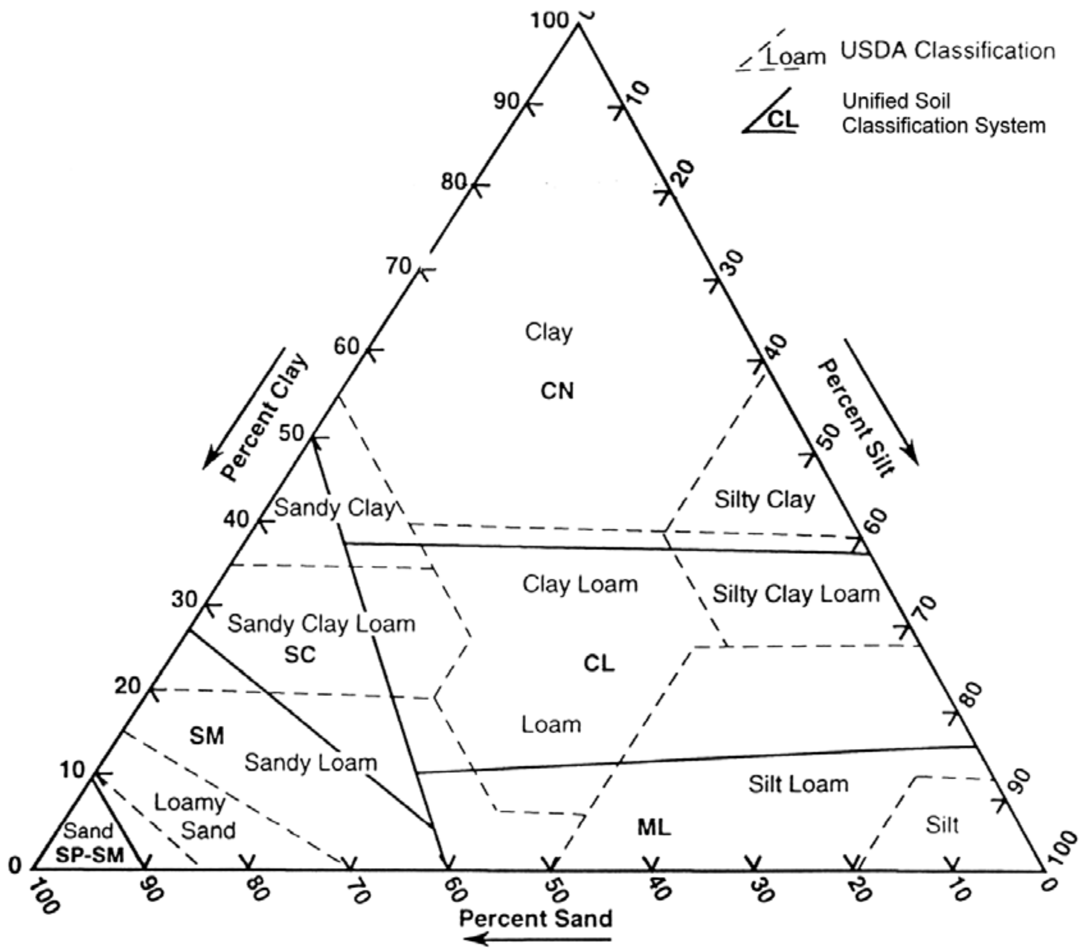



Figure 3-12. Guide for comparing the Unified Soil Classification System with that used by the USDA (adapted from Wright et al. 1981).

quantity of large fiber (>1.5 mm) litter decreases (Mitsch and Gosselink 1986). The ratio of carbon to nitrogen is a rough measure of the amount of decomposition of original organic material. The ratio is high (>20%) in undecomposed plant tissue and low (<10%) in humus (Birkeland 1984).

Soil organic matter is important to many soil properties. It considerably increases the water-holding capacity and cation exchange capacity in soils. Organic matter holds potential nutrients in organic forms that are not suitable for uptake by living plants. The organic acids which are produced during decomposition promote weathering of inorganic material, and form chelating compounds that increase solubility of some ions. The $C0_2$ that builds up during decomposition lowers the pH and thereby promotes weathering (Birkeland 1984). Because of the elongate shape of plant material, the common occurrence of piping structures, and the variable degree of organic decomposition, estimation and prediction of groundwater flow rates through organic-rich soils is difficult. Soil properties that affect groundwater flow are discussed further in the hydrogeology section of this chapter.

Soils maps and soils descriptions are available at county Soil Conservation Service offices. Hydric soils of the U.S. are described in a publication of the U.S. Department of Agriculture Soil Conservation Service (1991). Further discussion of soils can be found in Birkeland (1984) and Costa and Baker (1981).

## Geomorphic Processes

Landscapes are maintained by the flow of materials and energy through the system and the transformations which occur during transit. Wetland functions may be an integral phase in this cycle. Interaction of material and energy produces weathering, erosion, transport, and deposition of earth material, which are the four fundamental processes in landscape development.

### Weathering

Many rocks form under pressures and temperatures that are far different than earth surface conditions, and thus they are in unstable condition and subject to alteration. Degree and intensity of weathering is a function of climate, topography, and time. Most weathering takes place in the shallow subsurface and results from interaction of rock with groundwater. Weathering occurs in three ways: mechanical, chemical, and biological. Mechanical weathering processes include thermal expansion and contraction, frost wedging, and crystal growth (Bloom 1991). Chemical weathering, which is generally the dominant process, represents the transformation of materials as they are exhumed, eroded, and transported through the landscape. Chemical weathering processes, which are enhanced by wet and warm conditions, include oxidation, hydrolysis, dissolution, and conversion of silicate minerals (generally to clays). Biological weathering processes include chelation by plant roots and microbial activity which greatly enhances rates of chemical reactions. Bacterial activity is increasingly recognized as a major component in rock weathering. Press and Sevier (1986), Twidale (1990), and Bloom (1991) provide more detailed discussions of weathering.

### Erosion

As mentioned, most sediments and rocks have layers with differing potential for weathering and erosion. Where layers are undisturbed and horizontal, altitudinally zoned landform features and dendritic stream channel patterns predominate (Bloom, 1991). Where layers are deformed, differential erosion creates topographies which reflect the underlying geological structures (Figure 3-9).

There are a number of ways by which denudation rates, or volume of earth material removed from a landscape during a specific time interval, can be measured. Principal methods for evaluating denudation rates are measurement of sediment load in rivers, lake and submarine sedimentation rates, and depth of erosion. Denudation rates are discussed in more detail in Ritter (1986) and Bloom (1991).

Erosion rates are strongly influenced by climate. Analysis of denudation rates and sediment production has shown that sediment yield reaches a maximum when annual precipitation is between 25 and 37 cm (Figure 3-13). Marked decreases in erosive activity occurred when precipitation rose above or fell below this range, due, respectively, to increased vegetation cover and insufficient runoff. The amount of runoff is the best single indicator of

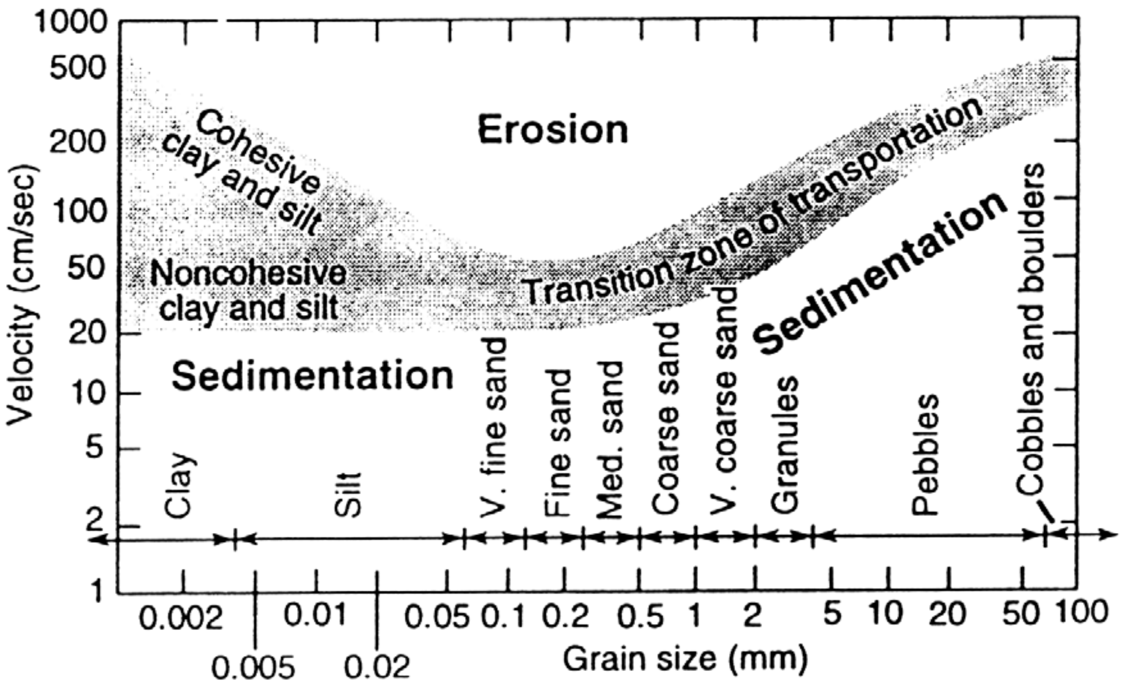



Figure 3-13. General relationship between sediment size, water velocity, and deposition and transport. Measurements were made on a flat bed of granular quartz sand. For a specific grain size, the lower limit of the gray zone demarcates the velocity at which all particles of that size fall to the bed. The upper limit of the gray zone demarcates the velocity at which all particles of a particular size continue to be reentrained from the bed. The gray zone is broad because many of the physical properties of water and grains are not accounted for by size and velocity alone. The gray zone in the silt and clay size portion is especially broad because of the electrostatic forces binding clay minerals.

denudation rate. Because most runoff occurs during storms, the intensity and duration of precipitation events, along with antecedent moisture conditions are of primary importance in evaluating denudation rates and sediment production.

Denudation rates from naturally vegetated areas are commonly less than 5 cm/1000 yrs. Enhancement of natural erosion rates by human activities ranges from two to three times with moderate land use to nearly ten times with intense land use (Saunders and Young 1983). Construction sites commonly have erosion rates far exceeding ten times geological erosion rates (Vanoni 1975). However, once completed, urban settings with their abundance of impervious surfaces (roofs and pavements), commonly have low erosion rates, although chemical loading and the ratio of runoff to rainfall are quite high.

Distinction is made between denudation rates which measure broad, long-term lowering of a landscape, and soil erosion which measures shorter term soil loss from a particular area. Soil erosion is often calculated using the Universal Soil Loss Equation (USLE or the Revised USLE, RUSLE) which considers the six most important erosion parameters: soil erosivity, potential for rainfall infiltration, slope length, slope gradient, land cover, and land management practices. Mitchell and Bubenzer (1980) review the USLE and other soil loss equations.

## Transport

Sediment may be transported by water, wind, or simply by the force of gravity. Wind is a significant transporting agent in coastal areas and the Southwest. In regions of high relief, earth material may be transported by gravitational mechanisms such as slumps, earthflows, debris slides. Ice and snow are an important element in erosion and sediment transport in some regions. For the vast majority of sediment, however, water is the principal transport medium and is the focus of the discussion here.

Water transported sediment is subdivided into dissolved, suspended, and bed load. Dissolved load includes all ions of weathered material; suspended load is generally fine material transported in the main body of flow and is kept afloat by the upward momentum in turbulent eddies; and bed load is generally coarse material that moves by rolling or sliding along the bed of a stream. The relative importance of these transport mechanisms depends upon the geologic setting, climate, and land use and land cover characteristics. Sediment transport is a complex process, and the division made between suspended load and bed load is arbitrary and depends on flow velocity and shearing stress.

Competence is the measure of the ability of flowing water to transport sediment of a particular grain size. Competence is primarily a function of water velocity (Figure 3-13), although sorting, suspended sediment concentration, and temperature are significant. Figure3-13 shows that silt- and clay-sized particles are kept in suspension by only slight currents, but, because of the high cohesiveness of clay particles, velocities required to initially erode them are capable of moving sand. This implies that ponded areas such as wetlands can be subjected to periodic episodes of moderate water velocities and not undergo erosion.

Ritter (1986), Bloom (1991), and Easterbrook (1993) provide an introduction into the role of water, wind, gravity, and ice in landscape evolution. Vanoni (1975), U.S. Geological Survey (1977), and Dendy et al. (1979) provide a review of methods to measure the volume of sediments transported by streams and rivers.

## Deposition

Like erosion and transport, the process of deposition is largely controlled by water velocity. Hence any area in a watershed where overland and channel flow is slowed is a potential site for deposition. Deposition is enhanced by low slopes, dense vegetation, and broad, rough shallow water areas. It is important to keep in mind that sediment storage may be temporary or long term. Temporary storage components of a landscape are controlled by intensity, duration, frequency, and timing of meteorologic events such as rainstorms, rapid snowmelt, and hurricanes. Long-term deposition is in large part determined by the subsidence history of an area. Subsidence may be caused by neotectonism,, sediment compaction, or groundwater pumping.

Deposition is measured in terms of accretion rates. Accretion rates are measured by a variety of techniques including sediment traps, artificial marker horizons, thermoluminesence, and radioactive isotopes. Easterbrook (1993) provides a review of methods for measuring accretion rates. Selley (1988) and Chamley (1990) provide more thorough reviews of sedimentologic principals and analysis.

### Sediment budgets

Site characterization is enhanced by compilation of a sediment budget, which is a quantitative analysis of the relationship among erosion, transport, and deposition within a watershed. Sediment budget calculations begin by identifying and delineating areas of erosion, transport, and deposition. Then dominant processes, such as raindrop impact, sheet flow, storm-induced channel flow, etc., operating in each area are identified. Rates of erosion, transport, and deposition are then calculated. Rather than calculating numerical values, erosion, transport, and deposition rates may be ranked as low, medium, or high.

The magnitude, duration, and frequency of recurrence of storm events significantly influences a watershed sediment budget. Areas in the watershed of a wetland may serve as either short-term or long-term sediment storage areas and should be distinguished from other areas which serve as sediment source and transport areas.

### Hydrogeology

Hydrogeology is defined here as those physical geologic processes which profoundly influence the hydrologic cycle, particularly in the subsurface. The focus of this section is on properties of rocks, sediments, and soils which influence groundwater flow. Movement of. water in the subsurface is discussed in Groundwater Recharge/Discharge (Chapter 3-2). Movement of water on the earth's surface is discussed in the portions of this handbook pertaining to hydrologic criteria.

Subsurface soil, sediment, or rock units which store and convey significant quantities of groundwater (generally thought of as capable of supplying water to public and private wells) are known as aquifers. Aquifers may be confined, unconfined, or perched. Water-saturated rocks and sediments overlain by permeable material extending from the aquifer to the land surface are termed a water table or unconfined aquifers. Water-saturated rocks and minerals overlain by an impermeable confining layer are termed artesian or confined aquifers. If a well penetrates a confined aquifer, water may rise above the confining layer, and in some cases, reach the earth's surface. This indicates that the water in the aquifer is under pressure. The potentiometric surface for a confined aquifer is the level to which water would rise in a series of wells that penetrate the aquifer. In some areas, impermeable strata of limited areal extent occur in generally permeable material. In such cases, water moving downward through the unsaturated zone is intercepted by the impermeable layer and accumulates, forming a saturated zone. Such a zone is termed a perched aquifer. Perched aquifers are common in glacial outwash where muds of former lakes, ponds and wetlands have produced impermeable layers in the subsurface.

Groundwater and soil moisture occur in cracks, voids, and pore spaces in earth material and therefore are of great importance in hydrogeology. Porosity is the percentage of a volume of rock sediment or soil: that is devoid of material. In soils and sediment, porosity is largely a function of grain size and degree of sorting, such that the larger the average grain size and greater the degree of sorting (grading) the higher the porosity. Grain shape, however, can significantly alter this general relationship. The smoother and more spheroid the grains, the more porous the medium.

As mentioned above, at least part of the pore space in sedimentary rocks has been filled with rock cement so that the general relationship between grain size and sorting, and porosity is altered. Transmission of groundwater through intrusive igneous and metamorphic rocks is restricted to joints and fractures. Extrusive igneous rocks, such as lava flows and volcanic ash, may have very high porosities.

Porosity is not necessarily a good indicator of a material's capacity to transmit groundwater. Permeability is the capacity of rock, sediment, and soil to transmit water without impairment to the structure or displacement components of the medium. Hydraulic conductivity is the measure of the ability of fluid to move through earth material. The terms permeability and hydraulic conductivity are commonly used interchangeably. As defined here, permeability is a function of the medium, whereas hydraulic conductivity is a function of both the medium and fluid. Hydraulic conductivity is equal to the discharge velocity under a hydraulic gradient of 100% and is measured as velocity (Cedergren l989). Determining hydraulic conductivity is one. of the most challenging aspects of hydrogeology.

Although there are laboratory methods to measure hydraulic conductivity of subsurface samples, they actually only represent minute volumes of earth material at a limited. number of points within a large mass. Therefore field methods that evaluate responses to induced changes in water levels in boreholes are generally used to determine hydraulic conductivity. Well tests used to determine subsurface permeability are of two general categories: 1) those that monitor the response (i.e. change and rate of change in water levels) of well pumping in surrounding observation wells, and 2) those that evaluate water-level response in the pumped well itself. A wide variety of techniques and formulae are available for determining hydraulic conductivities from pumping tests using surrounding observation wells (Heath 1983; Amoozegar and Warrick 1986; Cedergren 1989). Fetter (1988) provides further information regarding hydrogeologic concepts and principles.

## Geomorphic Trends

A landscape reflects the balance of atmospheric, geologic, hydrologic, and biologic processes acting on it at a given point in time. The balance that exists between landforms and processes is such that changes in the flux of materials and energy through the system change cause landforms to adjust, causing further alterations in the input/output system.

Landscape systems adjust toward a stable condition in which continued inputs of energy and materials no longer produce long-term changes in the system or its outputs. A system in equilibrium is one which processes materials and energy most efficiently. Dynamic equilibrium is a state in which elements of the landscape rapidly adjust to fluctuations in the processes acting on it (Ritter 1986). Dynamic equilibrium requires that inputs of energy and materials maintain an average balance with outputs over time. If the balance is exceeded by long-term changes or extreme events, systems react by changing in such a way as to create a new equilibrium state (i.e., toward a state in which the system is most efficient under the new set of conditions). The point at which a system becomes so imbalanced that it begins to change toward a new equilibrium state is known as a threshold. Threshold conditions are commonly brought on by climatic events. The capacity of a particular climatic event to induce threshold conditions (i.e. its ability to carry out work on a landscape system) depends not only on its intensity and duration, but also on antecedent conditions. Recovery rate is the speed at which a system regains equilibrium conditions after a disturbance. Landscapes in disequilibrium contain areas with high rates of erosion or deposition, incised gullies and streams, and areas with high percentages of pioneer vegetation.

Equilibrium implies that landforms and processes exist in an unchanging state, or within a fixed range of conditions. In reality, significant changes in inputs, forms, processes, and outputs do occur with time. Thus, equilibrium depends upon the time interval over which balance is being considered. Schumm and Lichty (1965) distinguished three different time scales for evaluation of equilibrium which they termed steady, graded, and cyclic times (Figure 3-14). Schumm and Lichty (1965) concluded that the perception of time is critical to the understanding of landform development and process, and that distinction between the time spans is essential to the perception of equilibrium. Steady time exists over a brief interval (days or months). In this time framework, landforms do not change and therefore they are truly time independent (Ritter 1986). Processes that most influence landscape equilibrium at these time scales are stochastic events such as storms, floods, and infestations. Graded time exists over perhaps hundreds to thousands of years. Equilibrium in this interval incorporates changes in which offsetting effects tend to maintain the system at some constant average condition. Processes that most influence landscape equilibrium at graded time scales are climatic changes. Cyclic time exists over perhaps millions of years. During time spans of this order of magnitude, fluctuating conditions are not offsetting and the average condition of the system is constantly changing. Processes that most influence landscape equilibrium at graded time scales are related to the geologic history of the landscape.

Because wetlands are generally low relief landforms, are subject to relatively wide variations in water levels, are transitional between aquatic and terrestrial ecosystems, and are underlain by unconsolidated sediment, they are commonly pulsed systems (Odum 1984; Niering 1987); that is, they are subject to short-term, high intensity events which commonly cause broad changes in the wetland landscape. These disturbances may be essential to the long-term capacity of a wetland to furnish a particular function. Because natural disturbances are commonly an integral process in wetland landscapes, it is important to be aware of the types of natural and man-made disturbances which may occur in a landscape. It is also critical to understand the magnitude, frequency, and timing of such events in the consideration of their impact on the long-term stability of the wetland and the ability of the wetlands to provide certain functions over time.

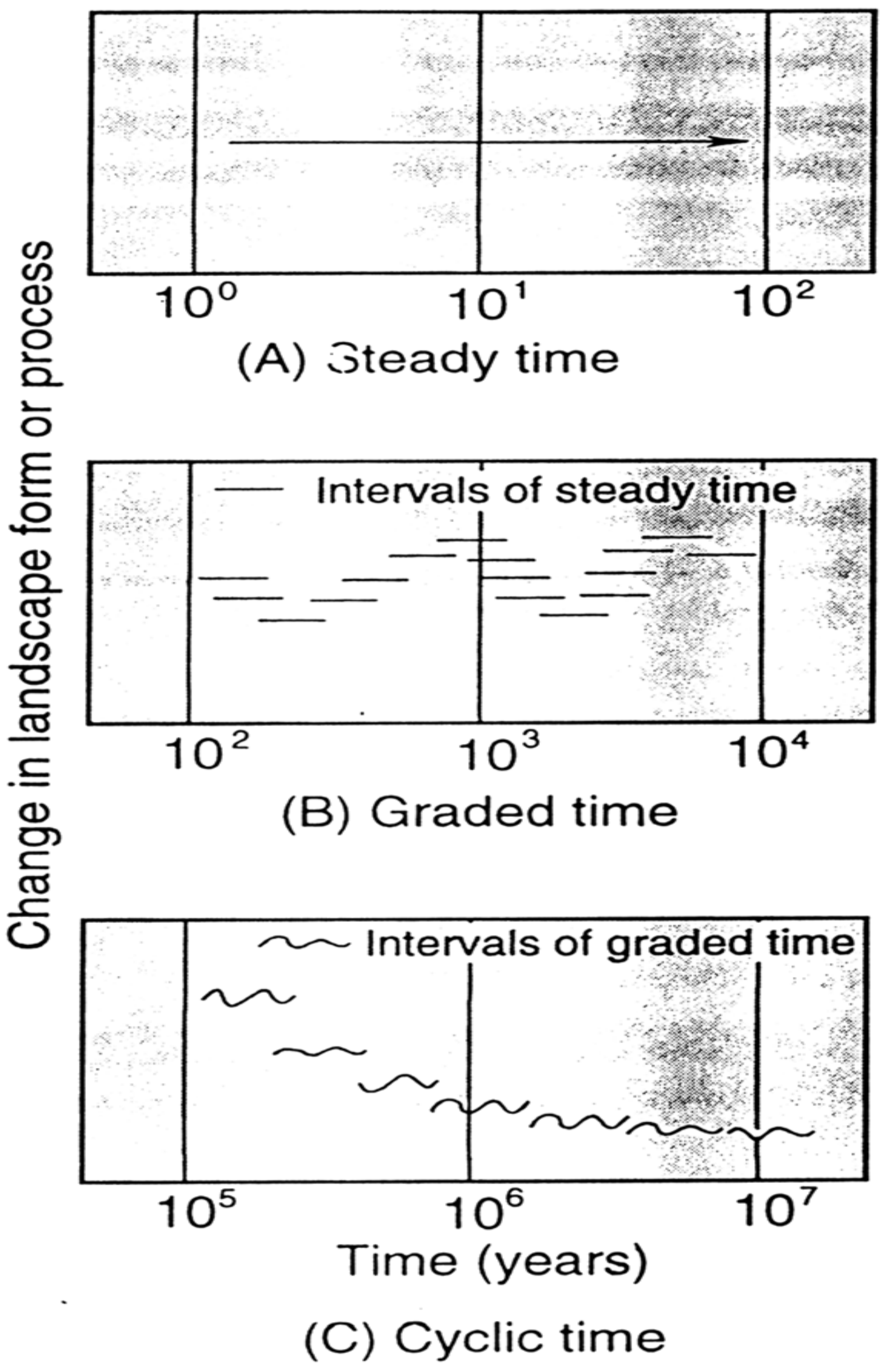



Figure 3-14. Different time intervals and associated landscape equilibrium. A. Steady time with no change in landscape form or process. B. Graded time with a long-term average for landscape form or process but with periodic fluctuations above and below the average. C. Cyclic time with gradual change in landscape form or process over long intervals. Landscape form and process include such things as channel form and gradient, sedimentation and erosion rates, and hillslope morphology. (adapted from Schumm 1977).

# 3-6 Developing Site Designs[1]

## Site Considerations

A viable conceptual design must consider site-specific conditions and constraints. Often, final site selection is based upon the compatibility of a given site with the objectives of the wetland restoration or creation project. This chapter presents general guidelines for developing viable alternative designs for a wetland site to assist in the selection of a project site and corresponding design. The procedure assumes that initial site assessment analyses were conducted and that information is available. The steps in the procedure are 1) establishment of design criteria, 2) brainstorming, 3) formalizing conceptual designs, 4) design phase analysis, 5) refinement of best designs, and 6) development of the final project design. These steps and the initial site assessment are discussed briefly below.

## Initial Site Assessment

The initial site assessment provides a database that reflects the existing site characteristics. As stated previously, all designs should integrate existing site characteristics to the fullest extent possible. However, some analysis of raw data gathered during the site assessment phase is usually required to fully understand the existing site conditions. Such a data set is particularly needed to analyze hydrologic conditions to accurately determine the amount of water available for wetland creation or restoration. These analyses are frequently similar to later analysis executed to support final design. However, they are usually less extensive and include assumptions about a variety of site parameters that are too costly to determine for every candidate site.

## Brainstorming

Information gathered during the initial site assessment should offer some insight to solutions to design challenges which exist at each site. A brainstorming session involving all of the discipline specialists should be arranged to investigate possible site plans. The plans should address the specific design criteria that have been established for the wetland project and focus on achieving the project objectives. All potential solutions that come to mind should be considered at this stage in the process.

[1] By Donald F. Hayes

One purpose of brainstorming sessions is to express raw ideas in a forum where the merits and problems of specific concepts can be discussed openly. An experienced specialist may be able to immediately recognize flaws in a specific concept that otherwise would not be identified, and may have specific objections to certain types of designs based on the requirements of the target species. The brainstorming also encourages collaboration and exchange of ideas between disciplines early in the design process.

## Formalizing Conceptual Designs

Formal conceptual designs should be developed for the most promising alternatives. Preliminary drawings and design calculations should be prepared for each alternative to support a fair and thorough comparison. Pre-design analysis provides information for preliminary design of flow control structures, culverts, gates, levees, berms, and other engineering works. These preliminary design calculations are essential to formalizing conceptual designs that can satisfy the project objectives and that are feasible to construct. The resulting drawings and calculations provide tangible evidence of each design's look and feel.

Once the initial designs have been specified, sized, costed, and checked, alternative designs should be evaluated by an assembled team of specialists. The merits and detractions of each design can be debated, and the best designs selected for further refinement. It is recommended that the group select no more than three alternative designs for further analysis. Suggestions for improvements to the best design should be solicited from the reviewers. The group may need to decide upon some specific criteria that will be used for selecting the final design.

During this process, each design must demonstrate the ability to satisfy the design criteria and requirements within the physical and economic constraints associated with the site. This step of the design process is critical because it provides a quantitative estimate of the construction, maintenance and operation costs that result from each alternative. Once preliminary drawings and calculations are complete for each alternative, cost, constructability, and compatibility with project objectives can be compared directly.

## Design Phase Analysis

Once the preliminary or conceptual design is complete, a thorough analysis of how the design fits within the ecosystem should be conducted. Post-construction hydrologic conditions including innundation frequency, water depths, hydroperiod, and groundwater flow should be carefully evaluated. It is likely that additional site data will be required to support the actual engineering design. Sections 4, 5, and 6 discuss data requirements for the three primary design components - geotechnical, hydrology, and vegetation. Methods and procedures for gathering these data are discussed in Section 2.

## Refinement of Best Designs

Sufficient analysis should be completed so that the alternative designs can be compared fairly on the basis of costs, environmental impacts, and effectiveness. Based upon the design phase analysis, the most promising designs can be refined to correct minor faults in the original designs, provide secondary objectives which were not included in the original conceptual design, or improve the cost effectiveness of the design.

## Final Design

Selection of the project site should be based on a review of the refined conceptual designs and upon the ability of each design to cost-effectively provide the project objectives. Once the project site and a conceptual design are selected, final design calculations, drawings, blueprints, and construction specifications should be developed for the site. Design procedures for substrate development, soils handling, hydrology, and vegetation establishment are provided in Sections 4, 5, and 6, respectively, of this handbook. Preparing the final designs may require that additional data be collected to verify previous information or a more thorough site investigation may need to be conducted.

# Section 3
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# Wetlands Engineering Handbook

## Section 4

## Substrate Development, Soils Handling, and Earthwork

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# 4-1 Introduction[1]

Soils and substrate are critical components of wetland ecosystems. They form the structural vessel in which the wetland is formed and serve as a biological interface to support macro- and microinvertebrates and microbial populations, to act as a medium for plant growth, and to facilitate water quality improvements. Soils can form an impervious barrier to retain water within the wetland or a pervious medium that allows groundwater exchange within the wetland system.

## Objectives and Scope

This section of the handbook presents and discusses design methods and requirements for those elements of a wetland project involving soils. Design components related to substrate and earth structures are discussed. The use of geotextiles in earthwork design and construction is presented. The general soils-related design process is depicted in Figure 4-1.

Engineering effort for site investigations and design for earthworks must be consistent with the size and complexity of the project. Wetland projects are rarely as life-threatening or costly as, for example, a major dam or bridge. The emphasis of this section is on relatively easily made designs using simple, standard methods, for use on small to moderate-sized projects where the cost of a more rigorous engineering effort far outweighs the potential cost savings. For fairly large projects, however, where more complex engineering subsurface investigation methods and design procedures will provide a definite cost effectiveness, the recommended methods presented in this section of the handbook should be replaced, where appropriate, by the more demanding methods.

The remainder of this section presents design considerations for substrates and for earth structures as part of a wetland restoration or creation.

Chapter 4-2 discusses substrate characteristics and development for wetland projects. Substrate design considerations, potential sources of substrate, and seedbanks contained within hydric soils are also discussed. The chapter presents a strong list of recommendations related to the development and placement of substrates at the wetland site.

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[1] By Mallory N. Gilbert, S. Joseph Spigolon, and Donald F. Hayes

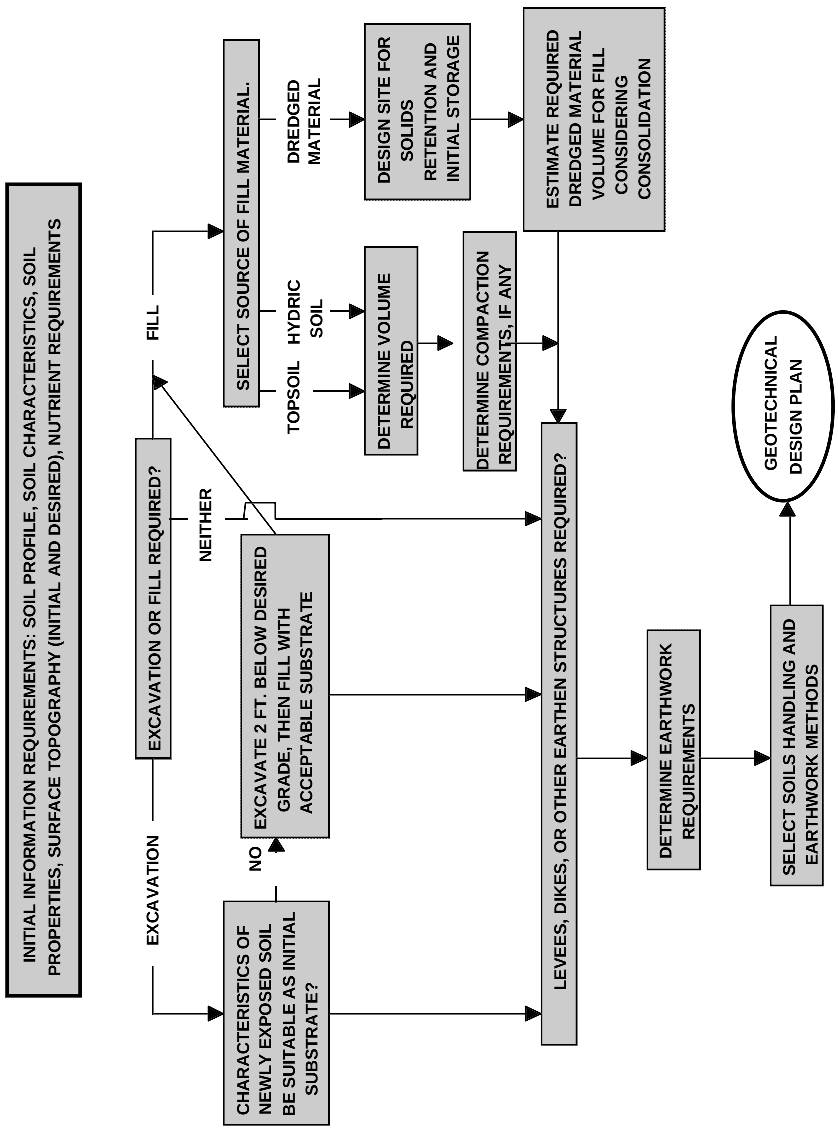


Figure 4-1. Decision flowchart for substrate development and earthwork design.

Chapter 4-3 deals with dikes and levees for water retention or control. Simplified geotechnical design methods are given. Topics include foundation stability, dike geometry, slope stability, seepage control, and erosion protection of completed slopes.

Chapter 4-4 addresses the use of geotextiles in wetland earthwork structures. The use of geotextiles for soft ground reinforcement and for erosion protection are explored. Geotextile materials and specification requirements for various geotextile functions are discussed. Also included is a discussion of the use of geotubes in wetland projects.

## Distinction between Subgrade and Substrate

During the planning and design of wetland restoration and creation projects, the soil science and engineering professions tend to view soils from rather different perspectives. Engineers view soil as a structural material that supports loads and resists erosion. While soil scientists are also concerned with the physical aspects of soils, their discipline further emphasizes the biological functions of soils and their importance as a medium for plant growth. Thus, two different, yet interwoven, perceptions and definitions of the soil components of wetland systems exist. This handbook distinguishes between the two by referring to the plant growth and biological medium as “substrate” and the collective soil matrix (i.e., extending below the A-horizon) that provides structural support as “subgrade.” This distinction is illustrated in Figure 4-2 and further refined below. Because “substrate “materials also possess engineering properties, it is important to recognize that the vertical demarcation between substrate and subgrade is often indistinct or overlapping in many wetland systems.

Of primary concern are the **physical properties** (the geotechnical engineering aspects) of the soils as they apply to site selection and construction of the wetland system. Equally important are the soil **chemical and biological** properties that influence the types of plant communities and other organisms that are planned or anticipated in the restored or created wetland system. The term **substrate** is used to refer to the part of the soil matrix that provides physical support for

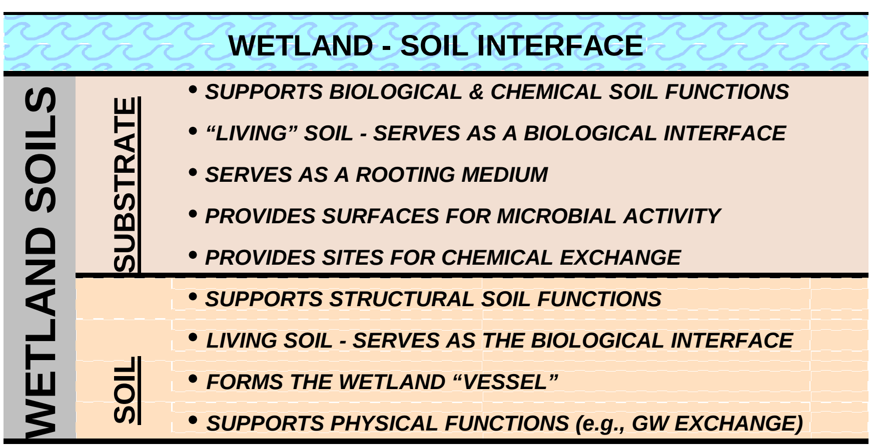


Figure 4-2. Distinction of wetland soil functions and nomenclature.

plants, a medium for macro- and microinvertebrates, microbial communities, and as a gradient through which nutrients are supplied for plant growth. Nevertheless, the engineering properties associated with the substrate must also be acknowledged in the wetlands design process. By definition, the created or restored wetland **substrate** is most frequently oriented above (or is the upper part of) the wetland **subgrade**.

As part of their function as the structural “vessel” for the wetland the **subgrade** soils must have an appropriate hydraulic conductivity to either hold water or allow groundwater exchange depending upon the source(s) of wetland hydrology. In either case, the subgrade soils may not be acceptable for use as a wetland **substrate.** Soils which provide the desired engineering structural support may prove to be too dense or impermeable to allow plants to take root or may be too pervious to support hydrophytes during periodic drawdowns. Additionally, the organic matter content of these soils may not be sufficient to support microbial activity or chemical exchanges necessary for some wetland functions. Since most wetland designs will include rooted vegetation and will perform functions that depend upon microbial activity in the substrate, a separate soil layer with properties conducive to plant growth and capable of supporting other wetland functions may have to be provided. Case studies where substrate materials have been applied successfully (Gilbert 1995) show that 15 -30 centimeters of substrate material over a prepared subgrade is sufficient for most emergent and scrub/shrub wetland systems. Subgrade and substrate materials should be placed so that the upper surface elevation of the wetland substrate soils will correspond to the desired finish elevations of the constructed or restored wetland area (Figure 4-3).

As noted above, soil **subgrade** and **substrate** can be indistinguishable in certain circumstances. For example, the hydrology of wetlands in the sandy Florida Gulf coastal plain is often groundwater dominated. Wetland plant species commonly desired in this area are well

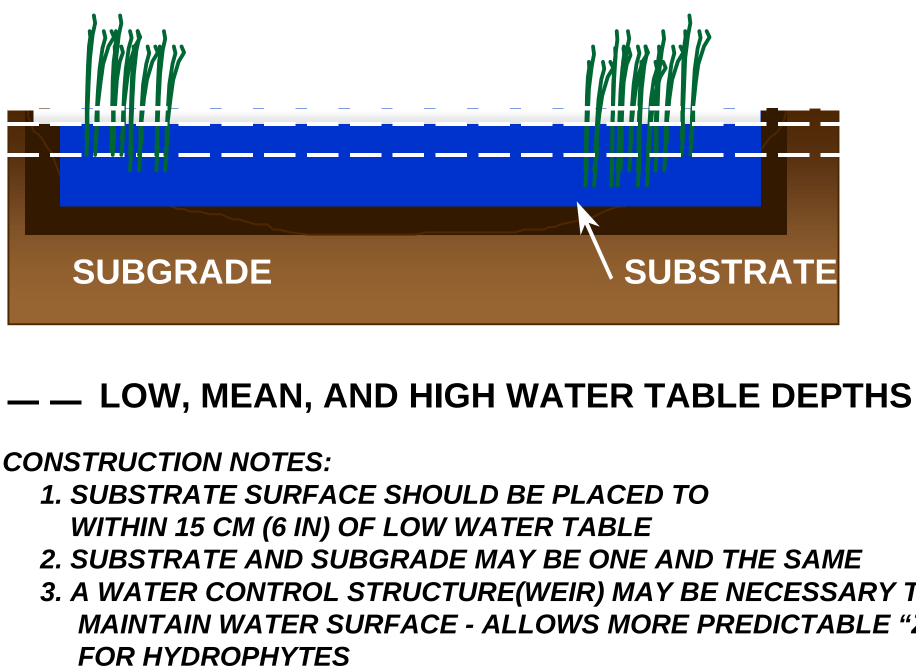


Figure 4-3. Conceptual diagram of a wetland with predominantly groundwater-driven hydrology with distinct subgrade and substrate layers.

adapted to the uniform, sandy native soil profile. In this situation, wetlands can often be created by simply excavating and regrading the deep sandy soil materials found on site. In these cases, it may not be necessary or desirable to install a specialized substrate to support targeted plant species. In this example, the finished grade of the bottom contours (subgrade soil elevations) would also correspond to the elevations of the new wetland substrate (the growth medium) (Figure 4-4).

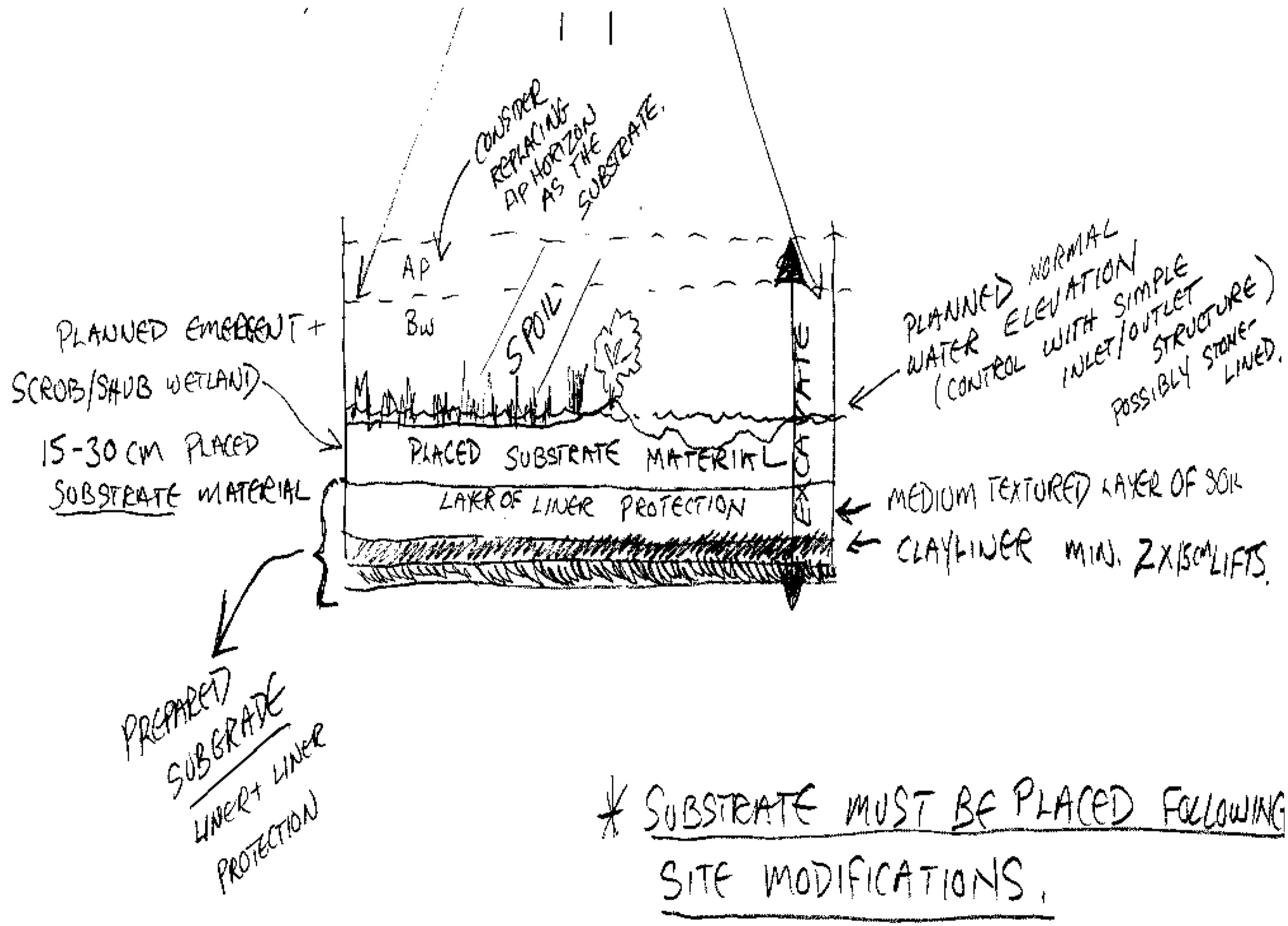


Figure 4-4. Conceptual diagram of surface water wetland with substrate material placed above subgrade.

# 4-2 Substrate Characteristics and Development[1]

Soils function as part of the wetland ecosystem as well as the structural vessel for the wetland itself. In their structural role, soils can function to perch and hold wetland hydrology or serve as a pervious medium that allows groundwater to move into, through, and out of a wetland system. In addition, soils serve as a biological interface to support macro- and microinvertebrates, microbial populations, act as a medium for plant growth, and facilitate water quality improvements.

Most of the chapters in this section discuss physical characteristics of soils as they apply to the engineering aspects of wetland construction. As these chapters illustrate, even the most intricate planting plan (vegetation) coupled with a generous volume of groundwater and surface runoff water (hydrology) cannot always be expected to overcome a pervious substrate (soils). Therefore, the geotechnical aspects of soils are acknowledged as critical to the success of wetland restoration and construction. Nevertheless, to balance the discussion of soils in the context of the constructed or restored wetland setting, the importance of the biological aspects of soils must also be addressed. Persons involved in this applied science must, therefore, be cognizant of both the engineering and biological functions of soils as unique but interconnected components of wetland systems. To reinforce this concept, a differentiation between soils as structural components of constructed wetlands and soils as sites of biological activity must be made. As discussed in Chapter 4-1, soils providing structural support are referred to herein as the ***subgrade*** while the soils providing biological and chemical support to the ecosystem are referred to as the ***substrate***. This chapter focuses exclusively upon the characteristics of wetland substrate and methods for developing or enhancing substrate for wetland restoration or establishment.

## Substrate Characteristics

In the initial phases of wetland restoration or establishment, the wetland substrate serves primarily as a medium for the growth of hydrophytic plant species. However, given time, the

[1] By Mallory N. Gilbert

substrate is expected to perform the same functions that are apparent in naturally occurring wetlands.

In most cases, the biochemistry and ecology of functioning wetland systems are driven largely by processes associated with wetland soils. The soils house the microbes that mobilize the nutrients that feed the plants that filter the sediments that provide the habitats that grow the insects that feed the fishes that feed the ospreys, *etc*. As illustrated here, the substrate is critical to the success of the project <u>and</u> the potential functions that can be provided by the wetland system.

In the last several years, ecologists have acquired a profound appreciation of the influence of soils on the flora, fauna, structure, and functions of various ecosystems. The origins of soil parent materials, soil physical and chemical properties, and the composition of soil microbial and invertebrate populations are recognized as critical elements that must be investigated in order to understand the complexities of any particular ecosystem. Primary differences between upland and wetland soils are the result of periodic or long-term anaerobic conditions (reviewed in Mitch and Gosselink 1993; McKee and McKevlin 1993). The reducing conditions that occur in most wetland soils influence several biochemical transformations that are unique to anaerobic environments.

For microorganisms to flourish in soils, there must be a food source to sustain the microbial populations. Under aerobic conditions, organic matter that accumulates on and within soils is consumed (oxidized) fairly efficiently; however, as soils become fully saturated, oxygen diffusion is slowed dramatically. The oxygen demand that results following saturation rapidly depletes available oxygen in the substrate. Anaerobic conditions ensue and a “turnover” of microbial populations occurs. Because resulting anaerobic microorganisms are not as efficient in their consumption of organic matter (anaerobic decomposition has been reported to be only 10 percent of aerobic decomposition) and wetlands generally have higher biomass production than upland areas (Hammer 1992), organic materials tend to accumulate on and within the wetland substrate. Although many naturally occurring wetland systems go though predictable cycles of “drawdown” during which their substrates return to aerobic conditions for several days, weeks, or months, organic matter content of wetland soils remains considerably higher than that noted in nearby upland soils. The organic matter content of naturally occurring <u>mineral</u> wetland soils can be as much as 30 percent (Mitch and Gosselink 1993) while <u>mineral</u> upland agricultural soils tend to average from 3 to 6 percent (Brady 1974).

Because organic matter tends to accumulate in wetland soils, the wetland substrate in turn becomes a “sink” for nutrients and contaminants held in the undecomposed organic materials. Anaerobic substrate conditions also drive chemical transformations of sulfur, carbon, nitrogen, phosphorus, iron, and manganese and are responsible for processes such as methanogenesis (reviewed in Mitch and Gosselink 1993, and references therein). Many of these transformations occur as a result of microbial populations that become active under anaerobic conditions. Other populations of microbes are known to be digesters/consumers of various pollutants and assist in the bioremediation of sediments. In fact, some wetlands are being constructed specifically to treat pollutants associated with waste water treatment plant discharges (Hammer 1989; Moshiri 1993).

In addition to the dynamics of the microbial populations, the specific chemical transformations that occur in the substrate are also dependent on pH and redox potential (reviewed in Mitch and Gosselink 1993, and references therein). In particular, pH influences the solubility of various chemicals and their mobility in the soil (*i.e.*, iron, aluminum, and manganese). The form and chemical structure of the compounds at various pH's and redox potentials will in turn affect the chemical and biochemical interactions that occur in microbial communities and at the soil/root interface (Black 1968). As illustrated, these processes are complex and may not only vary from wetland to wetland, but may vary greatly within a few meters in what appears to be a fairly uniform wetland plant community.

The state of the art of wetlands construction does not necessarily allow the wetlands designer to predict accurately how or at what level these diverse chemical and biochemical interactions are likely to occur in a newly constructed wetland system. However, the designer should be aware of these processes and their importance to the form and function of the wetland system. Mitch and Gosselink (1993), Faulkner and Richardson (1989), and others provide excellent overviews of the biochemistry of various wetland systems and interested individuals are encouraged to review these references and other citations therein.

As a result of increased organic matter content and the colloidal nature of many of the mineral sediments that are trapped in most wetland systems, wetland soils frequently have higher cation exchange capacities than upland soils. The higher cation exchange capacity in turn increases the potential of wetland substrates to bind nutrient cations and pollutants.

In general, nutrient availability is low in organic soils and peat-building wetland systems (where carnivorous plants have adapted by seeking "other" nutrient inputs). However, wetland systems with mineral soils tend to cycle greater volumes of water and have more diverse offsite hydrology inputs. As a result, the amount of nutrients available for plant growth tends to be higher (Mitch and Gosselink 1993). The pH of most mineral soil based wetland systems tends to be circumneutral while organic soils tend to be much lower in pH. The lower pH of the organic soils is often attributed to microbial activity that produces organic acids.

The physical characteristics of naturally occurring wetland substrates vary with the geomorphic setting in which they are found. Substrate textures may range from sands and sandy loams to clays and true organic soils in a variety of landscape positions and natural settings. Permeabilities of natural wetland substrates can vary greatly also, but nearly all substrate materials provide a reasonably good rooting medium for hydrophytic plant species.

Studies of how species specific rooting depths are correlated with soil bulk density, nutrient availability, and fluctuating versus stable hydrologic conditions in wetland soils are difficult to find. Although these data would be helpful in providing additional guidelines for substrate development, most of the research in these areas has been focused on upland agricultural crops. For example, roots of upland species are known to have difficulty penetrating naturally occurring fragipans, dense till, and mechanically induced "plow-pans" in agricultural settings. In general, plant roots tend to penetrate deeper into upland soil profiles because the plants are seeking water and nutrients in addition to mechanical support. Rooting of upland plant species is known to be affected by soil porosity which in turn affects the diffusion of oxygen, and nutrient availability (Brady 1974). Therefore, highly compact or dense soil layers (higher in bulk density) tend to be "physiological" as well as "physical" barriers to root development in upland soils. (This condition should not be overlooked when preparing the substrate of a constructed or restored wetland system for planting or seeding. Excessive compaction by heavy equipment should be avoided.)

Pore size distribution in soils is influenced by bulk density and can also be correlated with root development. For example, extensive root development is possible in sandy soils that have relatively high bulk densities but ample "macro-pore space". On the other hand, certain clay soils with poor structural development may have bulk densities 30 to 40 percent <u>less than</u> sandy soils and significantly higher <u>total</u> porosity. In spite of higher total porosity, root development in "tight" clay soils is likely to be inhibited because of a lower percentage of "macro-pore space."

Because hydrophyte physiology allows many wetland plants to supply their own oxygen via internal transport to root tissues, the physiological barrier presented by dense soils may not be as pronounced in wetland settings. Nevertheless, seedlings and planted materials must become established on constructed wetland sites. Therefore, research on the effects of soil bulk density and pore size distribution on hydrophyte establishment and root growth/development in wetland substrates would be helpful in establishing upper limits of compaction that can be tolerated during wetland construction.

In many natural wetland situations, water is abundant throughout most of the growing season. However, casual observation of emergent wetlands that experience regular drawdowns and seasonal fluctuations in water table suggests that water table depths have a significant influence on depth and lateral distribution of roots in the soil profile. Vertical rooting depth appears to increase where the roots must go deeper to follow a retreating water table during seasonal drawdowns. As such, the wetland designer must acknowledge the influence of hydrology on potential rooting depths in the constructed wetland. In time, even a well compacted clay liner designed to perch water may be vulnerable to root penetration or windthrow damage caused by the toppling of larger woody plants. Unless the hydrologic design can be modified to overcome erratic changes in water table depth, a wetland constructed as a perched seasonal/vernal association may revert to upland habitat if the perching liner is breached.

Data on soil water availability to hydrophytes and the "permanent wilting points" of various hydrophyte species would be helpful in fine-tuning substrate specifications for constructed wetlands. However, while research in this area is being considered,[1] published data are difficult to find. Some researchers have shown that the addition of organic matter to constructed wetland substrates can be effective in increasing the water holding capacity of wetland soils (Stauffer and Brooks 1992). Nevertheless, drawdown of the ground water table during the growing season is likely to result in the depletion of available soil water, even in substrates with ample organic content. When hydrophytes reach their "permanent wilting points," the substrate should not be expected to compensate for inadequate hydrologic conditions. Thus, even when planning the details of the constructed wetland substrate, the wetland designer must not loose sight of the

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[1] *Personal Communication* 1994: Rick L. Day and Keith Goyne, Department of Agronomy, The Pennsylvania State University, University Park, PA regarding research proposed to determine the permanent wilting point of selected hydrophyte plant species.

importance of hydrology. The reader should refer to Section 5 of this handbook for a complete discussion of hydrologic design and water budget calculations.

Currently available literature is not consistent in its appraisal of substrate material for use in constructed wetlands in all regions and territories of the United States. Successes range from simple hydration and supplemental fertilization of what is on the site at the time of finish grading (Garbish 1994) to the physical relocation of an entire wetland to a designated replacement area by “scooping” out uniform numbered sections and carrying them (more or less intact) to the replacement wetland site.[1]

In spite of the lack of specifics on substrate requirements for constructed wetlands, the scientific literature does provide us with data on the characteristics of soils in existing wetland settings (reviewed in Mitch and Gosselink 1993, and references therein). Although many of the published studies are site- and/or species-specific, there is a reasonable amount of information available on the physical and chemical make-up of naturally occurring wetland substrate materials. Furthermore, scientists have been working to consolidate this information into tabular formats that can be used to show trends and express generalizations. As noted above, Mitch and Gosselink (1993) provide an excellent overview of a number of wetland ecosystems and effectively present the dynamics of wetland substrate and chemical changes in each. The reader is referred specifically to Table 4-6 (p. 94), Table 5-1 (p. 117), and Table 5-9 (p. 152-153) in Mitch and Gosselink (1993). Substrate conditions are also discussed in some detail in publications addressing wetlands constructed specifically for wastewater treatment and/or water quality improvement (Hammer 1989; Moshiri 1993; Olson 1993, and references within). In addition, the pool of regional information available is likely to increase in the near future. The influence of site- or region-specific variables on the types of wetland systems possible in different geomorphic settings reinforces the need for specialized regional approaches to this science (*e.g.*, addressing the accumulation of soluble salts and resulting salinity dynamics in the substrates of restored and created wetlands in various parts of the western United States).

The Pennsylvania State University Cooperative Wetlands Center has been planning to test and monitor the development of a number of experimental substrate “mixes” of various organic matter amendments in a constructed wetlands.[2,3] In addition, a number of other constructed wetlands proposed in various parts of the country also are expected to be built using supplementary organic matter amendments such as composted leaves, animal manures, sewage sludge, wood pulp fibers, *etc*. Monitoring substrate functions in existing wetlands is helpful in designing constructed wetlands in similar settings (Vepraskas et al. 1994). Nevertheless, as this

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[1] Personal Communication 1995: Bernard G. Swegman, Chief, Surveillance Section, U.S. Army Corps of Engineers Pittsburgh District regarding observed unique approaches to wetlands restoration.

[2] Personal Communication 1994: Robert P. Brooks, Director, Penn State Cooperative Wetlands Center, Forest Resources Laboratory, The Pennsylvania State University, University Park, PA regarding experimental substrate treatments (organic matter amendments, *etc*.) proposed for a constructed wetland demonstration project planned for construction near Lock Haven, PA.

[3] Personal Communication 1995: Rick L. Day and Keith Goyne, Department of Agronomy, The Pennsylvania State University, University Park, PA regarding experimental subgrade/substrate treatments proposed for same site referenced above.

science develops, a move should be made away from experimental attempts to the development of regional standards for acceptable materials and procedures for substrate development. However, this field is still young and some degree of experimentation should probably be encouraged for quite some time. Undoubtedly, costs will influence the ultimate choice of the more desirable techniques.

## Substrate Design

Designers must focus on the primary functions the substrate is expected to perform in the constructed wetland. In short, the substrate must be a reasonably good medium to anchor and sustain targeted plant species; and it must be suitable to harbor the microbial populations responsible for diverse nutrient and chemical transformations that are unique to anaerobic/wetland conditions.

In all cases, substrate design should include evaluations of naturally occurring wetland systems in similar settings . Within reason, mimicry of a natural wetland system is desirable. The reference wetland should be located as close as possible to the anticipated construction or restoration site and should be accessible for data collection and evaluation. Soil parameters such as texture, permeability, bulk density, percent organic matter content, pH, cation exchange capacity, salinity (concentration of soluble salts expressed in units of electrical conductivity) and nutrient content may be evaluated. Rooting depths of dominant plant species should also be noted; these are helpful in planning substrate depths for the proposed wetlands construction site. In addition to the tests noted above, standard agronomic soil tests for agricultural crops and/or erosion control practices also can be completed. Designers are cautioned not to place too much emphasis on the results of these standard agronomic soil tests. Since they are largely for aerobic systems, they can provide good information about the availability of nutrients for upland plant species, but do not necessarily reflect nutrient availability under long-term saturated and anaerobic conditions. Nevertheless, quantitative information obtained on calcium, sulfur, magnesium, phosphorus, potassium, and various trace elements can be helpful in the design process. Potential substrate materials should also be subjected to the same suite of soil tests for comparison with the substrate in the reference wetland.

While not necessary, it is usually convenient and more efficient if the wetland system used as a reference for substrate design is used for observation and monitoring of other wetland components as well. Section 7 discusses the selection and use of reference wetlands for design and evaluation purposes.

Designers should also explore species-specific or unique local substrate characteristics that should be included in the constructed wetland system. While these may be relatively minor adjustments, they can be essential to successful establishment of targeted plant species. For example, some hydrophytes are known to require the presence of specific symbiotic microorganisms (*e.g.*, mycorrhizal fungi) on and around their roots to grow vigorously and flourish. If the need for the species-specific microbes is known, the roots of the targeted plants can be inoculated at the time of planting, or plugs of hydric soils that are known to contain the organisms can be transferred directly to the constructed wetland area. With a basic understanding of the substrate conditions in the reference site and knowledge of the minimal requirements of the targeted wetland plant communities, the constructed or restored substrate can be better designed.

## Target Substrate Features

As stated above, substrate materials for constructed wetlands should provide a good rooting medium for mechanical support and anchoring of emergent and aquatic species. They should be dense enough to remain consolidated following hydration but should not be so dense that initial rooting is inhibited. If placed over an existing subgrade, the substrate materials must be deep enough to allow for firm rooting without concern for "peeling off" from a denser layer below. If possible, substrate materials should also be capable of supplying a minimal amount of nutrients to aid in establishment of target plant species and should contain enough organic matter to sustain microbial populations. At the present time, studies indicate that with the onset of anaerobic conditions appropriate changes in the microbial populations will occur naturally and are followed by a gradual increase in the degree of observable chemical transformations and other wetlands related functions noted above (Vepraskas et al. 1994, 1995). In monitoring studies conducted at the Des Plains River Wetland Demonstration Site, Vepraskas et al. (1994, 1995) reported that the soil substrate along the edge of a deep-water marsh constructed in 1989 had developed chemical characteristics of hydric soils within three years of establishment. The substrate was shown to be accumulating phosphorus, and water analyses showed that reduction of nitrate and iron occurs during the growing season. Other work at the Des Plains site has shown the soil substrate of a wet prairie constructed in 1992 to be developing redoximorphic features where organic matter contents exceeded 4 percent (Vepraskas et al. 1994, 1995). Although, these data tend to support the observation that substantial organic matter amendments (10 to 50 percent) may not be necessary at the time of construction, further research in these areas should provide more specific data related to various substrate materials and treatments.

## Potential Substrate Materials

In natural wetland associations, native soil substrates are generally classified as either <u>organic</u> ($\geq$ 20 to 30 percent organic matter[1] content by weight, depending on clay content) or <u>mineral</u> ($\leq$ 20 to 30 percent organic matter content by weight, depending on clay content). To date, there has probably not been a successful creation of a functioning organic soil-based peat-building wetland system (bog or fen). Andreas and Host (1983) documented the natural development of a bog in an abandoned sandstone quarry in northeastern Ohio. However, this bog apparently developed over a period of approximately 70 years and the exact conditions leading to its development are not documented. Others have been pursuing the restoration of various

[1] Soil organic matter is defined as: " the organic fraction of the soil that includes plant and animal residues at various stages of decomposition, cells and tissues of soil organisms, and substances synthesized by the soil population. Commonly determined as the amount of organic material contained in a soil sample passed through a 2 - millimeter sieve." (Brady 1974). Measured percent organic carbon is multiplied by 1.72 to obtain the approximate percent organic matter of a soil sample.

*Sphagnum* species in former peat mine areas in northern New England.[1] Considerable research is still needed regarding the feasibility of short-term construction of these types of systems.

Mineral soils are currently the substrate materials most commonly employed in successful wetland construction projects. However, there are a number of options being promoted by various experienced wetland designers. Some options to consider include, but are not limited to, the following :

*a.* Use of hydric soils salvaged from the wetland area to be replaced or other wetland sources. Hydric soil can be spread or "mulched" on the surface of the constructed wetland area as an "inoculant" or can be placed in bulk fashion in a roughly 1:1 ratio of area and depth.

*b.* Use of upland mineral topsoils. In this case, topsoil is loosely defined to be the darker, surface soil layer(s) which may include portions or all of the 0, A, Ap, E, Bh, Bs, Bhs and AB soil horizons.

*c.* Use of the existing subgrade with supplemental fertilization.

*d.* Use of dredged material as a "beneficial use" application.

*e.* Application of livestock manure as a soil amendment to existing mineral subgrades.

*f.* Application of sewage sludge as a soil amendment to existing mineral soil subgrades.

*g.* Use of organic amendments such as composted leaves, bark, sawdust, pulp, etc. These may be used individually, in various combinations, or with slow release fertilizers as amendments to mineral soil subgrades.

*h.* Various combinations of the above.

## Organic Matter Amendments to Mineral Soils

Organic matter amendments such as those noted above may be helpful in improving the initial establishment of wetland vegetation (Stauffer and Brooks 1992). However, the identification of sources of the organic materials and the recommended rates of application are still somewhat experimental. As a result, coordination with local, state, and Federal regulatory agencies is encouraged, especially when considering sludge applications, manure applications, and the use of residual industrial materials such as pulp or cellulose fiber. Application of these materials is likely to require special permitting by state and Federal agencies, especially if they are to be applied to "Waters of the United States." In addition, the application rates of organic materials should be adjusted carefully to avoid compromising the ability of the substrate to support the root systems and stems of targeted plant species. Large amounts of organic material incorporated in a mineral substrate may affect the cohesion and structure of the soils and affect

[1] Personal Communication 1994: B. K. Andreas, Cuyahoga Community College, Highland Hills Village, OH regarding reclamation of "Harvested Peatland" in Maine. See Nilsson *et al.* (1990).

the soil's ability to provide mechanical support and a stable rooting medium for larger woody plants.

While all of the above options for organic matter amendments have their benefits, supplemental applications of organic matter are probably not necessary if the only objective is to raise the percent organic matter content of the substrate. If the substrate is already an acceptable rooting medium, will remain well hydrated throughout the year (does not experience prolonged periods of drawdown and aerobic conditions), and has sufficient nutrients available to establish wetland plants, the surplus biomass produced by most hydrophytes is likely to result in a natural increase of the percent organic matter content of the substrate within a few years of the wetland establishment (Garbish 1994).[1]

Nevertheless, increased organic matter content at the time of planting can be beneficial. Additional organic matter should increase the cation exchange capacity of the wetland soils (improve fertility), "lighten" the rooting medium for easier planting and root growth (if not over-applied), and improve the water holding capacity and drought resistance of the substrate during seasonal drawdown periods (Stauffer and Brooks 1992). Sludge materials, manures, and composted organic materials will also provide some nutrients to improve the probability of successful plant establishment. Current monitoring data indicate that substrates with > 3 percent organic matter content may be able to support the initial microbial populations necessary to start normal wetland substrate functions. In addition, soil redoximorphic features are reported to have developed after the first flood event in wetlands constructed in a floodplain where the substrates contain > 4 percent organic matter content (Vepraskas et al. 1994,1995). However, Vepraskas et al. (1994) expressed concern that plant utilization of reserve phosphorus in soil substrates of newly constructed wetlands may result in phosphorus deficiencies within 2 to 3 years. As a result, long-term maintenance of wetland vegetative communities may depend as much, if not more, on plant nutrient import in floodwaters or from watershed runoff as it does on the initial organic matter content of the constructed wetland substrate.

The use of raw organic materials low in nitrogen concentration (such as sawdust) as substrate amendments should generally be avoided. While the raw cellulose materials provide a carbon source for microbes, nitrogen availability is often low (an unbalanced carbon:nitrogen ratio). As microbes respond to the food supply, their populations increase and in turn compete aggressively for available nitrogen. As a result, fixation of nitrogen that would normally be available for the growth of higher plants is more likely to occur. If nitrogen fixation is an objective of the wetland construction (*i.e.*, removal of excess N in a deliberate water quality improvement scenario), the addition of surplus organic matter may be entirely appropriate (where the feeding microbes will be employed to fix the surplus N). However, the designer must recognize that the availability of N to the plant community is likely to be compromised in these situations.

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[1] Personal communication 1995: S. M. McIninch, Environmental Concern, Inc., St. Michaels, MD regarding use of organic matter amendments in substrates of constructed wetlands.

Where nitrogen fixation is not a primary objective and organic amendments are planned, some suggest that supplying supplemental nitrogen amendments with raw organic materials can yield promising results. Nevertheless, the use of well composted organics would still be preferred until published data can demonstrate the success of the nitrogen amendments. In addition, it is important to remember that a low fertility wetland system may, at times, be the “target” wetland that is being planned and constructed. In this instance, raw organic amendments to the substrate may be entirely appropriate.

The value of adding organic amendments to constructed wetland substrates appears to increase with the probability that the wetland is likely to experience significant or prolonged periods of drawdown during which the substrate dries and returns to aerobic conditions. Under such conditions, organic matter appears to improve the survival of the hydrophytes by both providing a protective mulch and by increasing the water-holding capacity of the substrate. Nevertheless, it is important to recognize the potential for organic amendments to decompose more rapidly under aerobic conditions. Unless the constructed wetland is capable of producing sufficient biomass to offset the decomposition losses, the longevity of the beneficial effects of the organic amendments may be limited. When constructed wetlands have been designed with adequate or surplus hydrology and hydration can be sustained throughout most of the year, the value provided by organic amendments may not be as apparent especially if there is already sufficient organic matter in the substrate to support active microbial populations. Putnam and Brown have overseen the restoration of well over one thousand acres of Pennsylvania “prior converted” wetlands in their management of the U. S. Fish and Wildlife Service “Partners for Wildlife” program. Their observations suggest that organic matter amendments are probably not as important to successful restoration as proper hydrologic design.[1]

## Beneficial Use of Dredged Materials

Dredged materials removed from saltwater, brackish, and freshwater navigational channels, harbors, and marinas have been shown to be highly successful substrate materials in a number of applications. However, acquisition, testing, and transfer of these materials may have to be coordinated directly with and through local U.S. Army Corps of Engineer District Offices. Where these materials are no longer readily available, there may be some opportunity to access older, non-regulated upland stockpile areas. Depending on the source of the sediment, the chemistry of dredged materials can change dramatically upon reoxidation. Therefore, thorough testing of the dredged materials is recommended prior to planning for their use. EM 1110-2-5026 (USACE 1986) provides an excellent overview of the potential for use of these materials as well as their limitations and possible problems.

## Use of Existing Soils

Where existing or manipulated subgrade/substrate soils already present on a site can serve as reasonably good rooting media, efforts to apply additional substrate materials are probably

[1] Personal communication 1995: D. J. Putnam, and D. F. Brown (managers of the U. S. Fish and Wildlife Service coordinated “Partners for Wildlife” wetlands restoration program in the Commonwealth of Pennsylvania) regarding hydrology design and organic matter amendments for restored and constructed wetlands in Pennsylvania.

excessive and largely unnecessary (Garbish 1994). These conditions are more likely to be encountered in coastal groundwater driven wetland systems or tidal situations where the textures, densities, and pore size distribution of soil profiles do not limit root penetration, where there is sufficient nutrient import to the wetland system on a regular basis (tidal exchange, upstream nutrient recharge, *etc*.), and establishment of wetlands hydrology is not dependent on "perching" of water above a slowly permeable subgrade. In addition, certain "permanently flooded" non-tidal situations may also allow for little or no substrate preparation. However, assuming that documentation of substrate functions is an objective in addition to plant establishment, a critical concern may be to ensure that there is enough organic matter in the upper 15 cm of the soil to sustain microbial populations while the planned plant communities are becoming well established. In some cases, organic matter increases will follow the successful establishment of the plant community - perhaps within a year or two. Thus, the benefits of applying supplemental organic matter is somewhat debatable. For wetlands that will be planted, Garbish (1994) recommended supplemental fertilization with slow release fertilizers such as Osmocote™ or Agriform™ at the time of planting.

Subgrades associated with highly disturbed sites such as surface or strip mined areas, frequently will present as good physical rooting mediums but may have other problems associated with iron, sulfur, and other chemical compounds that can become highly acidic upon hydration or may be potentially toxic in high concentrations. Samples of the proposed subgrade and substrate materials should be analyzed carefully during the investigative phase of the planning process. Release and stability of various chemical compounds under anaerobic conditions and the influence of alternating aerobic and anaerobic conditions on the substrate chemistry should be investigated. In these circumstances, the services of an agronomist, soil scientist, or mining chemist could be extremely beneficial.

Organic matter amendments are generally beneficial when working with mine spoils. However, mine spoil areas present special problems, and the dynamics of functioning wetland systems in these areas should be understood before design decisions are made (Hammer 1989, Moshiri 1993).

## Upland Topsoil versus Wetland (Hydric) Topsoil

Among experienced wetland designers, there are advocates of the use of both upland topsoils and hydric soils (separately or in combination) as potential substrate materials (Gilbert 1995; Pierce 1989). The practice of "mulching" with hydric soils gleaned from donor wetlands has been encouraged in some Corps Districts for several years. On the other hand, the use of upland topsoils as desirable or preferred substrate materials has been gaining in popularity.

Some of the advantages and disadvantages of upland and hydric topsoils as substrate materials are highlighted below.

### General

*a.* All naturally occurring topsoils (upland and hydric) contain seedbank materials.

*b.* Seedbank materials found in upland topsoils rarely survive in areas with prolonged wet conditions. As such, upland seedbank materials generally do not compete effectively with introduced, planted, or volunteer hydrophytes.

*c.* Seedbank materials found in hydric soils are usually adapted to wet conditions and, if able to germinate, frequently have been observed to become aggressive colonizers.

*d.* Hydric soils from functioning wetland systems similar to those planned for a particular wetland construction project are known to have microbial populations capable of performing wetland substrate chemical transformations. However, inadvertent "composting" of hydric soils gleaned from donor sites may occur if long-term stockpiling is done in aerobic conditions. The reoxidation of the hydric soils can result in fairly rapid decomposition of organic matter which in turn generates heat. If the soil becomes hot enough, the "composting" may have the effect of killing much of the microbial population as well as significant portions of the hydric soil seedbank. As such, long-term stockpiling of hydric soils may not be advisable. (Upland topsoils stockpiled for several weeks or months also may be subject to similar composting effects.)

*e.* Percent organic matter content in both upland and hydric soils is usually sufficient (> 3 percent by weight) to sustain healthy microbial populations.

## Advantages of Hydric Soil Seedbanks

*a.* They are dominated by native and/or locally adapted plant species.

*b.* The dominant seedbank materials are adapted to wet conditions.

*c.* They often provide rapid vegetative cover by hydrophytes.

*d.* Hydric soils usually contain ample organic matter to sustain microbial populations associated with wetlands functions.

*e.* Under the right conditions, transferred hydric soil substrates can provide a means of mimicking a disturbed wetland plant community. (Proceed with caution. See section below.)

## Disadvantages of Hydric Soil Seedbanks

*a.* Frequently, the wetland designer will have no idea what species are included in the seedbank materials (unless time is taken to germinate samples under controlled conditions). Plant species likely to volunteer from a hydric soil seedbank are usually the most aggressive pioneering species in the seedbank. Other species may remain dormant for many years. There also may be some potential to spread less desirable species or "noxious" weeds (i.e., *Lythrum sp.*, *Phragmites sp.*, *Typha sp.*, etc.).

*b.* The plant community observed on a hydric soil “donor” site may be the product of many years of succession. As such, totally unanticipated dormant species may be released when the soils are disturbed and reapplied to the constructed wetland site.

*c.* The more aggressive colonizing plant species may tend to dominate a constructed wetland within 2 to 5 years unless controlled by mechanical or chemical means. (i.e., *Typha sp.* will tolerate highly variable moisture conditions, and may suppress or out-compete the target species that dominated the “donor” site.)

*d.* Handling may be difficult. Application with heavy equipment may cause excessive compaction. Light tillage may be required (disking or harrowing) to create an acceptable rooting medium. However, improved aeration resulting from tillage may accelerate decomposition of organic matter if the site is not flooded for several days following the tillage operation.

## Advantages of Upland Mineral Topsoils

*a.* Upland topsoils are usually reasonably fertile with a supply of reserve nitrogen and phosphorus in organic matter.

*b.* Upland topsoils usually provide a good rooting medium. In general, up to 20 to 30 percent coarse fragment content (stones, pebbles, etc.) is not a problem.

*c.* Dormant seedbank materials usually will not compete with planted or seeded hydrophytes (which allows for more control of a planted vegetative community and better mimicry of a disturbed or reference wetland plant community).

*d.* There is some evidence that flooded and inundated upland soils with average amounts of organic matter will tend to cause the release of significant amounts of calcium, potassium, phosphorus, and nitrogen in forms available for plant uptake (Whitlow and Harris 1979, Reddy and Graetz 1988, Pierce 1989). Research also indicates that flooding of upland mineral soils and drained hydric mineral soils results in a convergence of soil pH toward neutrality (Whitlow and Harris 1979, Fennessy 1991, Mitch and Gosselink 1993). (Note: The tendency for pH convergence toward neutrality can be a disadvantage where “acidic” systems are being planned.)

*e.* Handling, transportation, application, and grading can be accomplished with conventional heavy equipment.

**Disadvantages of Upland Mineral Topsoils**

*a.* They must be planted or seeded to ensure rapid vegetative cover by hydrophytes (unless natural succession is planned).

*b.* Application with heavy equipment may cause excessive compaction. Tillage (disking or harrowing) may be required to provide an acceptable rooting medium.

*c.* If left as bare ground that is subject to only intermittent inundation, there may be a tendency for early successional “old field” annuals to colonize and compete with hydrophytes (i.e., Panicum spp., Setaria spp., Echinochloa spp., etc.).

# Application Options/Recommendations

Where native or introduced soils of the subgrade are acceptable as a substrate rooting medium, options may include:

*a.* Simple finish grading, erosion and sedimentation control, planting/seeding of hydrophytes, and supplemental fertilization where tests of the potential substrate indicate that sufficient organic matter is available and nutrients are likely to enter the system at regular intervals.

*b.* Organic matter amendments to increase percent organic matter content (recommended to improve water holding capacity and protect hydrophytes from desiccation if drawdown is anticipated). Plowing or disking to incorporate (tillage to 3 to 6 inches minimum) organic matter amendments and ensure soil contact is recommended. Incorporation will also help to minimize floating of excess organic materials. [Note: An additional means of providing organic matter to sites where hydrology is not expected or planned for several weeks is to seed the area with upland species such as cereal grains, clovers, or annual ryegrass. These grasses and legumes produce significant volumes of biomass in a relatively short time and assimilate and hold readily available nutrients. However, these plants cannot survive when inundated. The result is a supply of “green manure” that provides nutrients to adapted hydrophytes as the upland species die and become part of the substrate/water interface. If the site is planned to be planted or seeded to hydrophytes “in the dry,” disking or harrowing of the “green manure” prior to planting/seeding could be beneficial; or the site may be planted directly if flooding is anticipated shortly after planting. These plants also act to trap the “seed rain” (seeds transported to the wetland site via floodwaters, runoff, and wind) of volunteer hydrophytes.

*c.* “Mulching” with a thin layer of hydric soils to supply seedbank materials, microbial inoculation, and some additional organic matter. Mulching is an acceptable approach if the objective is to “kick-start” a successional colonization of the constructed wetland. However, the designer should be aware that the most aggressive pioneering hydrophytes are likely to dominate until successional colonization is well underway. Consequently, there may be little control over the structure and diversity of plant species that volunteer. This practice is not recommended if specific plant communities are planned.

Where native, manipulated, or introduced soils of the subgrade are unacceptable as a substrate rooting medium or the subgrade has been intentionally compacted or lined to create a slowly permeable layer/zone to hold or perch hydrology, consider the following:

*a.* Consider short-term stockpiling and reapplication of topsoils found on the site prior to excavation. This option assumes that the topsoils are acceptable as a rooting medium and contain sufficient organic matter [as a general recommendation, greater than 3 percent, as per personal communication with Vepraskas (1994)] to sustain initial populations of anaerobic microbes and provide reserve nutrients. Based on the author's experience and communications with others experienced in wetlands construction, the following substrate depths are presented as general guidelines for the indicated applications:

1) Herbaceous plant community: 15 cm

2) Herbaceous/shrub-scrub: 30 cm

3) Herbaceous/shrub-scrub/tree: 30 - 45 cm or deeper.

*b.* For any vegetative community planned for a wetland constructed on a manipulated or lined subgrade (i.e., clay-lined subgrade) designed to perch water but which may be subject to seasonal drawdown, the liner should be positioned deep enough that it will be protected from desiccation cracking and the effects of freezing and thawing. The depth of the protective covering will be expected to vary depending on regional conditions. A minimum depth of 40 to 60 cm of medium textured material should be considered and then adjusted based on the duration of drawdowns and the likelihood of deep freezing during drawdown conditions. The substrate can be considered part of the protective layer.

*c.* Although the wisdom of planting trees on a site that has been lined to perch hydrology is somewhat questionable, the substrate depth for trees noted above would still be recommended.

*d.* In those cases where substrate materials will not extend down to the lined subgrade, additional "protective subgrade" material can be placed between the liner (above the liner) and the substrate materials.

Following initial excavation and grading, the planned **subgrade** elevations of most constructed wetlands usually will be nearly level or somewhat depressional. Where supplemental **substrate** material is planned to be applied over the subgrade, stability of the substrate material following hydration is a concern. Where the design of the wetland calls for deep water area or islands, substrate materials may have a tendency to creep downslope after hydration. Design of a "side-hill" or sloping wetland substrate (which is fairly difficult to build) must ensure that the fully hydrated substrate does not become a "mudslide." Therefore, it is recommended that substrate materials be tested for slope stability whenever slopes steeper than 10:1 are planned over a large percentage of the substrate surface area. Bulk density, particle-size distribution (texture), liquid limit, and plastic limit are tests that are helpful in determining if a placed substrate is likely to slide on a prepared subgrade. However, a thorough slope-stability analysis must be conducted.

Placement of a substrate material that is finer in texture than the soil upon which it is placed will frequently result in perching of water in the substrate layer. Drainage into the coarser textured horizon below is inhibited by the affinity of soil water for the finer pore spaces in the substrate layer [the same affinity that causes water to rise above an apparent water table within a soil profile (“capillarity”)]. This phenomenon is well documented (Hillel 1971, Brady 1974), but knowledge of it may be a valuable tool in increasing the length of time that wetland substrates are capable of supplying water to plants during seasonal drawdowns.

In general, precise grading (“back-blading”) of the “finished” surface of the created or restored wetland is not recommended. Many practitioners have observed the micro-relief of “rough” graded areas to be very beneficial in improving species diversity.

## Summary

The complexity of the biochemical interactions in the wetland substrate has profound influences on the structure and function of natural and constructed wetland systems. Considerably more research is needed to expand the understanding of these interactions and to help establish “mileposts” by which to gage success in creating wetlands that readily assume a productive role in local ecosystems. The information presented in this chapter is intended only as an introduction to these complex issues.

# 4-3 Retaining Dikes[1]

A *dike* is an impervious wall or mound built around a low-lying area used to retain water or dredged material or to prevent flooding. A *levee* is an artificial bank, usually made of earth, confining a stream channel or limiting areas subject to flooding (Bates and Jackson 1987). The design and construction of dikes and of levees is identical. Therefore, in this discussion, both dikes and levees will be referred to as dikes.

Dikes are generally made of locally available soil materials, usually taken from near the toe of the dike. Hydraulic fill soils for dikes may be pumped from an appreciable distance. The wall (dike) may consist of an impervious core, supported by pervious shells, or the impervious core may be widened to form the entire embankment as a homogeneous cross section. Wetland dikes will rarely impound more than 1 m (3 ft) of water. As a result, dike heights are rarely greater than 2 m (6 ft) except where the dike crosses gullies or other natural depressions.

The subsurface investigation, selection of a material source, selection of a foundation preparation method, the embankment design, and development of specifications for earthwork construction require the specialized knowledge of civil, and particularly of geotechnical, engineers. Therefore, all planning, design, and preparation of construction specifications should be done under the direct supervision of a qualified engineer and should bear his approval.

Sources of dike design and construction guidance, containing a depth of information beyond that given here, should be consulted. The USDA-SCS Engineering Field Manual (Soil Conservation Service 1984) contains valuable design and construction advice, particularly Chapter 11, “Ponds and Reservoirs,” and Chapter 13, “Wetland Restoration, Enhancement, or Creation.” The primary U.S. Army Corps of Engineers sources include “Stability of Earth and Rockfill Dams,” Engineer Manual EM 1110-2-1902 (USACE 1970), “Design and Construction of Retaining Dikes for Containment of Dredged Materials,” Technical Report D-77-9 (Hammer and Blackburn 1977), and “Confined Disposal of Dredged Material,” Engineer Manual EM 1110-2-5027 (USACE 1987).

Several of the seepage and erosion control measures described below make use of the concept of a soil-water filter. Graded sand filters have been used for many years. Recently, geotextiles have been effectively used for this function. Criteria for a graded sand filter and for filter fabrics are discussed in Chapter 4-4, “Geosynthetics Applications in Wetland Structures.”

[1] By S. Joseph Spigolon

## Factors Affecting Design

The engineering design of a wetland dike includes the selection of location, height, cross section, materials, and construction method. The design and the construction method are dependent on wetland project constraints, foundation conditions, material suitability and availability, and availability of construction equipment. The final design will be a choice among feasible alternatives.

**Project constraints.** Several constraints on design are placed by the overall wetland project needs. Available construction time and funding are always factors. The location, height, and available space are usually dictated by wetland project water storage requirements. The design factor of safety against structural failure is selected on the basis of the additional initial cost to prevent the failure, versus the probability of the failure times the cost of the damage and its repair. Environmental safety and aesthetics must always be considered.

**Foundation conditions.** The foundation must have sufficient strength to support the dike without contributing to a translational or rotational failure of the dike slopes. The foundation compressibility must be such that the settlement of the dike will not exceed acceptable limits. The permeability of the foundation must either be sufficiently low that detrimental underseepage will not occur or the stratification must be such that an effective underseepage cutoff can be emplaced.

**Availability of materials.** All potential sources of construction materials for the embankment should be characterized according to location, type, index properties, and ease of recovery. Economical dike construction normally requires the use of nearby material, requiring little or no transport. Usually, this means using material from near the dike toe. Dredged material may be used if pumping is feasible from the dredge site to the wetland site. If the impoundment to be protected by the dike is to be excavated, then the soil being removed is likely to be used in the embankment. Economy usually also dictates balanced cut and fill in the local area, eliminating the need for transporting excess or deficient soils to or from a long distance.

**Availability of equipment.** Common earthwork construction equipment is generally used if the wetland surface is sufficiently firm. When the site consists in main or in part of very soft soils of poor trafficability, specialized equipment having a low ground pressure for soft soil operations may be needed. For underwater sources of fill soils, dredging equipment may be needed. The specialized soft soil or dredging machinery may not be available to meet the project schedule or the mobilization cost may be excessive. Less expensive alternatives, including moving the location of the dike or changing the source of materials, should then be considered.

**Construction methods.** Each construction method has characteristics that can strongly affect dike design. Soil material for the dike section may be hauled, cast, or pumped in a pipeline as a soil-water slurry. The soil is then left either uncompacted, semicompacted, or well-compacted. The design geometry of the dike section, although based on economics, must be compatible with the available materials, equipment, methods, and environmental considerations.

## Dike Design

The dike and its foundation, to form a water-retaining wall, must be stable and relatively impervious. The major causes of dike instability, and therefore concerns in design of a dike, are:

*a.* *Foundation stability.* The dike foundation may fail to support the dike because of the lack of shear strength, or the dike may have excessive settlement due to foundation compressibility, or the foundation soils may permit excessive underseepage.

*b.* *Dike geometry.* The freeboard, or height above water level, the width of the crown, internal settlement, and inclination of the side slopes affect overall stability.

*c.* *Slope stability.* The embankment materials may lack sufficient shear strength to stand at the design slopes, especially under conditions of adverse seepage. A major factor in determining the available shear strength in the embankment is the amount of compaction of the soils--whether they are (a) simply hauled or cast into shape and left uncompacted, (b) semicompacted by the action of the hauling or shaping machinery, or (c) compacted in thin layers (lifts) to specification requirements.

*d.* *Seepage.* Excessive seepage may occur through and/or under the dike or along water control structures placed in the dike. In either case, the downstream exit point of the seepage may become extremely unstable.

*e.* *Overtopping.* The dike may fail due to overtopping by either wave action or an unexpected water level rise. This generally occurs as a major erosion failure in the downstream slope.

*f.* *Erosion.* Erosion may occur due to overtopping, by wave action on the upstream shoreline, or due to piping through the dike.

## Foundation Stability

The foundation of the dike must (a) be capable of supporting the dike without a bearing capacity failure, (b) consolidate not more than a nominal amount under the weight of the dike, and (c) be relatively impervious to seepage.

**Bearing capacity.** A well-compacted dike with steep slopes should only be used when the foundation will support the concentrated load. As an approximate initial evaluation of bearing capacity, the dike may be reduced to an *equivalent long footing* having the same uniform contact pressure as the average of the weight of the dike, as shown in Figure 4-5. If the foundation is primarily cohesionless materials, then bearing capacity is rarely a concern because the weight of the dike increases the shear

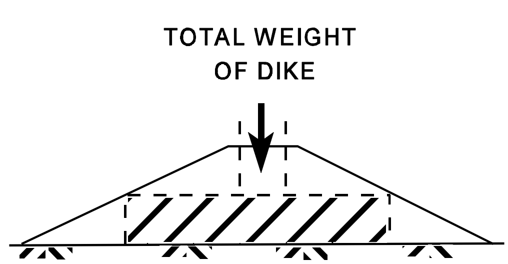


Figure 4-5. Equivalent footing for bearing capacity of foundation.

strength of the underlying soils. However, if the foundation is cohesive soil, then its strength under fairly rapid construction loading is not increased by the load. The ultimate undrained bearing capacity of a long smooth footing on clay is:

$$q_{ult} = 5.2 \ c \tag{4-1}$$

where $q_{ult}$ = ultimate bearing capacity ($lb/ft^2$) and c = soil cohesive strength ($lb/ft^2$) which can be estimated as 50% of unconfined compressive strength.

A factor of safety of at least 2.0 must be applied to this value. For a typical wetland dike, having a height of 2 m. (6 ft.) and a top width of 3.5 m. (8 ft.), and using Equation 4-1, it is only necessary that the average unconfined compressive strength of the soils within the upper 4-6 m. (12-18 ft.) be greater than 24 kPa (550 lb/sq ft), which is at the boundary between what engineers term very soft and soft cohesive soil.

If the foundation is too soft to support a compacted dike, three options are open: (1) If the very soft soil exists only to a shallow depth, it may be excavated and replaced with stronger, compacted soil, (2) use an upstream and/or downstream berm, or (3) decrease the dike weight by using either semicompaction, made with hauling equipment, or dumped fill. Hydraulic fill is most economical when used with semicompaction or simply with no compaction.

A *berm*, or dike extension, may be placed upstream or downstream or both. Berms provide the same effect as flattening the slopes, but are more effective because (a) they use less total material, and (b) they place weight where it is most useful, i.e., on top of the toe of a potential failure surface. A berm can also serve as a seepage control structure when placed over the downstream toe of a dike with a pervious foundation.

**Settlement.** If the bearing capacity is satisfactory for the chosen method of compaction and side slopes, the settlement should be estimated. For cohesionless soils, the equivalent footing of Figure 4-6 may be used with empirical charts for settlement on sand. Charts to determine the approximate average settlement are given in several geotechnical engineering textbooks and in "Soils and Geology; Procedures for Foundation Design of Buildings and Other Structures," Army Technical Manual TM 5-818-1 (USACE 1983).

For cohesive soils, either the equivalent footing of Figure 4-6 or the actual cross section may be used to calculate settlement. The pre-consolidation load and the compression index can be reasonably estimated from soil index properties, as discussed in various geotechnical engineering textbooks and in TM 5-818-1. The pre-consolidation load can be estimated from the unconfined compressive strength and plasticity index. The compression index can be estimated from either the liquid limit or the initial water content.

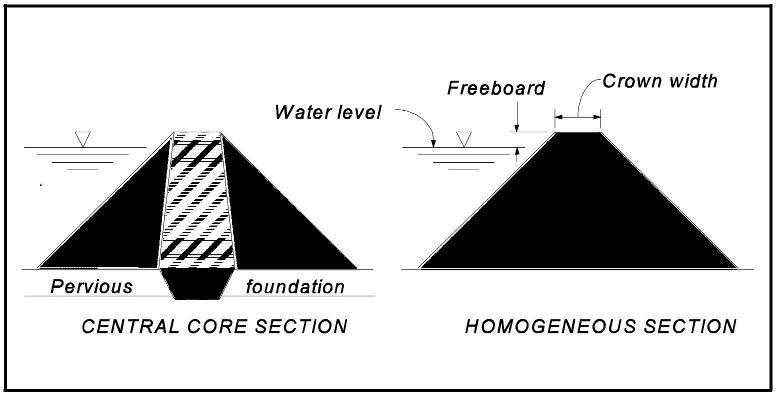


Figure 4-6. Cross section of central core and homogeneous dikes.

## Dike Geometry

Dike geometry refers to the height (including freeboard, or height above water level), width of the crown, and inclination of the side slopes. The side slopes are dependent on the character and strength of the foundation and of the embankment materials and the construction methods.

**Cross section.** Dependent on the availability of materials, the dike cross section may, as shown in Figure 4-6, have an impervious central core with supporting shells, or be uniform, or homogeneous. The central impervious core, or wall, may have any width suitable for retaining water. The soil must be carefully selected and placed to insure imperviousness. Generally, the central core must be wide enough to be placed, and perhaps compacted, longitudinally by common construction equipment. This implies a width of at least 1.8 to 2.4 m (6-8 ft) at the top and increasing slightly with depth. The central core may even be extended downward to act as a positive underseepage cutoff in the case of a shallow and pervious foundation layer. The shells to support the central core may be of any available material, including rock, cohesionless soils, and even a limited amount of organic soil.

When there is a sufficient amount of acceptable material of low to medium plasticity (including all USCS soil classes except GW, GP, SW, SP, and CH), then both the core and the two shells may be constructed of the same material, forming a uniform, or homogeneous dike section, as shown in Figure 4-7. Clean, cohesionless soils will be too pervious and high plasticity clay (CH) may experience detrimental shrinkage cracking. If there is a shallow pervious foundation, an impervious cutoff may be needed under the homogeneous section in the same manner as shown for the central core section. Whatever the material and method of construction, the strength of the shells must be sufficient to support them on the design slopes and must be capable of withstanding any seepage and/or erosion forces.

**Height and freeboard.** The height of the dike is dictated by project requirements for depth of water. Additional initial height may be needed to account for expected settlement of the dike on a compressible foundation. *Freeboard* is the additional height above flood stage, after full settlement, needed to provide protection against overtopping by wave action. A minimum of 0.6 m (2.0 ft), in addition to the settlement allowance, is recommended for fairly small ponded areas where wave action is limited by nearshore vegetation and/or by trees. Where open waters

**Table 4-1**
**Recommended Minimum Freeboard for Dikes (after USBR "Design of Small Dams," 2nd Ed., 1973)**

| Wind Fetch | | Minimum Freeboard | |
|---|---|---|---|
| km | miles | meters | feet |
| 0.4 | 0.25 | 0.9 | 3.0 |
| 0.8 | 0..5 | 1.1 | 3.5 |
| 1.2 | 0.75 | 1.15 | 3.8 |
| 1.6 | 1 | 1.2 | 4 |
| 4.0 | 2.5 | 1.5 | 4.6 |
| 8.0 | 5 | 1.8 | 5.3 |

are subject to strong wind, and significant wave action, the recommended minimum freeboard is given in Table 4-1.

**Settlement of dikes.** Allowance must be made in the constructed height of the embankment for settlement within both the dike and the foundation. Foundation settlement was discussed above. Suggested minimum allowances for embankment internal (self-weight) compression are given in Table 4-2. The information in Table 4-2 was based, in part, on Chapter 13, "Wetland Restoration, Enhancement, or Creation," of the USDA-SCS Engineering Field Handbook (Soil Conservation Service 1992).

**Table 4-2**
**Recommended Minimum Allowances for Dike Internal Settlement (based in part on Soil Conservation Service 1992)**

| Compaction Method | USCS Soil Type | Settlement Allowance, Percent of Height |
|---|---|---|
| Full specification compaction in thin lifts. | GW, GP, GM, GC, SW, SP, SM, SC | None |
| | CL-ML, CL, CH, ML, MH | Less than 5 % |
| Semi-compaction, construction machine only. | GW, GP, GM, GC, SW, SP, SM, SC | More than 5 % |
| | CL-ML, CL, CH, ML, MH | 5 - 10 % |
| Dumped and shaped; no attempt at densification. | GW, GP, GM, GC, SW, SP, SM, SC | More than 10 % |
| | CL-ML, CL, CH, ML, MH | 10 - 20 % |
| | Highly organic soils | More than 40 % |

**Crown width.** The desired crown width is dependent on the need for a roadway for maintenance and emergency operations. If not needed for other considerations, a roadway may also be available on a downstream berm or outside the dike proper. Slope stability or seepage requirements may dictate a minimum crown width. For construction purposes, the width of the crown may vary from practically zero to over 3.0 m (10 ft), dependent on construction method. If the central core, or the central section of a homogeneous dike, is to be semicompacted or compacted, there must be sufficient lateral space for operation of the compaction machines. This requires a crown width of at least 1.8 to 2.4 m (6-8 ft).

## Slope Stability

Dike slopes fail when the shear strength of the soil is less than the shear stress imposed by the self-weight of the soil and of pressure from the impounded water. When the near-surface foundation layer has a strength greater than that of the dike soils, then the slope failure will occur entirely within the dike. If there is a horizontal weak layer in the lower portion of the dike, then this will be the weakest section and is the preferred zone of shear failure. If the strength of the soil is fairly uniform throughout the cross section, and there are no weak horizontal layers along which failure is preferred, then the slope fails along a circular arc. Similarly, if the foundation soils are weaker than the dike soils or a particularly weak layer exists within the foundation, then the failure zone will extend into the foundation soils. The determination of safe slopes may be determined by either (a) rigorous slope stability analysis or (b) conservative empirical cross sections.

**Slope stability analysis.** If the embankment is fairly high and/or long, such that a large amount of embankment soil is to be used, a cost savings can be effected by determining the engineering behavior properties of the foundation and proposed embankment soils to a reasonable precision, and designing minimum slopes. When the soil properties have been well defined, the slopes and foundation of the proposed dike cross section should be investigated for translational and/or rotational stability by geotechnical engineering methods. Slope stability analysis programs are commercially available for use on desktop personal computers. The U.S. Army Corps of Engineers has an internally available program entitled *UTEXAS3* (Edris et al. 1992).

**Empirical cross sections.** For the typically low embankments at wetland sites, the cost of sampling the foundation and embankment soils and testing their properties with a sufficient precision to use in slope stability calculations may be more costly than simply using a conservatively safe cross section, as given in Table 4-3. Similarly, the use of semicompaction or uncompaction, and flatter slopes, may be more economical than a closely controlled, compacted embankment. Because the modification of the water content of soils for specification compaction can be expensive, time consuming, and weather dependent, the design should incorporate the properties of the soil at its natural water content or should require only a minimum of drying or wetting.

An additional consideration in the steepness of the *downstream* slope is maintenance. If mowing is to be done or other machinery is to be operated on the downstream slope, it should be no steeper than three horizontal to one vertical (3H:1V).

**Table 4-3**
**Recommended Side Slopes For Dikes on Strong Foundation (based on USBR 1973)**

| USCS Soil Type in Core [1] | Recommended Maximum Steepness -- Horizontal to Vertical | | |
|---|---|---|---|
| | Specification (Roller) Compacted | Machine (Semi) Compacted | Uncompacted |
| **Homogeneous Cross Section** | | | |
| GW, GP, SW, SP | Not recommended. Too porous. | | |
| GC, GM, SC, SM | 2.0 to 1 | 2.5 to 1 | 3.0 to 1 |
| CL, ML | 2.5 to 1 | 3.0 to 1 | 3.5 to 1 |
| CH, MH | 3.0 to 1 | 3.5 to 1 | 4.0 to 1 |
| OL, OH | ------ | ------- | 4.0 to 1 |
| **Central Core Section with GW, GP, SW, SP Material as Shells** | | | |
| GC, GM, SC, SM | 2.0 to 1 | 2.5 to 1 | 3.0 to 1 |
| CL, ML | 2.25 to 1 | 2.75 to 1 | 3.0 to 1 |
| CH, MH | 2.5 to 1 | 3.0 to 1 | 3.5 to 1 |
| OL, OH | ------ | ------ | 3.5 to 1 |

[1] Peat (Pt) or other highly organic soils should not be used.

## Seepage Control

Detrimental water seepage may occur through the dike and/or through a pervious foundation, as shown in the upper part of Figure 4-7, causing piping flow at the point of exit. Detrimental seepage has been observed in embankments of all heights, including one less than one meter (3 ft) high. This effect is particularly severe if the permeability of the soil is fairly high, or if there are void spaces left in the embankment because of the lack of compaction.

Seepage through a homogeneous embankment, with horizontal and vertical permeabilities equal, will exit

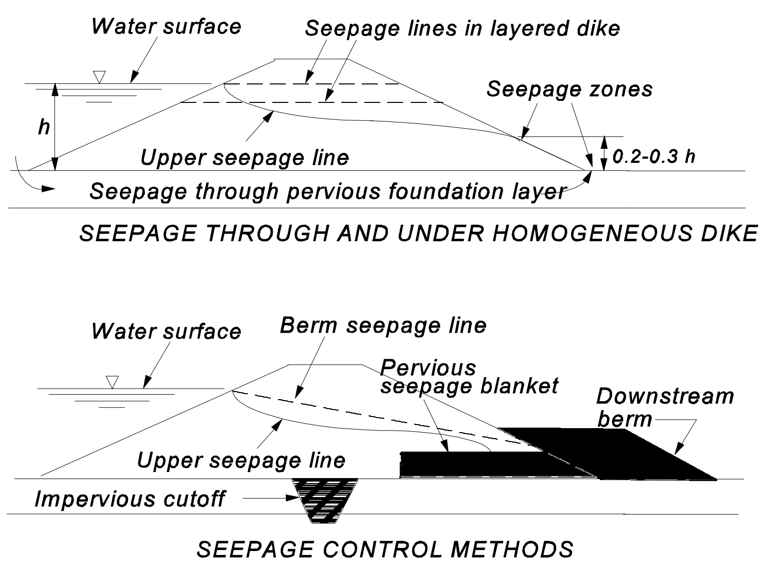


Figure 4-7. Seepage in a dike and seepage control measures.

above the toe at a height of about 20% to 30% of the height of the impounded water, as shown in Figure 4-7. Any horizontal layers within the dike that are relatively more permeable than the surrounding materials, and that extend through the dike, will act as a pipeline, permitting horizontal seepage higher up the slope. Underseepage will exit at the highest gradient point, at the toe of the slope, causing a boil, or uplift of soil. The net results of either form of seepage failure are that, at the exit point, there is (a) a reduction of shear strength of the soil, and/or (b) a physical erosion-removal of soil from the area around the toe, both contributing to slope instability. In the most severe cases, where rainfall is low and/or surface evaporation is high, seepage may contribute to lowering of the ponded water surface.

There are several design measures commonly used to control detrimental seepage through or under a dike. More detailed discussions of these methods than are given below are contained in several geotechnical engineering references, such as “Soil Mechanics Design, Seepage Control,” Engineer Manual 1110-1-1901 (USACE 1952).

**Seepage through the dike.** For seepage through the embankment, seepage control measures include (a) a seepage blanket at the downstream toe, (b) drain tile near the downstream toe, (c) an impervious core, and (d) a seepage berm.

*Seepage blanket*. As shown in the lower part of Figure 4-7, a highly pervious blanket of clean, cohesionless soil (gravel and/or sand) will draw the upper seepage line away from the slope. For wetland dikes, the horizontal blanket should start at the downstream toe and extend toward the centerline (upstream) a distance equal to the height of the dike. The blanket should be as thick as practicable, with a minimum of 0.3 m (1 foot). Because there will be a large difference in effective grain size between the blanket and the surrounding soil, the materials of the blanket must either (a) be proportioned as a graded filter, or (b) be encased in a suitable geotextile (filter cloth). The blanket should extend the entire length of the dike. Geotextiles are discussed in a later chapter of this section of the handbook.

*Drain tile.* An agricultural drain tile system can be used instead of a drainage blanket to draw the upper seepage line away from the slope. It is suggested that a 1.5- to 3-cm (4- to 8-in.) diameter standard perforated drain pipe be placed at about ground surface inward (upstream) from the downstream toe at a distance equal to 75% to 100% the height of the dike. The tile may be placed at ground surface or slightly above it. The drain pipe should be covered with at least 30 cm (1 ft) of sand, top and sides, with clean sand and/or fine gravel that will serve as a filter and as protection during construction. The pipe is also often wrapped in filter cloth for added filtration of fines. However, biological growth can clog filter cloth so this practice may not be desirable. [Geotextiles are discussed in another chapter of this section of the handbook.] Care must be taken to protect the drain and the filter sand from disruption by machinery during construction. A lateral drain pipe should be placed at regular intervals, and at depressions, to drain the seepage downstream. For more information about drain tiles, the reader is referred to Chapter 14, “Drainage,” of the USDA-SCS Engineering Field Manual (Soil Conservation Service 1984).

*Impervious core.* An impervious central core, as shown in Figure 4-7, with a granular soil downstream shell, will appreciably reduce the quantity of seepage. The central core should be made of as high plasticity clay as is available, placed and compacted at as high a water content as possible to inhibit void spaces between clods. If a pervious downstream shell is not feasible, a horizontal seepage blanket (described above) may be used.

*Seepage berm.* A soil berm can be placed at the downstream toe, as shown in the lower part of Figure 4-7. In the absence of a more exact seepage analysis, the length of the berm may be established by drawing a line, as shown in Figure 4-7, from the upstream inlet point to a point on the downstream slope at a height equal to 30 percent of the water height and continuing the line to intersect with the ground surface. The berm should enclose that part of the line outside the dike. The use of a berm provides the opportunity to make the downstream slopes steeper than shown in Table 4-3, as long as the lower part of the recommended slope line is contained within the berm. A berm also can provide a roadway for maintenance and permit a greatly reduced crown width.

**Underseepage through the foundation.** If a pervious layer exists from the existing ground surface to a short depth, or if the pervious topsoil layer (A-horizon) has not been completely stripped, and the seepage layer is short compared to the permeability of the layer, then unacceptably high exit pressures will exist at the toe of the dike. Methods for under seepage evaluation and control are discussed in detail in EM 1110-2-1901 (USACE 1952). The main methods for underseepage control are (a) a positive cutoff, (b) an upstream blanket, and (c) a toe berm.

*Positive cutoff.* If the underseepage layer is fairly thin, up to about three meters (10 ft) thick, then a positive cutoff core may be excavated and replaced with relatively impervious, compacted soil. If a central core section is used, the cutoff may be a downward continuation of the core.

*Upstream blanket.* If the pervious underseepage layer is too thick for a positive cutoff, (a) the total quantity of seepage loss, and (b) the intensity of the uplift pressure at the toe of the dike, may be decreased to an acceptable level by increasing the length of the underseepage path. A layer of relatively impervious cohesive soil, semicompacted or compacted, should be placed from the upstream toe of the dike for the full length of the dike. The width of the upstream blanket can be calculated by theoretical methods given in EM 1110-2-1901 (USACE 1952). The blanket thickness should be at least 0.15-0.25 m. (6-9 in).

*Toe berm.* Instead of placing upstream, the seepage blanket can placed downstream, starting at the toe. A more efficient and effective device is a toe berm, as shown in Figure 4-8. The intent of the toe berm is to increase the effective stress on the foundation soils at the seepage exit point at the toe. This also forces the exit point farther downstream, reducing the uplift pressure to an acceptable level. Engineer Manual 1110-2-1901 (USACE 1952) should be consulted for design details.

## Protection Against Overtopping

Outlet structures may be needed to prevent the impounded water from rising above its design level and overtopping the dike. This will occur when rainfall and/or drainage into the pond or lake exceeds the outflow due to evaporation or seepage.

The simplest form of structure is the *emergency spillway*. Two other common types of water control structures are the *sluice box* and the *drop inlet*. Both of the latter types make use of a drain pipe through the dike or through the foundation. The foundation location has the advantage that the pipe ditch can be excavated, the pipe and drainage material placed, before the dike itself is constructed. This allows longitudinal freedom for hauling and compaction equipment.

**Emergency spillway.** An emergency spillway is generally a flat notch cut in the dike or its abutments to relieve any excess height of water. If there are no other water control structures, the crest should be at least 8 cm (3 in.) above the normal pool elevation. If water control structures are used, a minimum of 15 cm (6 in.) should be allowed to permit the water level rise for normal operation of the structures to occur.

The shear strength of the spillway surface soils should be as high as possible to resist erosion. If possible, the spillway should be located in natural, undisturbed soil at a dike abutment. If this is not feasible, then the section of dike containing the emergency spillway should be fully compacted, in thin lifts, as discussed in a later chapter of this section of the handbook.

The crest width should be determined by the amount of expected excess water in the impoundment, as discussed in the hydrology section of this handbook. Side slopes should be no steeper than 3H : 1V. The flat central portion of the spillway crest should be as long as possible, at least 7.5 m (25 ft.). If this is not feasible, then a concrete covered spillway structure should be considered. The slope of the exit channel should be between 1 and 12 percent.

The exposed surface of the spillway should be heavily vegetated to inhibit erosion. Coarse gravel and cobbles can be used to further inhibit erosion, particularly on the crest. The bottom of the exit channel, where it intersects the existing ground surface, should be covered with coarse gravel, cobbles, or even boulders to serve as an energy dissipation section to further inhibit erosion. The coarse stone may be encased in a gabion.

**Sluice box.** The sluice box in the upper part of Figure 4-8 is constructed within the cross section of the dike. Its main advantage is that the upstream edge of the box can be used as a weir, to measure the quantity of water overflowing the dike through the outlet structure. Its length across the width of the dike can be any desired value, up to the full width of the dike.

**Drop inlet.** The drop inlet structure has been used on small U.S. Army Corps of Engineers and USDA Soil Conservation Service dams for many years. Designs are fairly standard and publications of those organizations should be consulted for details.

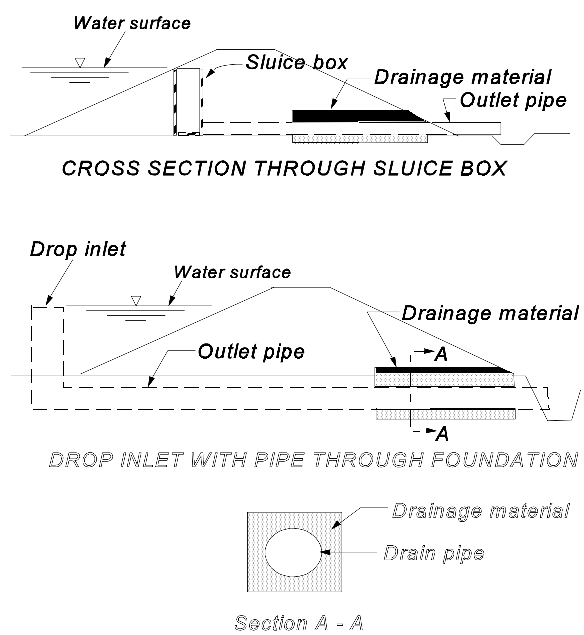


Figure 4-8. Water level control outlet structures.

The outlet pipe through the dike or the foundation must be protected against seepage along the pipe. In the past, metal anti-seepage collars were installed. However, as shown in Figure 4-8, drainage material blankets can be placed around the pipe near the outlet end to inhibit piping.

## Protection Against Erosion

Erosion of the surface of the completed dike may occur because of rainfall or, on the upstream slope, from wave action. The susceptibility of a soil to erosion is a function of its grain size and plasticity. Erodibility is low for coarse grains and increases as the grain size decreases to silt sizes (0.075 to 0.002 mm). As the plasticity of the fine-grained soil increases, usually with an increase in clay content, the erodibility becomes markedly less again. Therefore, the most severe erosion will take place in soils of fine sand to non-plastic silt sizes.

Rainfall erosion can be inhibited in several ways. A complete vegetation cover of all exposed surfaces of the dike with grasses having a thick root structure will reduce the velocity of flowing water to non-eroding levels. The grading and shaping of the surface to eliminate ruts, minor depressions, or minor gullies will inhibit the formation of erosion "nick points." The surface can be covered with filter cloth and gravel or crushed rock to protect underlying fine-grained soils.

Protection against the erosive effects of wave action on the upstream slope can take several forms, as shown in Figure 4-9, as long as they serve to absorb the energy of the waves. A stone riprap blanket can be placed from the crest of the dike to a point some distance below the lowest expected low water level. The riprap is usually crushed stone, placed on a sand blanket or a geotextile filter cloth. Where wave action is not severe, a thickness of coarse gravel and/or cobbles can be used to absorb the wave energy. If coarse grained materials are not available, the wave-contact zone can be covered with asphaltic concrete or may be paved with soil cement. It is usually desirable to provide a small berm at the lower end of the riprap to provide support against sliding.

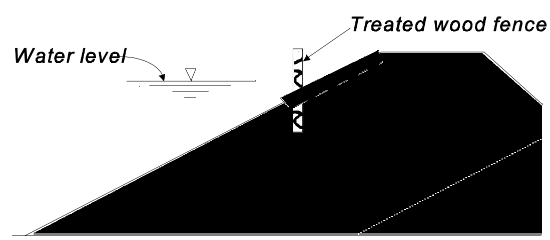


Figure 4-9. Upstream slope protection methods.

Another feasible wave protection device, useful where crushed stone or very coarse materials are not available, is a treated wood fence, as shown in Figure 4-9. The fence may consist of continuous driven poles or may be spaced poles with boards of wood or other available material. The objective is to form a wave energy absorption fence. The fence need not be impervious. Coarse or fine-grained soil may be placed behind the fence for stability, if desired.

# 4-4 Geosynthetics Applications in Wetland Construction[1]

Geosynthetics have become an increasingly important construction material on wetland projects over the past several years. Selection of geosynthetics for use on a wetland restoration or creation project is usually based on an improvement in the performance of soils handling, as a water barrier, for dike placement on soft soils, and use as a drainage blanket in dikes. Geosynthetics generally offer a substantial cost savings over alternative methods, provide more effective installation, reduce maintenance, and/or increase service life.

For a detailed discussion of the geotechnical engineering uses of geosynthetics, the reader should consult one or more of the several recent textbooks on the specific subject. One excellent and complete reference is the “Geotextile Engineering Manual,” a course text prepared for the Federal Highway Administration (FHWA 1982).

## Description and Uses of Geosynthetics

Geosynthetics are polymeric materials used in environmental, geotechnical, and transportation engineering and related construction activities. *Geosynthetics* is a general term covering geotextiles, geomembranes, geogrids, geonets, and similar products.

A *geotextile* is any *permeable textile material* used with soil, rock, or any other geotechnical-related material, for separation, reinforcement, filtration, and drainage. A *geomembrane* is any *impermeable membrane* used to function as a liquid barrier for pond liners, reservoir covers, canal liners, landfill liners, and similar purposes. *Geogrids* are designed primarily for reinforcement functions. *Geonets* are used for in-plane flow of liquids (water and other liquids) in a number of applications. The present discussion deals only with the use of geotextiles in wetland projects involving soils handling and/or earthwork.

### Geotextile materials

Geotextiles are usually made from synthetic polymers such as polypropylene, polyester, polyethylene, polyamide, and nylon. Some geotextiles are made from glass fibers, whereas others may incorporate steel wires or cables.

[1] By S. Joseph Spigolon

The synthetic polymers are formed into filaments, staple fibers, or slit films. Geotextiles are either (a) nonwoven, (b) knitted, or (c) woven. Nonwoven geotextiles are made from filaments and/or staple fibers. Woven and knitted geotextiles are made from yarns, which are made of one or several fibers.

Nonwoven geotextiles are formed from fibers arranged in a planar structure. The fibers are bonded together by either: (a) chemical bonding, using glue, rubber, latex, or synthetic resin, (b) thermal bonding, using partial melting of the fibers, or (c) mechanical bonding (needle punching), in which very small, very closely spaced barbed needles punch through the fiber mat and withdraw, leaving the fibers entangled.

Knitted geotextiles are formed by interlocking a series of loops of one or more yarns to form a planar structure. Generally, knitted fabrics have mostly been used as filters in pipe wrap applications.

Woven geotextiles are composed of two sets, warp and fill, of parallel yarns systematically interfaced to form a planar structure. The most commonly used yarns are monofilament, multi-filament, and slit film. Three basic weave patterns (plain, twill, and satin) are used to construct a wide variety of fabrics.

## Controlling functions and applications

Geotextile applications are generally divided into four basic, or primary, controlling functions:

*a.* **Separation**. Layers of different sizes of soil or rock particles are separated from one another by the geotextile. This prevents migration of fine particles into the void spaces of the coarser particles.

*b.* **Drainage.** The geotextile itself acts as a drainage layer or as a wick to transmit water through soils of low permeability. These specially designed geotextiles are referred to as "geonets."

*c.* **Filtration.** The geotextile is a filter fabric. It is used as an alternative to a graded sand filter, allowing the flow of water from a soil while preventing the fine soil particles from moving. This may be used in filter situations of soil-to-soil or from soil-to-pipe.

*d.* **Reinforcement.** The geotextile is used as a reinforcing element in the earth because soil has negligible tensile strength. The fabric produces either stress distribution or an increase in the soil modulus. Geogrids are specially designed earthen reinforcement.

The *separation* function is mainly used in roadway and railroad subgrades, although it may be applied to earth dams and dikes. The *drainage* application includes earth structures where there is a need for relief of water pressure against the structure or in preloading operations. The main applications in wetlands involve the *filtration* and *reinforcement* functions.

Filter fabrics are used in wetland soils handling projects for such applications as toe drains in dikes, upstream wave protection, pipe wrapping, silt screens, and erosion control. The reinforcement capability of geotextiles is used in wetland projects involving soils handling and earthwork. The present discussion deals only with the use of geotextiles for applications such as roadway reinforcement, retaining structures, dike reinforcement, foundation reinforcement, riprap placement, sandbags, and geotubes.

### Properties of geotextiles

Geotextiles vary considerably in manufacturing techniques, fiber types, filament types, weaving patterns, bonding methods, thickness, and composition. Therefore, these variations lead to a large range in their physical and mechanical properties. For example:

*a.* Weights of geotextiles (mass per unit area) commonly range from less than 100 $g/m^2$ (3 $oz./yd^2$) to over 1200 $g/m^2$ (36 $oz./yd^2$).

*b.* Tensile strengths range from 3.5 kN/m (20 lbs/in.) at failure to over 350 kN/m (2000 lbs/in.).

*c.* Costs range from $1.00 per sq. yd to over $25.00 per sq. yd. (1994 prices).

The properties and parameters for geotextile selection (adapted from the Geotextile Engineering Manual (FHWA 1982) are:

*a.* *General properties:* Type and construction; polymer; thickness and weight; roll length, weight, and diameter; specific gravity and density; absorption; surface characteristics; and geotextile isotropy.

*b.* *Mechanical strength properties:* Tensile strength (grab, strip tensile, and wide width strength); Poisson’s ratio; stress-strain characteristics, tensile modulus; dynamic loading; creep resistance; friction/adhesion (slick, rough, smooth); seam strength; and tear strength.

*c.* *Rupture resistance properties:* Burst strength; puncture resistance; penetration resistance (dimensional stability); fabric cutting resistance; and flexibility (stiffness).

*d.* *Endurance properties:* Abrasion resistance; ultraviolet (UV) radiation stability; chemical resistance; biological resistance; wet and dry stability; and temperature stability.

*e.* *Hydraulic properties:* Opening characteristics, including (a) apparent opening size (AOS), (b) pore size distribution, (c) percent open area, and (d) porosity; permeability and permittivity; soil retention ability; clogging resistance; and in-plane flow capacity (transmissivity).

Many of these properties are the subject of American Society for Testing and Materials (ASTM 1994) standards for materials and test methods.

## Use of Geotextiles as Filters

A cohesionless soil filter has been used for some time at the contact between two soils, or a soil and a pipe opening, to allow water to pass and to prevent the movement of the soils particles. Empirical criteria have been developed for sand filters, either as a single filter or a graded filter. The general requirements for a *cohesionless sand filter* are as follows:

*a.* *Piping requirement:* The $D_{15}$ of the filter must be equal to or less than five times the $D_{85}$ of the protected soil.

*b.* *Permeability requirement*: The $D_{15}$ of the filter must be equal to or greater than five times the $D_{15}$ of the protected soil.

*c.* *Uniformity requirement:* The $D_{50}$ of the filter must be equal to or less than 25 times the $D_{50}$ of the protected soil.

*d.* *Well screen/slotted pipe criteria*: The $D_{85}$ of the filter must be equal to or greater than 1.2 to 1.4 times the slot width, or 1.0 to 1.2 times the hole diameter.

where $D_{15}$, $D_{50}$, *and* $D_{85}$ *are the diameters of soil particles, D, at which 15%, 50%, and 85%, respectively, of the soil particles are, by dry weight, finer than that grain size.*

### Geotextile filtration function

A geotextile can be used in place of a granular filter. For a geotextile to effectively perform as a filter, it must remain free-draining by having opening characteristics compatible with the surrounding soil. If a soil contains some particles smaller than the effective opening of the cloth, they will pass through. However, as the finer soil passes through, larger particles may combine to bridge over the apertures. This bridging zone has been termed the *filter cake.* Once the filter cake has been established in a one-directional flow situation, no further soil is washed through and the system is in equilibrium.

The requirements for a filter fabric are similar to those for a sand filter. The fabric must prevent piping of the soil, and it must be, and remain, more permeable than the surrounding soil. Furthermore, the fabric must have sufficient tensile strength, puncture resistance, burst strength, and abrasion resistance to survive placement and provide adequate in-service performance.

The FHWA Geotextile Engineering Manual (FHWA 1982) contains a summary of geotextile design and selection criteria for filter and erosion control applications. The FHWA summary includes criteria for (a) soil retention, or piping resistance, (b) permeability, (c) clogging, (d) chemical composition, and (e) constructability and survivability. The criteria are given in the following paragraphs. The Apparent Opening Size (AOS) value is the opening size in terms of a

**Table 4-4**
**Piping Resistance Criteria for Use With Geosynthetics**

| Soils | Steady State Flow | Dynamic, Pulsating, and Cyclic Flow |
|---|---|---|
| Equal to or less than 50% passing the No. 200 sieve (0.074 mm) | AOS $O_{95} \leq B \bullet D_{85}$<br>$2 \geq C_u \leq 8$: B = 1<br>$2 \leq C_u \leq 4$: $B = 0.5\, C_u$<br>$4 < C_u < 8$: $B = 8/C_u$ | $O_{95} \leq D_{15}$<br>or<br>$O_{50} \leq 0.5\, D_{85}$ |
| Greater than 50% passing the No. 200 sieve (0.074 mm) | Woven: $O_{95} \leq D_{85}$<br>Nonwoven: $O_{95} \leq 1.8\, D_{85}$<br>AOS No. (fabric) $\geq$ No. 50 sieve | $O_{50} \leq 0.5\, D_{85}$ |

Notes:
1. When the protected soil contains particles from 2.5 cm (1 in.) size to those passing the U.S. No. 200 sieve (0.074 mm), use only the gradation of the soil passing the U. S. No. 4 sieve (4.76 mm) in selecting the fabric.
2. Select fabric on the basis of the largest opening value required (smallest AOS).

U.S. sieve equivalent for which 95% of the fabric pores are smaller than the diameter. The AOS is normally expressed as the $O_{95}$. The $O_{95}$ corresponds to the sieve opening size in millimeter determined by the AOS test. A more recent summary of geotextile design is provided by Koerner et al. (1994).

*a.* *Piping resistance criteria.* Criteria for selecting geosynthetics for soil retention (piping resistance) are given in Table 4-4.

*b.* *Permeability criteria.* Permeability should be based on the actual area of unobstructed fabric available for flow. The criteria for selecting geosynthetics based on permeability are:

1. For *critical/severe* applications, the permeability of the fabric should be equal to or greater than 10 times the permeability of the soil.

2. For *less critical/less severe* applications, with clean, medium to coarse sands and gravels, the permeability of the fabric should be equal to or greater than the permeability of the soil.

3. Optional additional qualifier, $O_{95} \geq 2\, D_{15}$.

*c.* *Clogging criteria.* The criteria for selecting geosynthetics based on clogging potential are:

1. For *critical/severe* applications, select fabrics meeting piping, permeability, and less critical/less severe clogging criteria and make soil/fabric filtration tests before final selection. Filtration tests are based on actual soil/fabric interaction and cannot/should not be done by the manufacturer.

2. For *less critical/less severe* applications:

   a) Whenever possible, fabric with lowest AOS No. from the piping criteria should be specified.

   b) For woven fabrics -- Percent Open Area ≥ 4%.

      For nonwoven fabrics -- Porosity ≥ 30%.

*d. Chemical composition.* Requirements and/or considerations for chemical composition are:

1. Fibers used in the manufacture of geosynthetics (filter fabric) shall consist of long chain synthetic polymers, composed of at least 85% by weight of polyolephins, polyesters, or polyamides. These fabrics shall resist deterioration from ultraviolet exposure.

2. The filter fabric shall not be exposed to ultraviolet radiation (sunlight) for more than 30 days total in the period of time following manufacture until the fabric is covered with soil, rock, concrete, etc.

*e. Physical property requirements.* Requirements for constructability and survivability are given in Table 4-5.

## Geotextiles in erosion control

Layers of coarse gravel, cobbles, small boulders, rock fragments (riprap), and/or gabions can provide effective erosion protection for streambanks, drainage channels, and dike slopes by dissipating erosive hydraulic forces due to wave action or moving water and providing anchorage to the natural soil. Geotextiles such as geogrids increase erosional resistance by (a) restraining the riprap or other large material from sinking into the natural soil, (b) preventing the underlying natural soil from being piped through the riprap, and (c) permitting natural seepage to occur from the protected soil to prevent a buildup of hydrostatic forces. A geotextile which meets the design criteria for a filter fabric given above can replace one or more layers (or all) of a required granular filter.

Special net, mesh, and grid-type geotextiles can be placed directly on a slope, without riprap cover, to temporarily hold soil, seeding, and mulch until vegetation has been established to control erosion. Hydraulic structures, such as culverts, bridge piers, and drop inlets also require erosion protection. If vegetation cannot be established or the natural soil can be scoured from under riprap placed directly on the natural soil, a geotextile can be used to replace the conventional

**Table 4-5**
**Physical Property Requirements for All Filter Fabrics**

| Test Method | Unprotected Fabric | Protected Fabric * |
|---|---|---|
| Grab Strength (ASTM D 1682) -- minimum in either principal direction. | 82 kg (180 lbs.) | 36 kg (80 lbs.) |
| Puncture Strength (ASTM D 751) | 36 kg (80 lbs.) | 11 kg (25 lbs.) |
| Burst Strength (ASTM D 751) | 2000 kPa (290 psi) | 900 kPa (130 psi) |
| Trapezoid Tear (ASTM D 1117) -- any direction. | 23 kg (50 lbs.) | 11 kg (25 lbs.) |

* Fabric is said to be protected when used in drainage trenches or beneath/behind concrete (portland or asphalt cement) slabs. All other conditions are said to be unprotected.

granular filter. In many of these applications, placement of the filter may be required below water. Geotextiles offer the advantage of being easier to place underwater in many instances.

### Filter construction considerations

The following construction considerations should be followed for all filter and erosion protection applications.

a. The ground surface to be in contact with the cloth should be smooth, with no depressions or holes, and free from large particles, limbs, or other debris.

b The fabric should be placed loosely, laid with the machine direction in the direction of anticipated water flow.

c. If seamed to reduce the cost of overlaps, only high-strength polyester, polypropylene, or Kevlar thread should be used. Overlapping J-type seams are preferred over flat, prayer-type seams. If flat, or prayer-type, seams are used, they should be double sewn. It is recommended that all field seams be double sewn.

d. Overlaps can account for over 25% of total fabric costs. Overlaps should be in the direction of water flow and stapled or pinned to the soil. A minimum overlap of 30 cm (12 in.) between adjacent rolls and between adjacent roll ends is recommended. Steel pins, 45 cm (18 in.) long, each with a 4-cm (1.5-in.) diameter metal washer, are used in firm, fine-grained soils. Longer pins are used in loose sand. Pin spacing varies according to steepness of the slope, from 0.6 m (2 ft) on a 1V: 3H slope to over 1.5 m (5 ft) on a 1V:4H or flatter slope.

# Use of Geotextiles and Geogrids to Reinforce Dikes

Soil has virtually no tensile strength. The tensile strength of geosynthetic materials may be used to advantage to reinforce the interior of a dike against slope failure or a soft foundation if placed in the tension area of potential failure zones.

## Embankment slope reinforcement

The use of geosynthetics, either *geotextiles or geogrids*, placed in one or more horizontal layers within an embankment will permit a steeper slope. Where the dike is long and the quantity of available fill soils is small or is otherwise too costly, less of the same material at the same amount of compactive effort will be needed. As shown in Figure 4-10, the placement of a reinforcing geosynthetic at the point of greatest potential tension, where the circular failure arc or the sliding wedge becomes nearly horizontal, is the point of greatest effectiveness. Where the potential failure arc or sliding wedge zone extends down into the foundation, as shown above in Figure 4-10, the motion is across the material and the geosynthetic is of limited value.

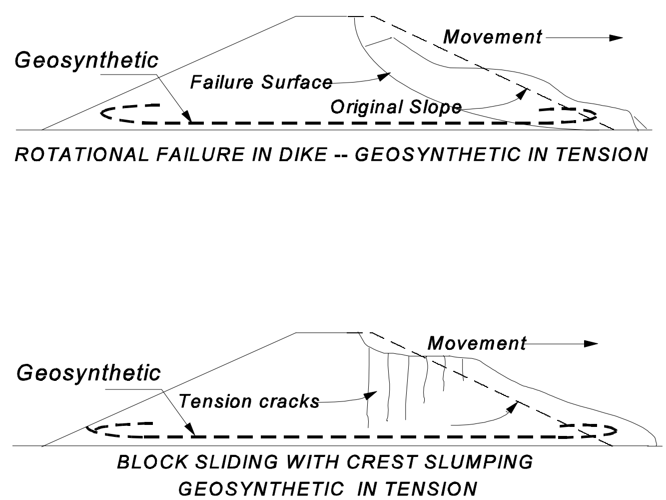


Figure 4-10. Embankment slope reinforcement with fabric.

The geosynthetic should be selected to have the highest practicable tensile strength. Geotextile placement should be transverse to the length of the dike, i.e., the machine direction transverse to the centerline, to prevent the use of seams in the direction of potential tension forces. Overlapping, therefore, occurs across the width with numerous overlaps along the length of the dike.

The foundation layer to receive the geosynthetic should be compacted and bladed smooth. The first layer over the material must be placed by end dumping and spreading in from of the machines to prevent direct wheel or tread contact. Machinery should be of such light weight that no wheel or track will cause a rut that may overstress the fabric. Light dozers or front-end loaders, with 17 to 20 kPa (2.5 to 3.0 psi) contact pressure, are useful for this purpose. The minimum fill cover under track or wheel compactors is 15 to 30 cm (6 to 12 in.). For sheepsfoot rollers, the minimum initial fill cover should be at least 30 cm (12 in.).

### Dike construction on soft foundations

A geotextile or geogrid may be placed on the surface of a soft foundation under a proposed dike. On a soft, compressible foundation this will not only serve to strengthen the dike against lateral spreading, Figure 4-11, it will serve to limit the amount of vertical movement of the dike due to foundation failure, as shown in Figure 4-11. As the dike is placed, the weight of the embankment soil pushes downward into the soft foundation soil, causing a lateral displacement of the soil and a “mud wave” at the dike toe.

In addition to use as a dike foundation reinforcement, geosynthetics can serve as a roadway reinforcement, to permit the use of low-contact-pressure construction equipment on a soft base. If the moving tire or track is viewed as having the same behavior as the long dike on a soft foundation, as shown in Figure 4-11, then the downward movement of the tire or track into the soft soil is called a rut, and the geosynthetic can serve to limit the amount of rut displacement. Similarly, if a load of fill soil is placed on the surface of a soft foundation soil, it may cause displacement. Then, as the soil is moved laterally to spread it, a mud wave may form in the front and to the side of the advancing soil mass. In these cases, geotextile or geogrid provides the needed tensile strength to permit operation.

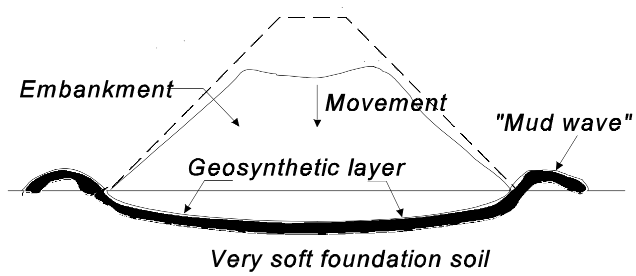


Figure 4-11. Potential embankment failure due to excessive displacement.

## Use of Geotextiles as Geotubes

Geotextiles may be sewn longitudinally to form a tubular shape, called a *geotube.* The ends of a geotube are also sewn shut and water escape exits, which are later sewn shut, are cut into the top of the tube at intervals. The geotube may then be filled from one end with hydraulically pumped dredged material to form a sausage-like shape. Excess water will permeate through the geotextile, but most or all of the soil material will be retained because of the filtering capability of the fabric.

In this manner, a very soft, low density slurry can be confined to form a barrier or dike of reasonable height to width ratio. The shape of the geotube after filling with low density material depends on the density of the slurry fill, the density of the surroundings, the circumference of the tube, and the stiffness of the bag material. The filled geotube will have a modified elliptical shape, with a major portion of the bottom being flat, and a height of 30 to 40% of the resulting width.

A geotube may be used to form either a permanent dike or a temporary barrier. As a permanent structure, it should be recognized that, as the interior slurry dewaters, the dike will shrink in size. Also, the geotextile material will be subject to ultraviolet rays from the sun that will cause deterioration. Therefore, if the wetland project requires the use of soft or loose dredged material and geotube is used to contain the slurry, some form of sunlight protection should be provided, perhaps by covering with soil.

Another interesting application for a geotube is as a water-filled temporary dike. The geotube is made from an impervious geomembrane material. The seams must be glued or thermally bound. Then, as a temporary retaining structure, it is simply filled with water. The height of the water-filled impervious geotube must be higher than the impounded water for it to function as a retaining structure.

# Section 4
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# Wetlands Engineering Handbook

## Section 5

## Establishing Proper Hydrologic Conditions

# Section 5
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# 5-1 Overview of Hydrologic and Hydraulic Analyses[1]

## Background

The long-term success of a wetland restoration project is dependent upon a viable water source and supportive hydrology. Surface water can enter a wetland through precipitation, runoff, streamflow, incoming tides; and spillover from an adjacent water body. Wetlands may also receive water from groundwater and natural springs. Water entering the wetland is continuously exchanged between the surface wetland, the groundwater, and the receiving waters. Water exits the wetland through natural drainage channels, natural groundwater gradients, seepage, evapotranspiration, outgoing tides, and water control structures. Regional rainfall often follows a seasonal pattern which can be evaluated and applied to the design of the wetland project. Other hydrologic features such as infiltration, seepage, and evapotranspiration are controlled by large-scale geomorphic features, soil type, terrain, and geographic location. These features may lend themselves to local modification to accommodate the wetland project.

Wetland hydraulic design is an iterative procedure, consisting of 1) proposed hydraulic design, 2) site drainage analysis and surface flow hydrodynamic analysis with the proposed features in place, 3) evaluation of the proposed design against the specified design criteria, and 4) modification of the proposed design. Designs must meet the design criteria and be compatible with site limitations. The project budget can influence the project design because maintenance requirements, initial investment, and annual costs will be limited by the funding available.

## Scope

This section provides an overview of the appropriate tools for the analysis, design, and construction of wetland hydraulic features. For an overview of wetland hydrology, please refer to Chapter 2-4. Chapter 5-2 describes surface and subsurface drainage analyses and surface flow hydrodynamic analyses. An overview of the design of water control structures is given in Chapter 5-3. Chapter 5-4 describes methods for erosion control and shoreline protection for wetland sites.

[1] By Lisa C. Roig

# Hydrologic and Hydraulic Design Process

Hydrologic design and analysis procedures principally involve a description of the temporal and spatial distributions of rainfall, runoff, water table fluctuations, and tides. The hydrologic processes affecting wetlands include direct precipitation, runoff, streamflow, infiltration, surface storage, subsurface storage, and groundwater flow. The circulation of surface water within the wetland, also called surface water hydrodynamics, can also be important for the purposes of wetland design and engineering depending upon the rate of water exchange, the currents within the wetland itself, and the design criteria. The types of design features most often considered for wetlands are water control structures, site grading, dredged channels, diversion structures, culverts and erosion control measures. The hydrologic analyses required to design these features may include one or more of the following: 1) determining the design storm or design tide; 2) determining the maximum and minimum water surface elevations; 3) determining the circulation patterns and maximum velocities; 4) determining the propagation of wind waves; 5) determining the extent and duration of inundation events; 6) determining the minimum required inflows; or 7) determining the maximum permissible outflows.

The hydrologic analyses required for the design of a wetland project are normally divided into two phases: 1) baseline hydrologic analysis of the site; and 2) hydrologic/hydraulic design and analysis. Baseline hydrologic analysis of the site is required before developing the preliminary designs and is more in depth than what would be produced during site selection. It provides information about the sources of water, their magnitudes and the current distribution of water on the site. A flow chart for developing a baseline hydrologic analysis of the site is provided in Figure 5-1. The baseline hydrologic analysis may also provide information during the hydrologic-hydraulic design process, but additional analyses will be required depending upon the feature to be designed. A generalized flow chart of the site design process is provided in Figure 5-2.

# Hydrologic and Hydraulic Analyses

Hydrologic and hydraulic analyses refer to the process of gathering, organizing, and applying hydrologic data. The purposes of these analyses are to understand the distribution, abundance, and dynamic behavior of water on the site. Varying degrees of hydrologic analyses are required during initial site assessment, during site selection, during the development of conceptual designs, and during the design of the engineering works. Hydrologic analyses that describe the relationship of the wetland site to the contributing watershed usually need to be done only once. The modification of onsite hydrology and its affect on the watershed downstream of the wetland project must be repeated for each design and for each set of seasonal hydrologic conditions specified in the design criterion. Table 5-1 lists the most common hydrologic analysis methods and describes their intended use. The data requirements for each type of hydrologic analysis are presented in Table 5-2.

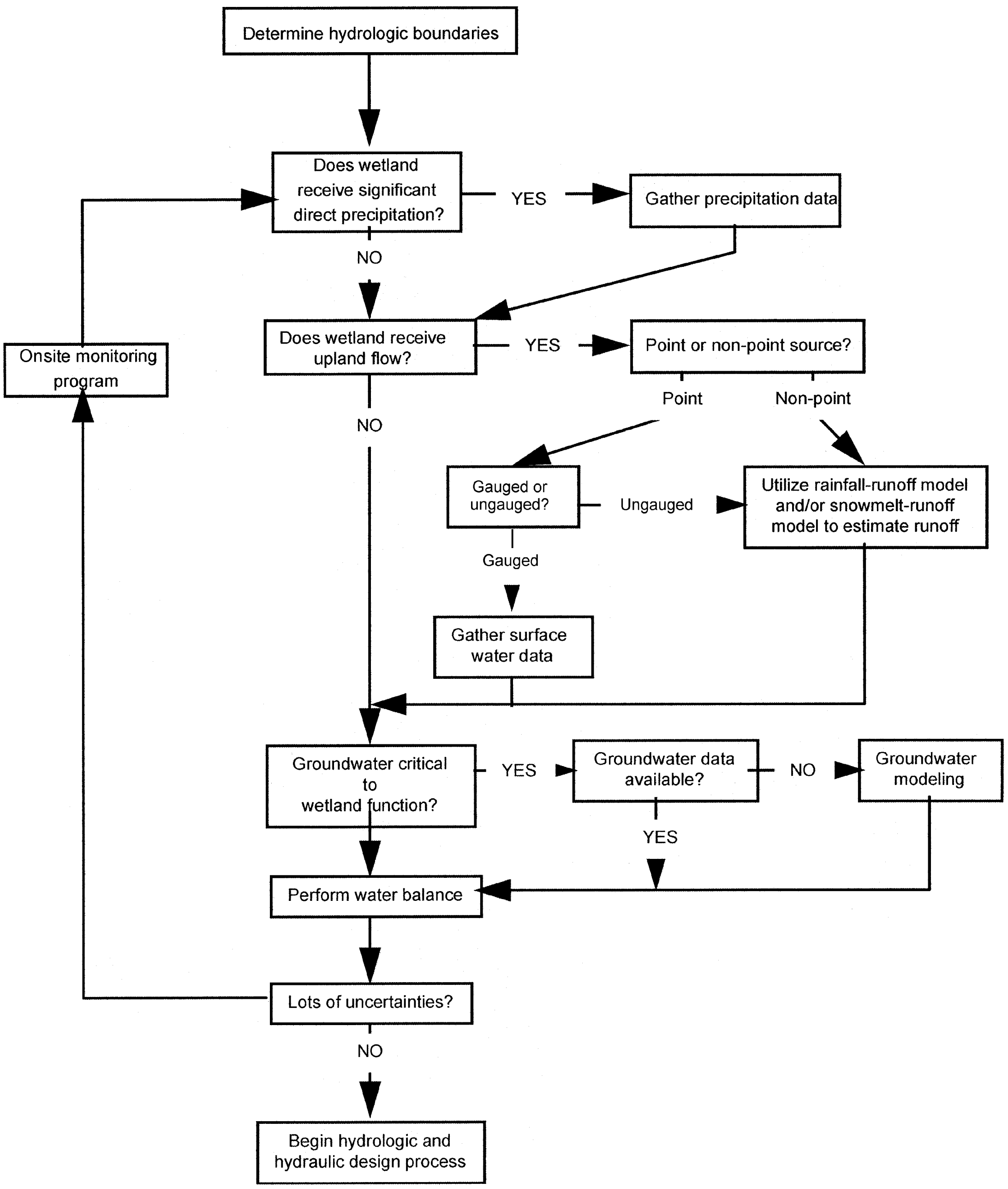


Figure 5-1. Baseline hydrologic analysis for wetlands.

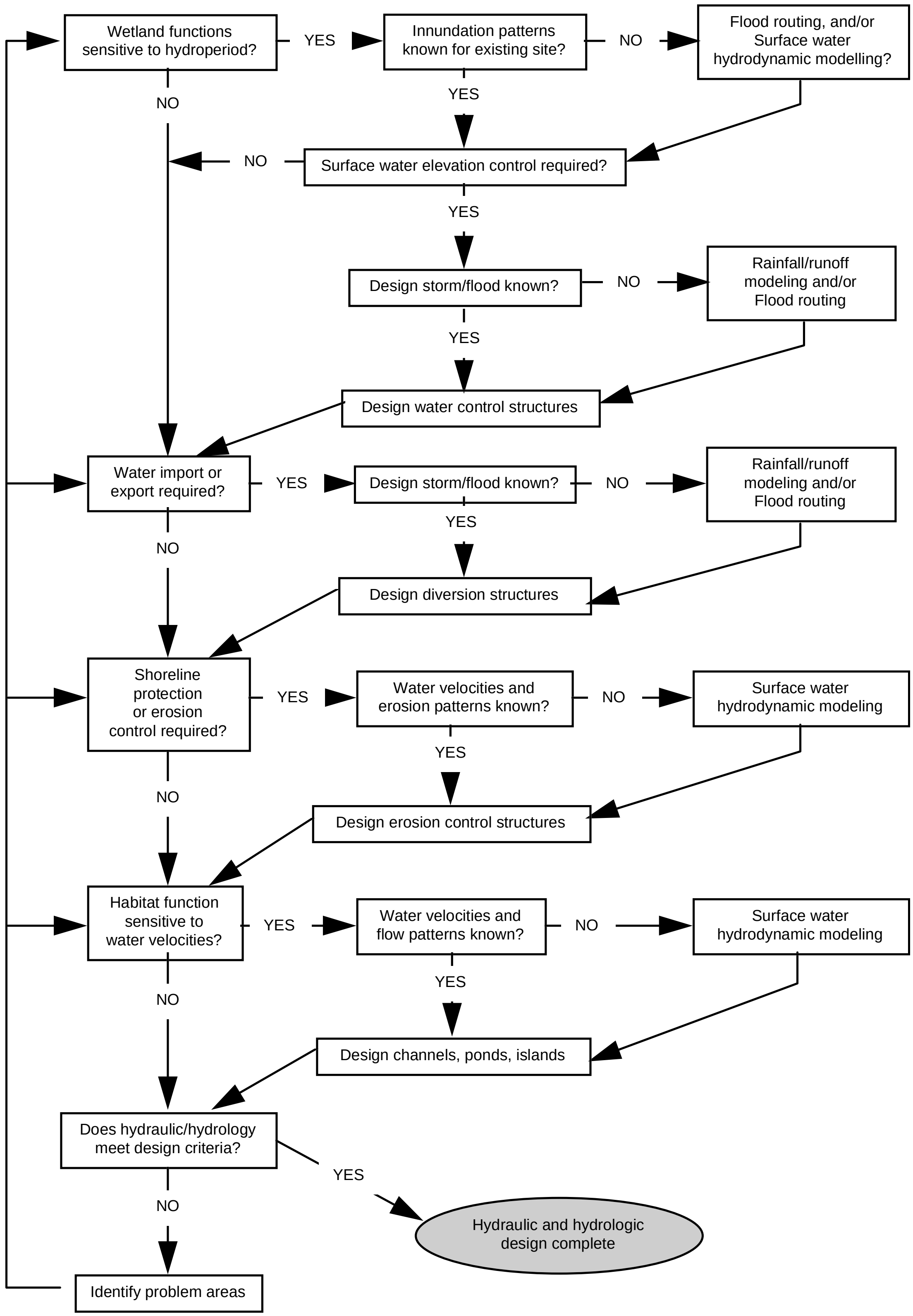


Figure 5-2. Hydrologic and hydraulic design process for wetlands.

**Table 5-1**
**Types of Hydrologic Analysis Tools**

| Hydrologic Analysis Tool | Purposes |
|---|---|
| Water Balance | Quantify evaporation or seepage.<br>Identify all water sources and sinks within the hydrologic unit.<br>Determine adequacy of supply. |
| Rainfall-Runoff Models | Quantify the amount of runoff generated by a rainfall event.<br>Determine the peak discharge at the outlet per storm event.<br>Determine the time to peak discharge at the outlet per storm event.<br>Determine the recession time per storm event. |
| Snowmelt-Runoff Models | Quantify the amount of runoff generated by a snowmelt event.<br>Quantify the amount of runoff generated by a snowmelt season. |
| Frequency Analysis | Determine recurrence interval of a storm event.<br>Determine reliability of a design structure. |
| Flood Routing | Predict temporal and spatial movement of a flood wave in a channel network. |
| Groundwater Flow Models | Predict temporal and spatial distribution of groundwater in one-, two-, or three-dimensions. |
| Surface Water Hydrodynamic Models | Predict temporal and spatial distribution of surface water in one-, two-, or three-dimensions. |

The following project attributes should be considered when selecting a hydrologic analysis tool: 1) the demands of the stated wetland design criteria; 2) the type of control structures or construction features to be designed; and 3) the project cost. These attributes are discussed briefly below.

## Demands of the Stated Wetland Design Criteria

Table 5-3 lists a few example hydrologic design criteria and their corresponding hydrologic analysis requirements. Note that the example design features listed are only a sample of the broad range of possible solutions. The appropriate design choice for a particular site will depend upon the site configuration and the results of the pre-design hydrologic analysis.

### Structural Features

Certain structural features require a specific hydrologic analysis to determine the design parameters. The most common type of analysis is the determination of a design storm or design tide. The design storm is the maximum storm event that an engineering feature can accommodate without failure. In wetland restoration, the discharge resulting from a design storm is used to determine the size of the outlet structure, the basin storage capacity, the minimum culvert

**Table 5-2**
**Data Requirements for Hydrologic Analysis**

| Hydrologic Analysis Tool | Data Required | Desired Period of Record | Desired Frequency |
|---|---|---|---|
| Water Balance | Precipitation | ≥ 1 year | daily |
| | Streamflows | ≥ 1 year | daily |
| | Groundwater storage | ≥ 1 year | weekly |
| | Surface storage | ≥ 1 year | daily |
| | Point sources and withdrawals | ≥ 1 year | daily |
| | Land use and vegetation cover | ≥ 1 year | seasonal |
| | Watershed characteristics | once | - |
| Rainfall-Runoff Models | Precipitation | storm duration | depends upon basin response time |
| | Streamflows | depends upon basin response time | depends upon basin response time |
| | Watershed characteristics | once | once |
| | Land use and vegetation cover | ≥ 1 year | seasonal |
| | Antecedent soil moisture | once prior to storm event | once |
| Snowmelt-Runoff Models | Average air temperature | melting season | daily |
| | Snow cover | " " | " " |
| | Snow water content | " " | " " |
| | Snow surface albedo | " " | " " |
| | Solar radiation | " " | " " |
| | Precipitation (rain and snow) | " " | " " |
| Frequency Analysis | Precipitation time series | ≥ 1 year | depends upon basin response time |
| | Streamflow time series | ≥ 1 year | depends upon basin response time |
| | Tide height time series | annual | at least hourly |
| Flood Routing | Basin inflow time series | duration of storm event | depends upon basin response time |
| | Channel cross-section profile, reach length, and bed slope for all channel segments | once for stable channels | once for stable channels |
| | Channel bed roughness for all channel segments | once for stable, un-vegetated channels | once for stable, un-vegetated channels |
| Groundwater Flow Models | Aquifer stratigraphy and hydraulic conductivity of each layer | once | once |
| | Initial piezometric surface throughout the basin | once per simulation event | once per simulation event |
| | Subsurface flow boundary conditions | once per simulation event | once per simulation even |
| | Sources and sinks of groundwater | duration of simulation event | depends upon basin response time |
| Surface Water Hydrodynamic Models | Basin bathymetry and distributed bed roughness | once for stable, un-vegetated channels | once for stable, un-vegetated channel |
| | Initial water surface elevation and velocity field | once per simulation event | once per simulation event |
| | Surface flow boundary conditions | once per simulation event | once per simulation event |
| | Sources and sinks of surface water | duration of simulation event | depends upon basin response time |

**Table 5-3**
**Hydrologic Analyses Required to Meet Example Design Criteria**

| Example Design Criteria | Type of Hydrologic Analyses Required | Example Design Features |
|---|---|---|
| Pass design flood without exceeding maximum specified water surface elevation in the wetland. | 1. Determine the design rainfall event.<br>2. Quantify the runoff from the design event.<br>3. Route the storm hydrograph through the wetland.<br>4. Determine the maximum discharge at the control point.<br>5. Design the structure to meet the design criteria. | Overflow structures, culverts, drop inlet structures, gates, valves, plugs, pumps |
| Determine maximum water surface elevation during design flood. | 1. Determine the design rainfall event.<br>2. Quantify the runoff from the design event.<br>3. Route the storm hydrograph through the wetland.<br>4. Determine the maximum water surface elevation. | Levees, overflow structures, access structures |
| Maintain water level within a specified range. | 1. Determine the design flood and design drought events.<br>2. Propose several possible designs as dictated by the site configuration and pre-design hydrologic analyses.<br>3. Quantify the surface flow abundance and distribution under both flood and drought conditions for each proposed design.<br>4. Compare the water levels achieved under proposed designs against the design criteria.<br>5. Refine the best designs and repeat the analyses. | Overflow structures, culverts, weirs, gates, valves, plugs, pumps |
| Do not exceed a specified water velocity in the wetland. | 1. Determine the design flood event.<br>2. Propose several possible designs as dictated by the site configuration and pre-design hydrologic analyses.<br>3. Predict surface flow hydrodynamics for each proposed design.<br>4. Compare the velocities achieved under proposed designs against the design criteria.<br>5. Refine the best designs and repeat the analyses. | Land surface grading and channel dredging, culverts, inlet and outlet structures |
| Reduce the flood peak of the 100 year storm by 20 percent. | 1. Determine the 100-year storm event.<br>2. Route the 100-year storm through existing wetland or channel network.<br>3. Determine the peak discharge.<br>4. Propose several possible designs.<br>5. Route the 100-year storm through proposed channel network.<br>6. Select the designs that meet the design criteria.<br>7. Refine the best designs and repeat the analyses. | Land surface grading and channel dredging, culverts, inlet and outlet structures, |
| Increase groundwater recharge at the restoration site by 20 percent | 1. Determine the infiltration rates, seepage rates, temporal and spatial distribution of groundwater at existing site.<br>2. Propose several designs with different surface water detention and storage capacities.<br>3. Predict the recharge and distribution of groundwater under each of the proposed plans.<br>4. Select the designs that meet the design criteria.<br>5. Refine the best designs and repeat the analyses. | Land surface grading, outlet structures, valves, gates, plugs |

dimensions, and/or the minimum channel conveyance. Similarly, the design tide is the tide with the maximum water surface elevation that can be accommodated by the engineering project. The design storm and the design tide are normally determined by means of frequency analysis.

The peak discharge resulting from a design storm is a useful piece of information for the design of a culvert or gate. If the watershed is gauged, the time series of discharge can be used to determine the peak flow. Unfortunately wetland restoration sites are frequently located in ungauged local depressions, floodplains and side channels. These small watersheds derive inflow from local drainage and urban runoff which may be supplemented by imported water. The peak flow in an ungauged watershed is determined by computing the runoff generated by the design storm.

Tidal data from a nearby harbor or marina can sometimes be used to determine the design tide when onsite data are unavailable. The peak tide height from the design tide will determine the height of levees, islands, and weirs. The tidal wave height may be either dampened or amplified as it passes through the inlet depending upon the inlet morphology. For large restoration sites, complex inlet morphologies, and ungauged tidal inlets, an onsite tidal gauge should be installed to determine the tidal phase and amplitude in relation to permanent local monitoring stations. If no local data are available a hydrodynamic model may be necessary to determine local tide levels.

## Project Cost

The overall cost of the project will bear upon the extent of the hydrologic analyses. Water balance, rainfall-runoff models, snowmelt-runoff models, and frequency analyses are low-cost procedures in terms of engineering labor. They are also less accurate than the more sophisticated modeling techniques. Hydraulic flood routing, groundwater modeling, and surface water hydrodynamic modeling can be expensive and time-consuming procedures. These more accurate and expensive analyses are well justified when the wetland restoration project involves extensive structural modification to the site. Because the use of simulation models reduces the uncertainty in the design parameters, a more efficient design structure can result. Appropriate use of models during the design phase could save millions of dollars in construction and material costs on large projects. Less accurate and less costly analyses are sufficient when the project requires only minor engineering works. However a higher factor of safety should be applied.

# 5-2 Surface and Subsurface Drainage Analysis[1]

## Surface Water Analysis Methods

The following paragraphs describe the types of standard hydrologic analyses used to interpret hydrologic data and make it useful for engineering purposes. The specifics of each of these analyses are described in standard hydrology texts, and so are not repeated here. Useful references include Maidment (1993), Bedient and Huber (1992), Viessman et al. (1977), and Hydrologic Engineering Center (1980). These methods include statistical data analyses, simple models, and empirical formulas.

### Hydrologic Data

Hydrologic records that are of value for wetland design include precipitation, wind, temperature, streamflows, lake levels, and river stages. Streamflow data are collected by various state and federal agencies, including the U. S. Geological Survey (USGS), U.S. Army Corps of Engineers (USACE), state departments of water resources, irrigation districts, and municipalities. The USGS serves as a clearinghouse for data from most of these sources, and the annual streamflow records for every station are published by state in Surface Water Supply of the United States, a USGS Water Supply Paper Series. Lake levels and river stages are often monitored by the USACE or the U. S. Bureau of Reclamation (USBR) in the vicinity of federally maintained dams, reservoirs, and levee systems. River stages are also monitored by state water resource agencies and municipalities that maintain any type of flood control project. Tide gauges in estuarine systems are operated by the USGS, and by the National Oceanographic and Atmospheric Agency (NOAA) in coastal areas. Precipitation data are collected by the National Weather Service, by local weather bureaus, and by state resource agencies. Contact the local office of the National Weather Service for more information.

### Water Balance

One meaningful way to organize data is to prepare a water balance. A water balance is a systematic method for quantifying the hydrologic components that are important within a

[1] By Lisa C. Roig

specified drainage unit. A water balance includes all of the major sources and sinks of water within the hydrologic boundaries of the system. It is a useful tool for identifying water supply problems, for identifying preliminary design opportunities, and for assessing certain impacts of proposed engineering measures. A water balance is often used to estimate the magnitude of unknown hydrologic components such as groundwater flow and infiltration losses. The Hydrologic Engineering Center (1980) has published a guide for the preparation of water balances. The procedure published therein is summarized below:

1. Identify the water supply components, including precipitation, streamflow, surface storage, groundwater pumpage, groundwater storage, imported water, and return flow.

2. Identify the water use components, including withdrawals, water rights, instream flow requirements, evaporation, evapotranspiration, and seepage.

3. Select the water balance boundaries which may be hydrologic boundaries, institutional boundaries, or a combination thereof.

4. Select the period of analysis which may be a historic drought period, a recent past period, a future period, a climatic year, a water year, or a calendar year.

5. Select the level of temporal and spatial resolution.

6. Write the water balance equation which can have several forms.

    a. For flow through systems, the water balance equation can be written in terms of flow rates, i.e., Downstream Flow = Upstream Flow + Local Inflow - Depletions - Withdrawals

    b. For surface storage systems, the water balance equation can be written in terms of volumes, i.e., Surface Storage Remaining = Inflow + Storage - Depletions - Withdrawals

    c. For groundwater storage systems, the water balance equation can be written in terms of volumetric change, i.e., Change in Storage = Recharge - Pumpage + Inflow - Outflow

7. Quantify the water balance components. Guidance for this important step is provided in Hydrologic Engineering Center (1980).

8. Interpret the results.

Two examples of water budget calculations applied to wetlands are Gilvear et al. (1993) and Vardavas (1989).

## Frequency Analysis

Frequency analysis uses the historic time series of measured rainfall, runoff, or tide height at a gauge to determine the probability of recurrence of a given event. Continuous data taken at a gauging station are quantized and tabulated in order to determine the frequency of occurrence of a particular flow rate or precipitation rate. The probability of occurrence of each quantized class of measurements is then computed according to the cumulative frequency distribution. The design event is chosen as the event having a probability of recurrence that is less than the threshold of risk prescribed by project objectives. Methods of computing the probability density function for hydrologic time series are treated extensively in the literature. A comprehensive treatment of the subject is provided by Bedient and Huber (1992) and in many other standard hydrology texts.

## Rainfall-Runoff Analysis

Rainfall-runoff prediction is extremely important for wetland hydrologic design. Most wetland projects are constructed in watersheds too small for historical streamflow data to be available. Several methods have been developed to estimate the storm hydrograph characteristics for watersheds that are not continuously monitored. The characteristics of the wetland hydrograph that may be important for the design of control structures are the peak discharge, the time to peak, and the recession curve. In the following paragraphs, simple hydrologic analysis techniques are described that can provide ballpark estimates of the runoff in ungauged watersheds. The limitations of each of these methods are described. It is recommended that simple techniques be used during pre-design evaluation of the site and as a first analysis tool during the design phase. During the course of the analysis, the engineer is likely to discover that the assumptions associated with the simple analysis result in a larger margin of error than is acceptable for design purposes. More accurate hydraulic routing and hydrodynamic modeling techniques may be required to completely describe runoff generation, distribution, and abundance in ungauged watersheds.

### Rational Method

The simplest rainfall-runoff method is the rational method. The rational method can be stated as

$$Q_{peak} = \sum_{j=1}^{n} C_j i A_j \qquad (5\text{-}1)$$

where

- $Q_{peak}$ = peak discharge at the outlet ($L^3/T$)
- j = index of catchment subregions
- n = number of catchment subregions upstream of the outlet
- $C_j$ = runoff coefficient corresponding to the predominant land use or vegetation type in subregion j
- $i$ = rainfall intensity (L/T)
- $A_j$ = surface area of subregion j ($L^2$)

While the rational method is simple to apply, some of the implicit assumptions limit its application:

*a.* Rain falls at a uniform intensity over the catchment area

*b.* The duration of rainfall is sufficient that the entire catchment area contributes to the discharge at the outlet (equilibrium hydrograph).

*c.* Storage and infiltration losses are proportional to the rainfall intensity, and are independent of antecedent precipitation. The rational method is often used in engineering because the peak discharge computed by this method is the equilibrium discharge, and is therefore greater than the discharge expected from an actual storm of limited duration.

In wetland hydraulic design, the specification of runoff coefficients is particularly important. The runoff coefficient accounts for depression storage, infiltration, and evapotranspiration of rainfall. If the wetland is completely submerged during a storm event then depression storage and infiltration can be ignored. The peak discharge for engineering design purposes will occur when all depression storage is filled and the soil is completely saturated. All excess precipitation will then be directed to the outlet as direct runoff. Therefore, the runoff coefficient for a submerged wetland is essentially 1.0 since evaporation from the water surface usually can be neglected during a storm event.

If the wetland catchment area or subregion is not completely submerged, then the runoff coefficient is estimated according to soil type, vegetation type, and depression capacity. Values of the runoff coefficient quoted in the literature for vegetated areas range from 0.05 to 0.35. Values of C are lower for sandy soils and higher for dense soils. The slope of the subregion also affects the value of C. Steeper slopes result in higher values of the runoff coefficient than mild slopes. Finally, the vegetation density affects the runoff coefficient. Higher plant densities reduce runoff and increase evapotranspiration, resulting in a lower runoff coefficient than for sparse vegetation.

The rational method has been used extensively in small urban watersheds where runoff coefficients for impervious materials are well known. The method is less reliable in vegetated watersheds because of the uncertainties associated with the runoff coefficient. For design of wetland hydraulic structures, the rational method is most useful for submerged wetlands with small catchment areas (less than 10 acres). The uncertainty in assigning appropriate values for the runoff coefficient increases with increasing catchment area. The assumption of an equilibrium hydrograph is reasonable for small watersheds but is rarely achieved in larger basins where the time of concentration is large.

## Unit Hydrograph

In wetlands with large catchment areas, the unit hydrograph may be used to estimate peak discharge for a storm of a given duration. This method permits the engineer to design for a realistic storm of limited duration, unlike the rational method which assumes that the storm duration is equal to or greater than the time of concentration. The assumptions of the unit hydrograph method are:

*a.* The watershed response is linearly related to rainfall intensity

*b.* The rainfall during a storm is spatially and temporally uniform

*c.* The watershed response is independent of antecedent precipitation.

The assumption of linearity is adequate to determine design discharges for culverts and gates. These assumptions are not appropriate for design of wetland channels and habitat areas.

The unit hydrograph for a storm of a given duration can be derived by monitoring the discharge at the outlet during a single storm event. The time-discharge response recorded for a two-hour rainfall event is assumed to have a characteristic shape which is constant for all two-hour storms. The magnitude of the discharge is assumed to be linearly proportional to the rainfall intensity. Therefore, the unit hydrograph represents the basin outflow (in cubic inches per second) resulting from one inch of direct runoff generated uniformly over the drainage area at a uniform rainfall rate during a specified period of rainfall duration (Sherman 1932). This method is advantageous when little historic data are available. The response of the watershed to a design storm can be estimated from storm hydrographs measured at the outlet over a short monitoring period (approximately one year). However, the assumption of linearity is not realistic, particularly when extended to extreme flow events. The uncertainty associated with estimates derived by the unit hydrograph method is high.

## Synthetic Unit Hydrographs

Before the widespread use of personal computers, a variety of techniques were developed to synthesize unit hydrographs in watersheds that have not been monitored. These methods generally rely on empirical runoff coefficients developed for a gauged watershed that are then applied to an ungauged site. These methods have proved to be of limited value because of the high level of uncertainty in these coefficients. With the advent of personal computers a large number of more accurate numerical hydraulic routing software have been developed to predict runoff generation from ungauged watersheds. Graphical user interfaces make these software packages easier to use than they once were. It is recommended that the wetland engineer pursue the more accurate and less empirical hydraulic routing techniques rather than the synthetic unit hydrograph techniques for the prediction of runoff generation when no streamflow data are available. Hydraulic routing is discussed in more detail in the following section.

## Correlation Models

If sufficient data are available and the hydrology of the wetland is sufficiently simple one can sometimes correlate a continuously monitored hydrologic variable to another, unmonitored hydrologic variable. For example, streamflow at an upstream gauge may be correlated to the water level in the wetland. If so, one can construct a correlation model to predict the water level in the wetland based on data coming from the stream gauge. To construct a correlation model, an onsite monitoring program is required to measure both of the parameters of interest synoptically and over a range of hydrologic conditions. These data can then be analyzed statistically to determine if a correlation exists. Once the correlation has been quantified, measurement of the second parameter can be discontinued. When collecting data for a correlation model it is important to include data collected during extreme events, such as floods and droughts. This procedure reduces the uncertainty of predictions made using the correlation model during extreme events. A comprehensive treatment of correlation models can be found in Kleinbaum and Kupper (1978) or in any linear regression text. An example application of a correlation model for wetland hydrology was presented by Richter (1995).

# Surface Flow Hydrodynamics

Wetland engineering requires that hydraulic control structures and construction features produce a pattern of inundation that promotes the growth of beneficial wetland vegetation. The frequency, duration and depth of inundation events will have a combined effect on plant species distribution. Certain aquatic animal species exist in narrow ranges of hydraulic conditions that are related to the maximum current velocity, the minimum current velocity, the degree of vertical mixing, the salinity, and the stability of the channel substrate. The specified wetland design criteria should include the exact inundation duration and frequency requirements, the desired substrate, and the water quality (particularly salinity) specifications for the desired assemblage of vegetation and wildlife. The engineer must solicit the aid of a wetland biologist who is familiar with the desirable species in order to determine these design criteria.

Surface flow hydrodynamics and hydraulic flood routing are two techniques for analyzing the spatial and temporal distribution of surface flows in a wetland. Hydraulic flood routing is used to compute the storm runoff generated in basins or sub-basins and to route the storm runoff through a network of one-dimensional drainage channels by one of several numerical routing methods. Surface flow hydrodynamic modeling is a technique by which the shallow water equations are solved numerically in either one, two, or three dimensions. Hydraulic flood routing computes a flood hydrograph at each computational point in the system. Surface flow hydrodynamic modeling provides the depth of water and the velocity, magnitude and direction at each computational point in the system and at each computational time step. Flood routing is most commonly used to determine peak discharges, time to peak, and recession curves for complex channel systems. Hydrodynamic modeling is used to determine current patterns and flow depths in complex flow regions which may be channelized or spread over a basin with an irregular topography.

## Methods of Analysis for Surface Flow Hydrodynamics

### Hydraulic Flood Routing

Nonlinear methods of hydraulic routing within the wetland watershed are useful for determining peak discharge, for predicting the temporal response of the wetland to a flood event, and for analyzing spatially and temporally heterogeneous hydrologic events. Hydraulic routing utilizes physically based equations of open channel flow to account for channel resistance and storage capacity. The degree of accuracy for these methods is high provided that the appropriate forms of the equations are applied, and the hydrogeomorphic data supplied to the model are accurate. The data required for hydraulic routing include:

*a.* Temporal and spatial distribution of rainfall for the design storm

*b.* Spatially distributed runoff coefficients, or inflow storm hydrographs for each of the catchment subregions

*c.* Channel and floodplain cross sections over the basin

*d.* Channel roughness characterization

*e.* Downstream boundary condition

Data required for hydraulic routing must be generated as part of the wetland design project. Recent developments in computer software have made processing and analyzing geomorphic data much easier than in the past. Geographical information systems (GIS) and graphical data displays provide special purpose tools that are ideally suited to watershed analysis. A software package called GEOSHED has been developed to analyze hydrologic characteristics of catchment basins (Richards 1993b).

The effort required to perform hydraulic routing can result in a net cost savings over designs based on the rational method or the unit hydrograph, in spite of the greater amount of data required. A large degree of uncertainty is associated with both the rational method and the unit hydrograph method. This uncertainty can result in overestimation of the design discharge and the need to specify a high factor of safety. A project that is overdesigned for the site will have concomitant excess material and construction costs. Design phase site evaluation and data collection is a cost-effective approach because time charged in preconstruction analysis is typically cheaper than time charged during construction.

Hydraulic routing models are sufficiently complex that a computer program is employed to perform the calculations. Computer models also permit the engineer to specify more spatial heterogeneity in the catchment subregions than can be considered using hand calculations. Thus, the physical characteristics of the wetland watershed can be accurately represented, which reduces uncertainty in the calculated peak flows. Hydraulic routing models represent drainage of the catchment area as flow through a network of one-dimensional conveyance channels.

The simplest routing methods, such as the Muskingum Method, are based on continuity of mass. Travel time through a reach is estimated from the channel storage capacity. In practice, the travel time coefficients for Muskingum routing are back-calculated from observed storm hydrographs. Models based on physical characteristics of the watershed are preferred for wetland restoration projects because measured hydrographs are rarely available. Hydraulic routing can be calculated by simultaneous solution of the equations of momentum conservation and mass conservation. Examples of physically based routing models are the diffusive wave model, the kinematic wave model, and the dynamic wave model (Henderson 1966). Many public domain computer programs exist to facilitate hydraulic routing calculations, including the model HEC-1 (Hydrologic Engineering Center 1981). The GEOSHED software package integrates a GIS database with HEC-1 to perform hydraulic routing calculations in spatially heterogeneous watersheds (Jones et al. 1990; Nelson et al., 1993; Richards 1993b).

A friction coefficient must be specified for solution of the momentum equation in open channel flow. This coefficient describes the resistance force caused by the bed and the vegetation. Manning and Chezy coefficients are widely used. In wetland watersheds, resistance due to vegetation is high, and the effect of the vegetation on the flow can extend throughout the water column. Manning's n values from 0.1 to 0.35 have been reported for hydraulic routing in wetlands, with higher values corresponding to greater vegetation densities. Recent research indicates that Manning's n values in vegetated channels are not constant, but vary with flow velocity and depth. (Roig 1994).

The methods discussed herein for computing the peak discharge in an ungauged watershed include the rational method, the unit hydrograph, and hydraulic routing. Of these methods, hydraulic routing provides the highest degree of accuracy and reliability. The rational method is adequate for small wetlands that are largely inundated during the design storm, and where over-design of the structure will not result in excessive construction costs. Collection of geomorphic data for hydraulic routing can be a worthwhile investment because peak flows are more accurately estimated. A more efficient design for the control structure will result.

## TABS-MD and FastTABS

A two-dimensional, vertically averaged hydrodynamic model can be used to predict circulation and ensure that hydrodynamic conditions meet biological requirements. Parameters such as channel dimensions, gate operation schedules, and weir heights can be adjusted within the model to test the design against biological design criteria (Richards 1993a). Example applications of a two-dimensional hydrodynamic model are presented by Evans and Roig (1995).

The Waterways Experiment Station has developed a multidimensional, vertically integrated finite element model system (TABS-MD) which will accurately model the surface flow in wetlands. In addition, a graphical interface (FastTABS) has been developed which permits the user to rapidly analyze various wetland plans. FastTABS provides both pre- and post-processing functions. The flexibility to modify the numerical grid resolutions is particularly useful in wetland environments where engineers must address a variety of environmental and operational questions.

The TABS-MD hydrodynamic modeling system consists of a group of models which include hydrodynamics, transport, and sedimentation. The two-dimensional, vertically averaged hydrodynamic model is based on RMA2V, a model originally developed by Norton, King, and Orlob (1973). It has been further developed by the WES Hydraulics Laboratory and is referred to as RMA2-WES. RMA2-WES computes the water surface elevations and vertically averaged flow velocities using the finite element method. Both steady-state and dynamic solutions can be obtained. Boundary conditions are specified as flow rates, water elevation, or water velocity. A fully implicit finite difference discretization in time permits the modeler to choose a variable time step that can accurately capture the changes in the boundary conditions over time. Hydrodynamic parameters such as Mannings n and eddy viscosity can be defined by element type or by individual elements or nodes. These parameters may be temporally and spatially varied. An essential modeling feature for wetland modeling is the ability to simulate intermittent flooding and draining of the marsh surface over the simulation period.

The FastTABS computer program was developed by the Brigham Young University Engineering Computer Graphics Laboratory in cooperation with the Hydraulics Laboratory, Waterways Experiment Station. It is a graphic pre- and post-processor for the TABS-MD hydrodynamic modeling system. This allows the wetland designer to quickly and easily construct a finite element mesh, generate hydrodynamic results with RMA2-WES, analyze the results for validity, and perform modifications. Results can be presented on an areal basis by contouring (either by contour lines or color shading) or on a nodal basis via time-series plots of water surface elevations and velocities. Results can be saved as graphics files and in spreadsheet format.

### Wetlands Dynamic Water Budget Model

A link-node model for wetland hydrology and hydraulics has been developed by Walton et al. (1995). This model incorporates interactions between surface water flows, vertical processes, and horizontal groundwater flow. Some of the processes that can be described with this model include channel and overbank flows, tidal forcing, riverine inflows, upstream basin flows, wind shear, flooding and drying, bottom friction, hydraulic structures, canopy interception and drainage, infiltration, surface water evaporation, soil water evaporation, transpiration, and variably saturated horizontal groundwater flow. The model has been used to evaluate alternative wetland management scenarios.

### Other Hydrodynamic Models

The modeling systems described above are not the only hydrodynamic models available for shallow water flows. However, few other commercially available models are targeted for wetland applications. Other hydrodynamic models for wetlands are being developed in the academic and research arena, some results of which are published in current scientific journals. These models are generally available by contacting the author of the model.

## Groundwater Interactions, Seepage, and Infiltration Analysis Methods

Naturally occurring wetlands frequently exist in areas with a high water table. Some wetlands occur because the water table actually rises above the land surface, contributing to the surface flow. Other wetlands occur in areas of active groundwater recharge because the abundant and widespread surface flow in the wetland saturates the soil and eventually intersects the water table. For the purpose of wetland design the engineer would like to know whether the net seepage is positive (from the surface water to the groundwater) or negative (from the groundwater to the surface water). This piece of information is frequently obtained by means of a water balance as discussed above. A water balance accounts for all measurable sources, sinks, and storage of water in the wetland. Two hydrologic components, seepage and evapotranspiration, are typically not measured. If the engineer can estimate evapotranspiration from a knowledge of the vegetation cover, then the only unknown component of the water balance is seepage, which can be found by difference. The other methods that are available for estimating groundwater contributions are much more complex. Groundwater flow modeling may need to be used when groundwater is determined to be the major source of water to the wetland, when there is insufficient water supply data to prepare a proper water balance, or when the site is large and spatially complex. Monitoring wells can be helpful for determining the piezometric surface which sometimes gives an indication of the flow direction.

## Subsurface Data

Networks of monitoring wells are maintained by certain local, state and federal agencies for special purposes. Irrigation districts often monitor aquifer levels to determine irrigation water supplies. Municipalities that rely on groundwater for domestic and industrial water supply also monitor the local aquifer levels. The USGS and USBR maintain monitoring networks in some regions for research purposes and for environmental impact assessment. Unfortunately, there is no central clearinghouse for groundwater data that encompasses all participating agencies. State departments of water resources are a good source of information about the extent and availability of existing groundwater data.

## Modeling

### Water Balance Models

A water balance is a systematic method for presenting information about sources, sinks, and storage of water within a bounded region. Many wetland design problems are concerned with the control and management of surface water resources. But the engineer must know the magnitude and direction of seepage in order to design appropriate engineering works. The water balance is a suitable method for determining seepage if sufficient surface water data are available and if the flow behavior of the aquifer will not be significantly impacted by the engineering design. A water balance requires data about the annual precipitation, streamflows, and evapotranspiration. If the watershed is ungauged, a surface water monitoring program must be initiated in order to construct a water balance. The Hydrologic Engineering Center (1980) has published a guide for the preparation of water balances.

### Infiltration Models

Infiltration of surface water into the soil is important for determining rainfall-runoff relationships. It is also important for computing the groundwater storage volume and soil moisture. Most rainfall-runoff models compute the infiltration as a percentage of the total precipitation reaching the soil surface. This percentage varies depending upon the soil type, the vegetative cover, the land surface slope, the antecedent soil moisture conditions, and the depth to groundwater. A variety of methods have been developed to determine infiltration rates based on these factors. An overview of the most frequently used models is provided in Maidment (1993). These models include the SCS Runoff Curve Number model, the Horton model, the Holtan model, and the Green-Ampt model.

### Groundwater Models

Groundwater modeling is a technique by which the equations governing groundwater flow are solved in one, two, or three dimensions over a spatially discretized domain. A computer program is employed to solve the resulting system of equations. Groundwater modeling will not be necessary for most wetland restoration and creation projects. The exceptions are wetlands where groundwater is the principal source of water and the flow of water in the aquifer is likely to be impacted by the wetland engineering works. A complete discussion of groundwater modeling is beyond the scope of this handbook. An introduction to the subject has been published (Bear et al. 1992).

# 5-3 Design of Water Control Structures[1]

## Introduction

Man-made wetlands require some means to control the quantity and depth of water at a given location. Consequently, hydraulic structures are a basic part of creating, restoring, and enhancing wetlands. Throughout history, man has been building structures to contain or control water. The result is that methods have been established to achieve this purpose and the "hard" engineering is relatively straightforward once the conceptual design has been established. Wetland structures generally fit into one of four categories: water containment structures, water control structures, erosion control structures, and habitat structures. This chapter describes water containment structures and water control structures; Chapter 5-4 discusses erosion control structures.

## Inflow Design Considerations

Water is the basic component of a wetland site. The source of the water may be natural runoff delivered to the site by stream or overland flow, groundwater, or through tidal action. In such cases, the quantity and timing of the inflow is uncontrolled but may be statistically estimated through appropriate hydrologic analysis. Water may be delivered to the site through rigid controls such as by pumping or through an operated control structure (Watson and Hobson 1988). The inflow to the site may be semicontrolled through the use of restricted entrances such as small or gated culverts or by raised weirs that allow inflow to the site only if the water supply is above some fixed or adjustable elevation. Tidal inflows may be moderated through the use of limited width openings or weirs in levee systems (Chabreck 1976). If structural options are used for the inflow, the design should accommodate changing conditions on the supply side of the structure as well as on the wetland side. Channels or other distribution systems may be required on the wetland interior to help spread the flow throughout the site.

[1] By Charles H. Tate, Jr. and Trudy J. Olin

## Structure Types

### Water Containment Structures

Containment structures confine water, sediments and in some cases nutrients and contaminants within a wetland. Permeable containment structures capture sediments, while allowing water to pass through the structure. Impermeable containment structures serve to impound water within the wetland and inflows must be discharged through pipes or culverts or over weirs or spillways. Common containment structures include:

*a.* levees

*b.* dikes

*c.* embankments

*d.* dams

*e.* gabions

*f.* fabric bags

*g.* walls

*h.* liners

Levees, dikes, and embankments are all terms used to describe an earthen structure used to contain or control the direction of water flow; Section 4 describes the characteristics of these earthen structures. As in Section 4, the function of these structure is similar for the applications described here. Thus, “dike” in the following paragraphs refers to all of these structures.

Dikes can be effectively used in a wetland system to control flow paths and to minimize short-circuiting. Often these structures are used to subdivide a wetland area to allow operational management, to control flow paths (Watson and Hobson 1989), or to establish differing habitat areas. These are the structures normally used in wetland construction due to cost, material availability, and material suitability. General engineering practice is to build dikes with a narrow base, steep sides, and a uniform cross section limited only by stability requirements. These guidelines may be inappropriate for wetland construction. The side slopes that are under the water should be varied to create variable widths of emergent vegetation (Grimball 1992). The slopes above the water surface should be designed based on the wetland functions such as habitat. Slopes that are too steep or too flat may not be suitable for specific habitat. Variable slopes would accommodate multiple habitat requirements. The top width of dikes should include maintenance needs such as equipment access and patrols. Usual causes of dike failure are overtopping, undermining, sloughing, piping, or seepage along water control structures placed through the dike. The design of the dike should eliminate these dangers as much as possible (Soil Conservation Service 1992). Erosion control should be provided where the dike is subject to a high energy environment due to waves or high velocity flow. This protection may be supplied by vegetation, riprap, or geotextiles or a combination of these. Burrowing animals may undermine dikes and should be accounted for in the design and maintenance process. In addition to containing the water, dikes may be used to direct or control the flow path through the wetland site. Such dikes may extend from the boundary or containing dikes or may be separated from the boundary to provide isolated habitat. Clusters of islands may also be used.

Water containment structures may also be constructed with walls made from wood, steel, concrete, fabric bags, gabions, or any other suitable material. Liners may be used with pervious construction materials to form an impermeable surface. Table 5-4 lists some structure types with materials and design considerations.

## Water Control Structures

Some type of water level or flow control structure is usually required to control the hydraulic regime of a restored or created wetland. Water control structures control the surface elevation, volume, direction, depth and velocity of flow into and out of a wetland. Inlet and outlet control allows flexible operation of the wetland through volume and flow rate control in conjunction with the duration and season the wetland will be inundated. Such flexibility may be essential for establishment and survival of wetland vegetation and to attract the desired wildlife. Natural open channels are the simplest water inlets and outlets. As necessary, these channels can be protected using concrete or stone lining, and flow control can be added with a control structure such as a weir.

Most wetland designs will incorporate some type of inlet or outlet structure, flow splitter, or diversion structure for controlling the flow of water through the wetland. These structures can be completely passive, or require manual or automated operation. Regardless of their construction or operation, all water control structures require periodic maintenance, occasional clearing of obstructions, and performance monitoring.

Outflow is usually controlled by overflow structures, submerged culverts, or, on rare occasions, by pumps. Overflow structures usually consist of overflow weirs constructed using flashboards, sills, spillways, and drop inlet pipes. Culverts often have some form of adjustable flow control device on one end. These structures may be located in the ponded area or remotely located in the embankments of the wetland. Controlling the outflow from a wetland is directly dependent upon the wetland function being obtained and the ultimate use and design of the wetland system. The wetland area may be designed for flood conveyance which would require sufficient capacity to temporarily store runoff for later release. The pool elevation might need to be regulated to maintain proper water depth for specific habitat needs. The possibility of total drawdown of the wetland might be necessary for wetland management purposes. Table 5-5 presents common water control structures and important design considerations for those structures.

For impoundments with dikes 1 ft or less in settled heights the Soil Conservation Service (SCS) states that vegetated spillways may be used in lieu of structures with dewatering done by cutting the dikes. For impoundments with dikes more than 1 ft in settled height, the SCS recommends the following outflow structures:

## Table 5-4
## Water Containment Structures and Design Considerations

| Structure Type | Materials | Design Considerations |
|---|---|---|
| Dikes | Earth - silty or clayey sand, sand or gravel: permeable dikes will be constructed from coarsest material, impermeable from finer materials | • Dike height limited by foundation stability and by base width required by angle of repose of dike materials<br>• Erosion susceptibility of materials should be considered - slope erosion and toe scour may occur - dike protection may be required under certain conditions<br>• Soil characteristics as related to dike construction are listed in SCS (1992)<br>• Low cost structure<br>Reference: Eckert, Giles, and Smith 1978, SCS 1992, US Navy 1971, Hammer and Blackburn 1977 |
| Cofferdam | Cells filled with granular material. Cells may be constructed from any material, but usually steel sheet-piling. | • Cofferdams are used as temporary structures in construction where isolation of a site from the adjacent water body is required. Fill can be placed behind permanent cofferdams.<br>• Maximum height 60 feet under optimum conditions (maximum economic height typically about 20 feet) (Eckert, Giles and Smith 1978)<br>• Good erosion resistance<br>• Susceptible to toe scour<br>• High cost structure<br>Reference: Eckert, Giles, and Smith 1978, US Navy 1971 |
| Gabions | Galvanized or coated wire baskets filled with 4- to 10-inch-diameter rock and stacked and wired together | • Gabions form a somewhat permeable wall: may not retain fine materials unless paired with filter fabric<br>• Maximum height approximately 10 feet with multiple thicknesses or counterforting (Eckert, Giles and Smith 1978)<br>• Susceptible to toe scour when placed on erodible substrate: flexible gabion apron may be required.<br>• Moderate cost structure<br>Reference: Eckert, Giles, and Smith 1978 |
| Geotextile Containers | Synthetic fabric bags filled with sand, sand-cement, concrete or fine soils or sediments. | • Geotextile containers can be used for dike construction, island construction and for training structures (see also erosion control structures)<br>• Maximum height typically 16 feet or less for freestanding structures (Eckert, Giles and Smith 1978)<br>• Permeable fabric bags must be paired with filter cloth or a stone filter layer to retain fine materials<br>• Propagation of natural vegetation through containers filled with fine materials can occur<br>• Good erosion resistance; Articulated mattress at toe may be required to prevent toe scour<br>• Low cost - 3-5 year life for sand filled, sand-cement bags have extended life, and concrete filled bags can be considered permanent (Eckert, Giles and Smith 1978)<br>Reference: Eckert, Giles, and Smith 1978, Fowler and Sprague 1993, USACE 1977 |

**Table 5-4 (continued)**
**Water Containment Structures and Design Considerations**

| Structure Type | Materials | Design Considerations |
|---|---|---|
| Cantilevered Retaining Wall | Arch web or Z-type steel sheet piles; wood; concrete | • Maximum wall height approximately 15 feet under optimum embedment conditions; adequate embedment in firm bottom strata required (Eckert, Giles and Smith 1978)<br>• Good erosion resistance; Toe scour occurs under some conditions<br>• Moderate to low cost structure/sheet piles can be rented for temporary structures<br>Reference: Eckert, Giles, and Smith 1978, US Navy 1971 |
| Anchored Retaining Wall | Arch web or Z-type steel sheet piles; wood; concrete | • Maximum wall height approximately 40 feet under optimum embedment conditions; adequate embedment in firm bottom strata required (Eckert, Giles and Smith 1978)<br>• Good erosion resistance; Toe scour occurs under some conditions<br>• Moderate to high cost<br>Reference: Eckert, Giles, and Smith 1978, US Navy 1971 |
| Liners | Clay or synthetic materials | • Transport of leachate or very fine particles and associated contaminants into groundwater can be restricted with the use of appropriate lining material<br>Reference: Koerner 1998 |

*a.* A straight drop structure, which may be equipped with removable stoplogs, constructed of treated timber, metal, sheet piling, rock, or concrete.

*b.* A pipe provided with a swivel elbow and riser.

*c.* A pipe drop inlet structure, which may be equipped with a gate, valve, or plug for controlling flow.

*d.* A pipe provided with a perforated riser.

Hydrologically isolated wetlands that do not have a contributing drainage area will require outlet control structures only if groundwater inflow and precipitation will likely exceed evapotranspiration and the available water storage volume.

## Sediment

Reduced flow velocities found in wetlands, whether natural or man-made, allow sediments transported into the wetland with the inflow to settle to the bottom. Trapped sediments occupy part of the wetland volume, thereby reducing its effectiveness at removing future sediments from the inflow. Because nutrients are often associated with the sediment particles, incoming sediments can increase the vitality of the wetland. However, wetlands which receive large

**Table 5-5**
**Water Control Structures and Design Considerations**

| Structure Type | Function | Materials | Design Considerations |
|---|---|---|---|
| Distribution Header | Distribute flow over width of wetland | Perforated pipe<br>Pipe w/fixed or movable tees<br>Channels with multiple outlets | • Uniform flow distribution is important to subsurface flow systems (Watson and Hobson 1989)<br>• A distribution header may be located above or below ground. Above ground headers can feed into a gravel trench for uniform distribution.<br><br>Reference: Watson and Hobson 1989 |
| Headgates | Water level regulation | Sheet metal | Headgates are typically a simple device consisting of an angle iron frame fitted to the face of the inlet flume or pipe, and extending above it. Within the frame is mounted a sheet metal "gate" which is raised and lowered by means of a threaded rod and flywheel. |
| Pipes/ Culverts | Water level regulation | PVC<br>Galvanized<br>Concrete<br>Cast Iron | • Relatively maintenance free<br>• Suitable for water level regulation for small impoundments<br>• Submerged inlet - perforated collector pipe configuration or short riser with hooded inlet - may have swiveling elbow to horizontal outlet pipe<br>• Swiveling pipe structure limited to small diameter pipe and small flows<br>• Inlet may be susceptible to sedimentation<br><br>Reference: Hammer 1992 |
| Swales with and without Swale Blocks | Vegetated open channel for transport and infiltration of storm water | Earth, natural vegetation | • Swale blocks are simple earthen berms placed perpendicular to the flowline of the swale. Swale blocks are used to create temporary detention within a section of swale to permit time for infiltration.<br>• Inlet/oulet structures sized to pass maximum-design storm flows, sited to minimize short circuiting<br><br>Reference: Wanielista et al. 1986 |
| Parshall Flume | Utilized to measure and control flow rate | Concrete<br>Sheet metal<br>Treated or rot resistant wood | |
| Flashboard Culvert | Utilized to control water level and outflow | Metal pipe riser with flashboard (stoplog) fittings/wood stoplogs | • Asphalt or other coatings necessary in corrosive waters<br>• Typically risers no larger than 0.8 meter (Hammer 1992)<br>• Not suited to large flows or widely varying flows<br>• More susceptible to blockage than stoplog structure<br><br>Reference: Hammer 1992 |

**Table 5-5 (continued)**
**Water Control Structures and Design Considerations**

| Structure Type | Function | Materials | Design Considerations |
|---|---|---|---|
| Weir | Utilized to stabilize water levels or prevent complete drainage of wetland with tidal fluctuation. Aquatic plants proliferate, waterfowl habitat is increased, navigable waterways are maintained. (Nyman, Chabreck and Kinler 1993) | Sheet piling<br>Wood<br>Stone<br>Concrete<br>Vegetated earth | • Effects: Species diversity and long-term vegetal mortality effects due to limited drainage should be considered.<br><br>Reference: Nyman, et al. 1993 |
| Stoplog Structures | Utilized to maintain variable water levels in impoundment | PVC<br>Wood<br>Concrete walls/ wood stoplogs | • Water level control achieved by adding or removing stoplogs<br>• More expensive than flashboard culverts or swiveling pipe structures - less susceptible to blockage, better handles large flows - utilized in larger impoundments (Hammer 1992)<br><br>Reference: Watkins 1992, Hammer 1992 |
| Flow Splitter | Direct or distribute flow within a single wetland "cell", or between multiple cells | Pipes, Flumes<br>Wiers, Slotted baffle plates, Perforated distributor pipe | • Typically, orifices are parallel and of equal size, at the same elevation<br>• Flumes minimize clogging problems for high solids applications<br><br>Reference: Watson and Hobson 1989 |
| Baffles/ Finger Dikes | Direct flow, increase flow path to maximize retention time, optimize length to width ratios, minimize short-circuiting | Earthen dikes<br>Steel plates<br>Riprap<br>Gabions | Baffles increase the retention time by reducing short-circuiting of flows and are useful for maximizing sedimentation efficiency and other processes, such as biodegradation, that are a function of retention time |

sediment loads can fill rapidly with sediment. Accordingly, a provision to either remove the sediments prior to reaching the wetland or an occasional dredging of the wetland may be necessary. Most sediments can be removed by employing a settling basin upstream of the wetland to protect it from the incoming sediment load. The settling basin should not be considered as habitat area and plans must be made to remove the sediments from the settling basin periodically. Easements and methods of access for sediment removal should be included in the design along with the information that this portion of the site will be subjected to construction activity on some periodic basis.

Fine sediments take longer to settle and will often pass through a settling basin into the wetland site. Over time there will probably be a loss in water volume as these sediments fill the site. Long period renovation may need to be considered in the design based on the fine sediment load to the site. Vegetation reduces the flow velocity due to the resistance of the roots, stems, and leaves to the flow and fine sediments freqently deposit in vegetated areas of the wetland.

In some watersheds, one or several contaminants may be associated with sediments coming into the wetland. Since most contaminants are tightly bound to fine sediment particles they will be found in areas of sediment deposition. If contaminants are likely to exist in significant concentrations, their impact upon the ecosystem and the likelihood of future remediation requirements should be carefully considered in wetland planning and design.

## Outflow

Outflow structures may be of prime importance especially where there is little or no inflow control. Outflow structures are of two basic types. One is where water flows over a control that is at a fixed or variable elevation. Drop pipes, flashboards, and spillways are examples of this type of structure. The other is where flow passes through a bottom or midlevel outlet such as a culvert or permeable material such as riprap (Swanson, Franzen, and Manning 1987). The “hard” engineering design and structure (or structure combination) selection should be based on the site requirements for water level fluctuation and flow. If the requirements are for minimum water level fluctuations but with large variations in flow then an overflow structure with a long crest length may be required. If, instead, floodwaters are to be stored, then large fluctuations in the pool depth must be included in the design of the outlet structure(s) and the dike system. A design event should be selected around which the outlet structure(s) is designed. A failure point and mechanism should be designed into the system to minimize damage for events that exceed the design event. The failure point should be located where it can easily be repaired. For structures where the water flows over a control, the design concerns will be how long to make the control, how high will the water get over the control, and what value to use for the discharge coefficient for the control. The materials used for the control are typically wooden boards, metal culvert pipe, plastic pipe, riprap, concrete, or reinforced vegetation. All of these types of materials and structures are subject to having the discharge coefficient vary due to debris accumulation, changing vegetation densities, or material degradation. Accordingly, the design process should look at both the new and the aged conditions. Bottom or midlevel releases are typically accomplished with culverts that may be gated to control the outflow or by gated structures such as sluice gates in a dam. Uncontrolled culverts may be designed such that the higher flows are controlled by either the entrance or the outlet of the culvert. Again, debris or other blockages may affect the actual flow through such structures. There have been hybrid structures where a flashboard located in the center of a dike was used to control the water level with the water getting to the flashboard through a culvert.

Operations and maintenance must be included in the design process. There is little rationale for designing an outlet structure that requires frequent operations if the personnel and financial resources are not available. Wetland sites should be designed to be relatively operation- and maintenance-free. Materials used for the outlet structure should match the site conditions. Acidic water may cause a corrosion problem for metal or concrete structures. The addition of fly ash in the concrete mixture may lengthen the life of concrete structures in such an environment. Pipe abrasion by coarse sediments, particularly for plastics (National Academy of Sciences 1978), can be a problem and should be considered in material selection. If the outlet structure is designed and constructed for a specific design life, the design should include plans to replace the structure as needed.

Life safety should always be considered when selecting an outlet structure. Many wetland areas will be used for authorized or unauthorized recreation. Attempts to exclude unauthorized access to wetland sites are usually doomed and should not be the primary safety feature of a design. Strong roller action at outlets and unobstructed culvert openings should be avoided.

# Basic Design Methods

Basic design of outlet structures includes selecting overflow or subsurface structures, selecting a design event for hydraulic design, and selecting appropriate materials for the outlet structure.

## Overflow Structure Design

The portion of an overflow outlet structure over which the water passes is referred to as a weir. For most circumstances, as long as the water downstream of the weir is below the crest of the weir then free overflow will occur at the weir. For free overflow conditions the following equation can be used to design a weir for specific conditions.

$$Q = CLh^{1.5} \qquad (5\text{-}2)$$

where:

Q = flow rate, $m^3$/sec
C = discharge coefficient, $m^{0.5}$/sec
L = the effective horizontal length of the weir in feet, m
h = the height of the energy line above the weir in feet, m

The water velocity in wetlands, as in most impoundments, will be sufficiently slow so the water surface can be used as an approximation of the energy line approaching the weir (h). The water surface elevation (about five times the depth of flow over the weir) should be used as the elevation of hydraulic grade line (HGL) at the weir because of potential flow acceleration effects at the weir. If the approach velocity to the weir is greater than 0.5 m/sec, the velocity head should be added to the water surface to determine the elevation of the energy grade line (EGL) at the weir. The velocity head is defined as

$$velocity\ head = \frac{V^2}{2g} \qquad (5\text{-}3)$$

where:

V = horizontal velocity of flow, m/sec
g = gravitational acceleration, m/sec$^2$

The effective length of a straight or semistraight weir is the actual length minus the effects of end contractions and the width of any piers or other obstructions along the length of the weir and associated end contractions. The weir length should be modified as follows to determine the effective weir length (Chow 1959):

$$W_L{}' = W_L - \Delta W_L \tag{5-4}$$

where:

$W_L$ = actual weir length, m
$W_L{}'$ = actual weir length, m
$\Delta W_L$ = change in weir length (note that all changes *shorten* the weir length), m, calculated as:

| | |
|---|---|
| $\Delta W_L = 0.05h$ | for each end contraction |
| $\Delta W_L = 0.1h + W_{obstruction}$ | for blunt obstructions |
| $\Delta W_L = 0.05h + W_{obstruction}$ | for streamlined obstructions |

and

$W_{obstruction}$ = width of weir obstruction at widest point, m.

The discharge coefficient (C) depends on the efficiency of the weir in question and varies the water depth flowing over the weir and the water depth just in front of the weir. For sharp-crested or nearly sharp-crested weirs with free overflow, the value of C is approximately 1.83 m$^{0.5}$/sec (Streeter 1971). For smooth broad-crested weirs such as wide spillways, C is approximately 1.7 (Streeter 1971).

If the weir is submerged from the downstream side, it acts as an orifice and the discharge coefficient C changes based on the amount of submergence. Complex design charts for orifice outlets can be found in Chow (1959). Submerged conditions should be avoided if the upstream water level is to be controlled by the weir.

Drop inlets such as riser pipes can be treated as weirs with the circumference of the inlet being the weir length. This concept works up to the point that the overflowing water creates a submergence effect. This effect generally starts when the water depth above the weir crest equals 45 percent of the radius of the riser pipe (USACE 1989).

## Submerged Flow Structure Design

Submerged outlet structures have several methods for design depending on the type and complexity of the outlet structure. Uncontrolled culverts are one of the more popular outlet structures used. The Federal Highway Administration has developed design methods for most culvert conditions based on extensive laboratory and field investigations (USFHWA 1984). Gates or other controls may be added to culverts to allow variable control of subsurface releases. Restrictions, if used, should be placed on the upstream end of culverts to prevent clogging of the culvert by sediment or debris. Design information for large outlet structure gates may be found in EM 1110-2-1602 (USACE 1963) or hydraulic engineering handbooks such as Chow (1959). For smaller controls such as gate valves trial setting may be required to achieve the desired flow control although King and Brater (1963) has information that may be useful. Porous structures may be used that pass flow from all or a fixed portion of the water column. Rock is probably the most common material for this type of structure but any porous medium or construction would fall into this category. Flow conveyance is difficult to determine for these structures due to unknowns in pore sizes and flow paths. The potential for clogging should be investigated prior to using this type of structure. Where water flows into and out of a wetland through the same structure, porous structures can be used to attenuate the water surface fluctuations. Groundwater flow analysis methods would be helpful in designing such structures.

## Design Event

Hydraulic structures are designed to routinely pass flow up to some design event that is usually based on a statistical probability of occurrence. The statistical event varies based on the type of structure being built, the damage costs that would result due to structural failure, and the risk to life due to failure. Many Soil Conservation Service projects are based on an event that has a statistical probability of occurring once every two years. Flows that exceed this event may cause flooding. Most US Army Corps of Engineers projects are designed for probabilities of once every 100 years or greater. This implies that the design conditions will be exceeded less often. Design event determination for a wetland site should be based on cost effectiveness and the cost of failure. Once the design event has been determined and the hydraulic structures designed, a failure point and mechanism should be determined and included in the project. Failure points should be located where reconstruction can easily occur, keeping in mind the available access for equipment and the cost of reconstruction. The mechanism could be a lower reach of a dike or an overflow spillway that would wash out without endangering the remainder of the dike system or other structures. An option to a failure point could be to construct overflow structures to allow greater than design flows to pass through the project without causing failure of the structures. The overflow structures should be designed to handle flows up to some statistically probable event, keeping cost effectiveness in mind.

## Materials

Due to cost considerations, most wetland outlet structures will be constructed with standard materials such as steel, cast iron, concrete, plastics, and wood. In determining which materials to use considerations should include the desired life span of the project, the potential for mechanical degradation, and the potential for chemical degradation. These considerations may also dictate the type of outlet structure. Steel and concrete are subject to abrasion and acid attack. Plastics and aluminum may be more resistant to acid attack but are less resistant to abrasion. Asphalt or other coatings will usually increase the life of steel products. Stainless steel is more resistant to attack but is expensive. Wood may last depending on the type of wood and its exposure to wet/dry cycles. Natural materials such as rock can be degraded through freeze/thaw cycles. Life cycle costs should be evaluated when selecting construction materials realizing the potential replacement costs and cycles for replacement of outlet structures.

## Structure Selection

Existing hydraulic structures are extremely varied due primarily to the need to satisfy highly varied design constraints. The final choice for the design is limited only by the imagination of the designer using the constraints mentioned above. However, several basic structures are normally used.

An adjustable weir constructed with removable flashboards is very common. Historically these structures have been constructed with metal or wood frames and wood flashboards. Recently all-plastic structures have been used (Watkins 1992). These structures are usually sized such that one person can handle the flashboards to make adjustments to the water level in the wetland site. If longer weir lengths are needed then several individual weirs can be included in the design. Spillways or overflow sections of dikes are often used with the spillway surface constructed of an erosion-resistant material such as concrete or rock. Vegetation can be used for spillway surfaces based on the amount and duration of flow. Drop inlets constructed with corrugated metal pipe are often used for ponded wetlands. Trash or debris protection should be included in the design of these structures to prevent clogging. Occasionally horizontal pipes will be placed at the desired water surface elevation to pass flow directly through a dike.

Simple corrugated metal. concrete, or plastic pipe culverts are the most common subsurface outlet structures. Large wetlands that may pass large flows sometimes have large outlet structures similar to those found at dams. Porous structures are not common but may be useful in tidal areas or along streams subject to frequent flooding.

# 5-4 Shoreline Protection and Erosion Control[1]

## Introduction

Shorelines and structures associated with created and restored wetlands are often exposed to the erosive forces of nature. Wetlands invite the use of bioengineering for erosion protection, and there is a greater emphasis on project aesthetics than in other types of erosion control projects. Bioengineering alone cannot provide adequate protection for some wetlands and must be combined with other forms of erosion protection. A design goal for a wetland protection project should be to use the minimum amount of structural protection necessary. Innovation is often the key to an appealing and successful project.

This chapter presents considerations for project planning and lists protection alternatives that might be considered for shoreline protection and erosion control. The text provides a checklist for things that need to be determined when planning wetland protection. The chapter does not replace more detailed erosion protection engineering manuals, many of which are referenced here. Neither does it replace the use of qualified consultants, especially ones familiar with the type of erosion problem of concern, or the particular area where the problem is occurring. Many factors such as public safety, economics, aesthetics, demographics, governing agencies, climate, strength of the erosion forces, and geology play an important role in determining the final protection alternative selected and designed. The blending of these factors requires judgment which can only be obtained from training and experience.

A good understanding of what needs to be considered for an erosion protection project, reflection on what successful techniques have been used in the past, and the experiences that can be borrowed from others are much more useful, beneficial, and efficient than any handbook.

## Steps to Develop Protection for Wetland Erosion

The development of shoreline protection and erosion control measures requires several steps. These steps are:

[1] By Jack E. Davis, Steven T. Maynord, John McCormick, and Trudy J. Olin

*a*. Understand the system and determine the mechanisms of erosion

*b*. Consider general design requirements

*c*. Develop a list of alternatives to protect against the cause of the erosion problem

*d*. Design the protection

*e*. Estimate the costs of the project

*f*. Construct, inspect, monitor, and maintain the project

In many cases there is significant overlap or iteration between these steps. The steps are discussed further below.

## Understanding the System and Determining the Mechanisms of Erosion

Determining the mechanism that is leading to erosion of a wetland is the most important step in the design process and may also be the most difficult or uncertain. This is true particularly at sites where wetlands are being created and no historical perspective is available. An expert is often needed to predict or identify erosion mechanisms.

In selecting sites for creating riverine wetlands or in protection of existing riverine wetlands, one must be cautious about locations that are experiencing instability over long reaches of the system. For example, in streams where equilibrium has been disrupted by changes in the basin such as altered water levels at the downstream end, altered flowrate, or altered sediment inflow. System instability is often indicated when the channel bed elevation is degrading which can be observed by the presence of scarps or headcuts moving upstream through the system. Similar system instabilities may be associated with tidal wetlands where instabilities in the wetland are part of a much larger regional instability. When system instability is present, a comprehensive treatment plan is required and expert consultants should be retained. Solutions to system instabilities are outside the scope of this handbook.

Local instability is erosion that is occurring in a system that is otherwise in equilibrium. Local instability includes bank erosion that is part of the natural erosion process (caused by stream migration or waves) occurring at isolated locations such as open-water headlands, river bends and constrictions, and reaches around structures. This handbook addresses local instability.

### Causes Versus Mechanisms

A differentiation between erosion causes and mechanisms must be made. Causes are the action or events that create forces on the wetland experiencing erosion. Mechanisms are the processes through which the bank fails. For example, a recreational boat causes waves that strike the bank and lead to failure through the mechanisms of tractive force and turbulence removal. The cause of erosion was boat wakes while the mechanism for erosion was tractive forces and turbulent removal of sediments. Hydropower operations cause water level changes that can lead to failure through the mechanism of piping. The distinction between causes and mechanisms for erosion is important because protection methods are generally designed to address mechanisms and not causes. The following presents a list of causes of local instability that occur in tidal and riverine environments.

*a.* **Wind Waves** are often the dominant cause of local instability in tidal wetlands and along fringe wetlands in lakes. The zone of attack from wind waves is near the waterline but fluctuating water levels expand the zone of attack over larger portions of the bank. Waves can undercut banks leading to mass failure. The failed material piled at the toe of bank is washed away by the waves and the undercutting cycle starts over.

*b.* **Boat Waves**, like wind waves, can cause instability along wetland shorelines. Boat waves differ from wind waves in their size, frequency and duration but are otherwise similar with respect to their zone of attack and erosion mechanisms.

*c.* **Boat-Induced Currents** can cause instability in wetlands especially where large commercial vessels travel in narrow, confined waterways or where large, commercial vessels travel near banklines in larger waterways. Boat-induced currents occur from the propeller jet and from the displacement effects of large vessels traveling in relatively confined waterways. The zone of attack can be both the bottom and sides of waterways. The erosion mechanism is the tractive force removal of bottom and bank material resulting from boat-induced currents.

*d.* **Channel-Meander** is a major cause of instability in riverine wetlands and is caused by current induced forces. The zone of attack is on the downstream portion of bendways and erosion is most severe at intermediate to high stages. Tractive force removal of material at the toe of the bank is the failure mechanism. The bank is undermined and fails due to loss of the geotechnical strength. The failed material is easily removed by the flow and the erosion cycle continues.

*e.* **Channel Braiding** is a cause of instability on streams having an overload of sediment or steep slopes where bars and islands can form producing a wide shallow channel. The bars and islands may function as wetlands. Erosion of banks, islands, and bars in braided channels occurs as a result of flow being diverted against the bank by the bars and islands. Zone of attack is highly variable and can occur at any position along the length of the channel. The mechanism leading to bank and island erosion is tractive force movement of the bank material.

*f.* **Ice and Debris** can reduce flow area and concentrate or deflect flow against otherwise stable banklines. The concentrated flow causes bank erosion through the mechanism of tractive force removal of bank material. The impact of ice and debris can gouge banklines, damage vegetation, and damage improperly designed protective measures.

*g.* **Water Level Fluctuation** is a cause of instability in riverine, depressional, and tidal wetlands and along reservoir shorelines. If water levels do not fluctuate, a distressed bank often erodes until it achieves a stable condition. As a distressed bank approaches a stable condition, a change in water level will disturb that condition. Water level fluctuations allow waves and currents to attack a bank at ever-changing elevations. Causes of water level fluctuations include naturally varying and controlled stream discharges, naturally varying and controlled lake levels, astronomical tides, seiches, wave setup, climatological effects, and navigation. A rapid drawdown in water level leaves banks in an unstable condition because the counterbalancing force of the water has been removed from the saturated bank and positive pore water pressures decrease the geotechnical strength of the bank. On steep banks, this imbalance in forces can cause a mass failure of the bank. On banks containing layers of different materials, rapid drawdown causes saturated banks to drain through the porous layers in the bank. Water movement through these porous layers may remove the porous material, leading to collapse of the bank. This failure mechanism is referred to as piping or sapping and is also found in riverine environments not having rapid drawdown but having saturated overbanks from ponds or poor drainage.

*h.* **Flow Constrictions** at bridge crossings, training structures, and floodplain encroachments cause local instability and result from the increased tractive force being able to erode otherwise stable banks.

Other causes of instability include rain splash, freeze-thaw, overbank drainage, and human activity. Overbank drainage and rain splash tend to be small-scale local instabilities but should be considered in designing protection methods. Freeze-thaw decreases bank soil strength which increases the potential for tractive force removal of the bank material.

# General Design Requirements

After determining the causes and mechanisms of erosion, several general design considerations must be evaluated. As in the determination of cause, many of these considerations require someone experienced in their evaluation. Use the following considerations as a checklist to insure that important design factors are not overlooked.

## Design Considerations

**Geomorphology**. Geomorphic evaluations involve determining the beginning point, ending point, and alignment of the protection. The protection may only need to extend along a limited reach of the threatened wetland. In other cases, the protection may have to be extended beyond the limits of the threatened wetland to insure adequate protection over the design life of the project. For example, in the riverine environment, a prediction must be made of the anticipated channel migration. In a typical meandering stream, migration of bendways is predominately in the down valley direction. Because of down valley movement, extending the protection far enough downstream is more important than the upstream limit.

For habitat and aesthetic reasons, less emphasis is given to a smooth alignment for wetland protection projects when compared to nonwetland protection projects. Accepting the existing alignment is almost always the case in existing wetlands. Created wetland boundaries are aligned for reasons of project function and economy. For example, a circular island shape was chosen for a proposed island wetland restoration project in the Chesapeake Bay to minimize the required length of shoreline protection for a maximum wetland area.

**Ecological and Physical Barriers**. Shoreline protection or erosion control alternatives should be designed so they do not inhibit the movement of organisms in or out of the wetland. For example, steep banks with crevices (e.g. riprap, block revetment) provide feeding areas for fish, but may trap small crustaceans and young animals. The selected alternative should not adversely restrict water flow in and out of the wetland. If the flow to the wetland is restricted, the change should not adversely affect water temperatures, dissolved oxygen concentration, and other concentrations of other chemical constituents. If the export of nutrients from the wetland is important, the alternative should not limit that transport.

**Aesthetics.** In a wetland environment, preservation of a natural appearance is important from both human and wildlife perspectives. Development and preservation of habitat and habitat diversity should be high priorities. Diversity of aquatic habitat is the result of diverse water depths and current velocities. Bank protection methods such as the indirect methods of dikes and groins promote diversity of aquatic habitat whereas relatively smooth revetments tend to reduce diversity. Rock structures and other bank protection methods provide stable substrate for macroinvertebrates. The impact of protection methods on aesthetics depends on the degree to which the protection measures are visually compatible with their surroundings. (Henderson 1986)

**Hydraulic Setting.** Quantifying the hydraulic setting is often required to determine the causes and mechanisms of bank erosion. Factors included in quantifying the hydraulic setting are outlined below.

*Design Event.* Identifying the design event is needed to select a protection method. The design event is the selection of event for which the erosion protection is designed. For example, erosion protection would be designed to allow a certain level of damage (or none at all) for a particular flood or storm event. The event is usually associated with a return interval, e.g. a flood with an expected occurrence of at least once in ten years, or once in 25 years. The conditions under which the protection should function needs to be identified to ensure an appropriate level of protection is designed.

While some of the protection alternatives presented here can be designed based on a selected design event, many lack the design guidance for such a design, mainly because they have not been extensively used or evaluated in the field. For these protection alternatives, demonstrated performance of the alternative under comparable conditions at a different site is the best guide.

When the major cause of erosion is wind waves or current forces, delineation of a design event is easier to determine than designs for causes like boat wave attack or debris damage. For the causes such as boat-induced erosion or debris damage, it is not possible to determine a return interval for various event levels. Usually a less rigorous method is used, such as assuming a maximum wave height for the case of boat waves.

*Water Level Fluctuations.* Evaluation of water level fluctuation is needed to address potential geotechnical failures such as mass failure and piping. In the case of mass failure due to water level fluctuations, bank grading to a stable slope and protection of the slope against undermining is usually warranted. Piping-related failures are often addressed by grading to a stable bank angle, improving overbank drainage, and placing extensive filters on the regraded bank.

*Wind Waves*. Guidance for the estimation of wind-waves at a project can be found in the Corps of Engineers' Shore Protection Manual (SPM 1984). Another useful Corps of Engineers' tool for coastal engineering projects is the Automated Coastal Engineering System (Leenknecht et al, 1990). The system contains several programs useful for coastal engineering studies, including the estimation of wind waves.

The calculation of wind waves for a project requires information about wind speeds and directions, wind fetch, and water depth. In general, stronger winds, longer fetches and deeper water cause larger waves, and the wave direction is directly related to wind direction, as well as the influence of the water bottom. Values for these variables must be determined before wind waves can be predicted.

Local wind data should be reviewed to determine common or extreme wind events. A useful method is to categorize winds according to the number of occurrences for different combinations of wind speed and direction. Table 5-6 gives an example of such categorization of wind information. The wind speed and direction for which you want to estimate wind waves at the project site can be readily selected from the table.

Several corrections to measured wind data are usually required before they can be used for calculating waves. The corrections account for the elevation at which the wind was measured, whether it was measured over land, water or from a ship, and the temperature difference between the water and the air. Further, the wave estimation methods in the SPM require that wind speed values be converted to wind stress values. All of the corrections and conversions identified are outlined in the SPM.

**Table 5-6**
**Percent Occurrence of Wind Speeds and Direction**

| MPH | North | NE | East | SE | South | SW | West | NW |
|---|---|---|---|---|---|---|---|---|
| 0-10 | | | | | | | | |
| 10-15 | | | | | | | | |
| 15-20 | | | | | | | | |
| 20-25 | | | | | | | | |
| >25 | | | | | | | | |

To determine the general wave environment for the site, the corrections may often be neglected. However, the corrections should be considered if the wave calculations will be used in a final design. The equations presented below can be used for a quick assessment of wave conditions.

Calculating wave height and period by the SPM method requires that wind speeds be converted to wind stress. This can be done using the equation

$$U_A = 0.71 U^{1.23} \tag{5-5}$$

where:

$U_A$ = wind stress, m/sec
U = wind speed, m/sec

Assuming fetch-limited conditions, the wave height can be approximated as

$$\frac{gH}{U_A^2} = 0.283 \tanh\left[0.530\left(\frac{gd}{U_A^2}\right)^{\frac{3}{4}}\right] \tanh\left\{\frac{0.00565\left(\frac{gF}{U_A^2}\right)^{\frac{1}{2}}}{\tanh\left[0.530\left(\frac{gd}{U_A^2}\right)^{\frac{3}{4}}\right]}\right\} \tag{5-6}$$

where:

H = wave height, m
d = water depth, m
F = wind fetch, m
g = gravitational constant, m/sec$^2$

The wave period can be approximated as

$$\frac{gT}{U_A} = 7.54 \tanh\left[0.833\left(\frac{gd}{U_A^2}\right)^{\frac{3}{8}}\right] \tanh\left\{\frac{0.0379\left(\frac{gF}{U_A^2}\right)^{\frac{1}{3}}}{\tanh\left[0.833\left(\frac{gd}{U_A^2}\right)^{\frac{3}{8}}\right]}\right\} \tag{5-7}$$

where:

T = wave period, sec

The wind fetch is the extent of water over which the wind blows before reaching the shoreline of interest. On smaller bodies of water waves are usually fetch-limited, meaning the length of the fetch limits the size to which the waves will grow. But, on larger bodies of water other conditions may apply. Waves may reach a fully developed condition for a given wind reaching their maximum size before reaching the end of the fetch. Another condition is a duration-limited condition where the wind does not blow long enough for waves to grow as large as they could for the given fetch. Also, when the width of the fetch has an effect on wave growth, the condition is called a restricted fetch condition. A restricted fetch condition can be identified by drawing radial lines out from the point of interest to the nearest obstruction along the radial line (for example, a shoreline across the lake). If the lengths of the radial fetches are significantly different from one another, the fetch may be restricted. A phenomenon of wave-growth over a restricted fetch is that the largest waves are often generated along a fetch that is not in line with the winds but rather in line with one of the longer fetch lengths. See Smith (1990) for a good description of the phenomenon and calculation techniques for predicting waves.

Generally, deeper water yields larger waves. For a given wind speed, direction, and fetch length, the wind waves generated on a deep lake will be larger than the waves generated in a shallow coastal estuary. However, waves will not be any larger once the depth exceeds a limiting depth no matter how deep the water is. Water depth also influences the form of waves to the point where they break on shore. As waves shoal (propagate into shallow water), their speed slows. Shoaling increases the steepness of the wave's profile, increasing the wave's height. When waves become too steep, they break. A simple rule is that the wave height will not exceed the water depth. That is, a wave with a height of 1 m would begin to break in a water depth of about 1 m.

## Currents and Water Level Computation

Currents and water level computation in the riverine environment is beyond the scope of this handbook but an overview of the general concepts will be presented. The first step requires determination of a design discharge which comes from either computation of runoff from rainfall records and basin parameters or analysis of discharge gauging station records, if available. Gauging station data also provide information on the characteristics of the hydrograph (variation of discharge and stage with time) and the rate of rise and fall of the stream. Next, water surface profiles are computed using a design discharge in models such as HEC-2 (HEC 1990). Water surface profile computations on major rivers and streams are often computed by the US Army Corps of Engineers and the Soil Conservation Service. Local or District offices should be contacted for available information. The water surface profile computations provide the needed quantities of depth and average channel velocity for use in design of riverine protection. The design portion of this chapter will show how average channel velocity and depth are used to design the protection.

*Vessel Effects* are primarily a function of vessel speed, vessel shape and displacement, distance from vessel, and water depth. Regarding vessel shape and displacement, the two broad categories are commercial vessels, which are relatively slow but have large displacement, and recreational vessels, which are relatively fast but have small displacements. Commercial vessels rarely move fast enough to produce significant waves but they do produce substantial rapid drawdown when operating in confined channels. Methods for prediction of drawdown magnitude as well as other navigation effects can be found in PIANC (1987). Waves from recreational vessels decay rapidly with distance from the vessel and methods for their prediction can be found in Bhowmik et al. (1992). Bhowmik et al. (1992) measured wave heights on the upper Mississippi River for uncontrolled runs during a busy holiday weekend and during controlled runs of various size recreational vessels and found a maximum wave height of 0.6 m.

**Top Elevation of Protection.** Wetlands, particularly in a tidal environment, have relatively low top bank elevation and protection often extends over the entire bank. In the riverine environment, many successful projects have been built with the top elevation of the structural protection well below the top-of-bank or design water surface. Bioengineering techniques are often used to protect the upper bank. Factors affecting the required top of structural protection in the riverine environment are stage duration, erodability of upper bank soil/vegetation, variation of hydraulic forces on the upper bank, bank slope, method of protection, and consequence of failure. USACE (1994b) provides a method for estimating the variation of hydraulic forces on the bank in the riverine environment.

**Toe and Flank Protection.** One of the most overlooked aspects in a bank protection project is consideration of the toe and ends of the design. Successful protection in both the tidal/coastal and riverine environments requires an evaluation of the potential for scour at the toe and ends. In the river, toe scour and the fact that many species of vegetation cannot withstand long term inundation are the primary reasons that bioengineering by itself will not provide stable bank protection. Some form of structural protection is often required at the toe of the river bank and must be able to withstand the changing bed elevation found in alluvial channels. In the wave environment, waves striking a hardened bank concentrate energy at the toe of slope that can result in scour and undermining of the protection. Procedures for estimating toe scour in the riverine environment are given in USACE (1994b) and in the wave environment in SPM (1984).

Once the scour has been estimated, there are two methods for providing scour protection. The first is to extend the protection down to the maximum estimated scour depth. This is often the preferred method in dry construction but becomes difficult and expensive when excavation is done underwater. The second approach is to place a flexible material that will adjust to the channel scour. This approach lets the stream do the excavation. Riprap is the most common material to use in flexible or “self-launching” aprons. Gabions and articulated concrete mattresses are also means of providing a flexible toe structure. Guidance for self-launching riprap and scour depth estimation in the riverine environment is given in USACE (1994b). In the wave environment, guidance for self-launching riprap is given in SPM (1984). Scour protection using gabions or articulated concrete mattresses should provide an apron length twice the anticipated depth of scour.

When considering the ends of the protection, it is desirable to terminate the protection in areas where the erosion forces are reduced. Unfortunately this is frequently not possible and the ends of the protection must be designed to not fail when the adjacent unprotected areas experience erosion. When using armor protection like riprap, increased layer thickness at the ends will allow the protection to adjust to minor adjacent erosion.

**Geotechnical Setting** Geotechnical design considerations include slope stability, filters, and subsurface drainage. Slope stability deals primarily with the stable bank angle which is a function of height, bank material, stratigraphy, stage fluctuation, groundwater conditions, and overbank loading. The purpose of filters and subsurface drainage is to control the movement of water and bank material beneath and through the protection. The indirect and sacrificial methods presented later in this chapter generally do not require a geotechnical analysis of the bank being protected.

**Surface Drainage**. Surface drainage rarely causes failure of a protection alternative, but may cause maintenance problems, destroy vegetation, and damage the aesthetics of a site. The basic steps in preventing erosion from surface drainage are to (1) protect all bare ground unless slopes are flat and wavewash and runoff are moderate, (2) collect overland flow and wavewash, and (3) provide outlets to the river or open water body.

**Filter Layers and Fabrics.** Many protection alternatives require a filter layer between the protection-sediment interface. The filter layer's purpose is to prevent the filtering of sediments through the protection which would ultimately undermine or destabilize the protection. The filter layer can also distribute the weight of protection more evenly over the substrate. Filter layers are comprised of well graded gravel and stone. In many instances, a filter layer may be replaced by an acceptable filter fabric, the pores of which are specified based on the characteristics of the sediments. Additional information on filters is provided in Section 4.

**Safety Factor**. The consequences of failure must be considered. Only limited information is available for the design of many bank protection alternatives. Without well founded design information, determining a factor of safety is difficult and usually a conservative design is selected to compensate for uncertainties, or the design is based on convenience of construction, of materials, or some other feature. If the designer has experience with a particular protection alternative or the wetland region in question, then a factor of safety based on experience may be built into the design.

If the construction environment is difficult, or materials lack consistent quality, then as a factor of safety the design should account for the prospect of sections of below-average construction or low-quality materials. Safety factors can be reduced somewhat if inspection and maintenance are scheduled up front. That is, after a certain operating time if the project is showing signs of failure, remedial action could be taken to correct the problem.

**Locally Available Materials**. The cost of any project can be reduced if inexpensive locally available materials are used. A project design should always consider the advantages of using local materials in some element of the design.

**Vandalism**. Anticipate vandalism especially in areas where the public has access. Either employ hard-to-damage materials and designs or anticipate periodic maintenance. Consider using a protection scheme that will still work even if some portions of it are damaged. For example, some geotextiles tubes may be punctured by vandals allowing the contents to flow out. The decorative blocks of some concrete block revetments may be stolen. Removing the blocks compromises the system. Having an articulated concrete mattresses makes the blocks much harder to remove.

**Educating the Public**. Educating the public to the purpose of the project and making them feel a part of the project may help to reduce the frequency of vandalism and damage by people inadvertently working or recreating in the area.

**Fate of Materials**. Consider the possible fate of materials used in the bank protection design should the project fail or exceed its design life. Many geotextiles, tires, synthetic materials, metals, and treated woods do not degrade rapidly and may remain as an unappealing result of the project or pose a danger to humans and the environment.

**Effect of Alternative on Local Waves and Currents**. The impact of bank stabilization on areas adjacent to the protection must be considered in the design. In a naturally eroding stream system, bends migrate down valley. By stabilizing one portion of this system, the natural down valley movement is interrupted. The stabilized section causes the point of attack in the next downstream section to be fixed rather than transient. Depending on bank erodability and other factors, this constant point of attack can alter downstream erosion patterns and rates. Bank protection that significantly reduces channel area or deflects currents can increase downstream or opposite bank erosion.

Bank protection alternatives may influence the wave field near the protection. Waves refract and diffract near bathymetric variations and structures. For example, refraction will cause wave crests to bend around a mound of material on the bottom. The wave crest may bend so much that it collides with itself on the backside of the mound. The colliding wave crests can damage shorelines or protection works where otherwise the wave would have had no effect. Waves that pass by the end of a structure, such as a breakwater, will diffract into the region behind the breakwater and may cause unexpected damage.

Wave refraction and diffraction are complicated processes and questions about them should be referred to an expert.

**Access.** The selected bank protection should not adversely affect organisms requiring access to the wetland. For example, a riprap revetment may present a barrier to small or immature animals that must get from the wetland to open water. The voids between the revetment stones could act as a trap into which an animal may become trapped.

If the public has access to the site, the protection must not present a danger to them or their property.

Access also affects the selection of the protection method. In many wetland creation and restoration projects, land access for construction is not feasible for a variety of reasons. In many of these same projects, water access by large construction equipment is limited by shallow depths. Where larger construction equipment does not have access to the site, more labor-intensive alternatives may be required.

**Animal Activity**. Animal activity in and adjacent to protection methods can undo otherwise stable systems. Certain coastal crab species burrow passageways into exposed banks. These passageways, especially in conjunction with rapid drawdown from tows in confined waterways, can lead to a piping-type failure of the bank. Conversely, certain types of bank protection structures may create an ecological problem by preventing the use of the bank by such burrowing animals.

Another type of animal activity that has repeatedly caused problems is the consumption and destruction of vegetation protection systems by various animal species. Whenever vegetation is used in a protection plan, damage to the plants by animals and techniques to prevent it should be considered in the plans.

**Water Chemistry**. In tidal wetland environments, the tolerance of protection materials to seawater must be considered. Metals will corrode. Timber will rot. Certain species of vegetation will not tolerate certain levels of salinity (high or low).

**Construction and Ease of Repair**. Conditions can dictate the type of alternative selected because of limitations on the type of equipment that may be used. Conversely, costs must be increased to overcome poor construction conditions. If construction is expensive or difficult, then repairs or modifications will probably be costly as well. In any case, the ease of repair of the selected protection for the project of interest should be considered when designing the project and predicting future maintenance costs.

**Navigation Hazard**. If the public has access to the site by water, possible hazards to navigation from partially or fully submerged structures both offshore and on the bank must be considered.

# Erosion Protection Alternatives

After determining the causes and mechanisms for bank erosion and quantifying the environmental setting of the wetland to be protected, a list of applicable protection methods can be developed. A combination of methods is often necessary to provide a desirable level of erosion protection. Table 5-7 presents common erosion control structures and their design requirements. The advantages and disadvantages of these alternatives are discussed below.

## No Action

This alternative is selected when the environmental setting is mild enough not to require protection. However, natural systems are sometimes self-stabilizing. That is, they will erode until they form a more stable bank. It is possible, at times, to let an erosion problem continue if it appears that it will stabilize with time and that the wetland will not suffer unrecoverable losses. Experience and familiarity with the location is important in the somewhat subjective decision whether to take no action or apply protection.

## Vegetation and Natural Materials

In low energy environments, well maintained vegetation and other natural covers often provide adequate erosion protection. Advantages and disadvantages of this alternative are summarized below.

**Table 5-7**
**Erosion Control Structures and Design Considerations**

| Structure | Materials | Design Considerations |
|---|---|---|
| Riprap/ Revetments | Stone, cinder blocks, sand-cement bags | Riprap sized to resist stream velocities, wave impact and wash. Multiple layers may be required. Bank must be properly sloped.<br><br>Good erosion resistance. Toe scour problematic when water depth is less than maximum wave height. Filter material behind revetment needed to prevent fine materials from being washed out from under revetment.<br><br>Stone revetments - applicable to wide range of wave conditions with varying stone size.<br><br>Cinder blocks, sand-cement bags limited to smaller breaking waves<br><br>Riprap useful for all size projects and sites requiring immediate intervention<br><br>Low to high cost: materials typically low cost if readily available in area, placement costs can be high, depending upon conditions and material requirements for hand placement and transportation.<br><br>Reference Eckert, Giles and Smith 1978, Baker 1980, McCartney 1976, Binns 1986. |
| Windrow Revetment | Stone cobbles or graded fieldstone | A riverbank stabilization method utilized for high vertical banks. A trench is excavated parallel to river and filled with stone. The stone is covered with soil and the area reseeded. Over time, the bank may evolve to a steeply sloping configuration which will support vegetation.<br><br>Aesthetically acceptable, natural looking stabilization method. Minimal disturbance to natural bank.<br><br>Limited to relatively non-cohesive banks.<br>Reference: USACE District Omaha 1980. |
| Tree Revetments | Green, felled trees | A streambank stabilization technique, trees are laid parallel to bank, overlapping 1/3 to 1/2 in shingle fashion. Trees are cabled to deadmen buried in the bank. Rock is placed along the bank with the trees.<br><br>Certain species are more appropriate than others, having more branches and being less susceptible to attack by beavers (this will be somewhat site specific). Conifers and junipers work well.<br><br>Recommended for small to intermediate streams free of ice.<br><br>This revetment type provides excellent fish habitat.<br><br>Reference: Binns 1986. |
| Gabions | Galvanized wire baskets filled with 4- to 10-inch-diameter rock and stacked and wired together | Maximum height approximately 10 feet with multiple thicknesses or counterforting (Eckert, Giles and Smith 1978)<br><br>Susceptible to toe scour when placed on erodible substrate. Flexible gabion apron required.<br><br>Moderate to high cost structure<br><br>Reference: Eckert, Giles and Smith 1978, USACE 1977 |

(Sheet 1 of 4)

**Table 5-7 (continued)**
**Erosion Control Structures and Design Considerations**

| Structure | Materials | Design Considerations |
|---|---|---|
| Articulated Concrete Mats | Interconnected concrete blocks | Used along steep riverbanks with moderate to high water velocities<br><br>Reference: Way, Miller, Bingham and Payne 1992. |
| Geotextile Containers | Woven/ nonwoven permeable synthetic fabric/with or without impermeable liner | Utilized for underwater stability berms, breakwaters, sills, groins, breach and gully repair and scour protection.<br><br>Bags filled with granular material or, if lined, with fine material through which vegetation may propagate<br><br>Reference: Fowler and Sprague 1993 |
| Groins | Rock, geotextile bags, gabions, piles and netting | A structure placed perpendicular to the shore to influence current direction and enhance sediment accretion<br><br>Reference: Binns 1986, Abam 1993. |
| Floating and Fixed Tire Breakwater | Tires | Floating breakwaters can provide some wave attenuation, principally in low wave climates with short wavelengths. Floating tire breakwaters have been demonstrated to reduce wave energies by up to 80 percent. Materials to be protected must be somewhat scour tolerant: material retention is not a function of the floating breakwater.<br><br>Floating breakwaters should be placed in water depths sufficient to float them at mean low water.<br><br>Fixed tire breakwaters are threaded onto treated poles. Other materials could possibly be utilized for greater durability.<br><br>Some turbulence and backwash will occur behind the breakwater<br><br>Portable.<br><br>Low cost materials. Assemblage and anchorage may be high cost.<br><br>Reference: Eckert, Giles and Smith 1978, Knutson, Allen and Webb 1990, Markle and Cialone 1986. |
| Wood Breakwater | Timbers | A permeable structure, provides wave resistance by embedment in bottom. No deadmen or tiebacks required.<br><br>Breakwater top located about 6 inches above normal high water level and slightly above elevation of marsh root mat<br><br>Locate 20 to 50 feet offshore, about 10 feet seaward of lower vegetation limit, flatter slopes allow greater widths. Some sedimentation may occur behind the breakwater.<br><br>Suitable sites have flat bottom and shallow water nearshore, less than 3 feet deep 50 to 100 feet offshore.<br><br>Simple, nailed construction. Heavier construction may be required in high wake environments due to traffic at low tides. Small wood breakwaters not suitable for high energy environments<br><br>Cost approximately one-third to one-half that of wood-end bulkheads<br><br>Reference: Broome, Rogers, and Seneca 1992. |

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**Table 5-7 (continued)**
**Erosion Control Structures and Design Considerations**

| Structure | Materials | Design Considerations |
|---|---|---|
| Triangular Breakwater | Aluminum, tripod | A wave attenuation device.<br>Flow -through design, stringers on front and back at 45-degree angle off the vertical. Fence cross sections are triangular. Vertical stabilizers extend into the sand bed.<br>Reference: Ouzts and Machemehl 1977 |
| Offshore Sill | Sand covered with stone, stone, gabions and sandbags, other suitable materials. | Sills reduce wave height by initiating wave breaking, protecting the land form behind the sill.<br>Sill crest is typically at about low mean water, and 3 to 4 feet in width. Best located where tidal fluctuation is 2 feet or less (Eckert, Giles and Smith 1978).<br>Low to medium cost structure. Placement costs may be most significant for sandbags and gabions requiring individual placement. Requires less material than a breakwater.<br>Reference: Eckert, Giles, and Smith 1978, USACE 1977 |
| Log Cribs | Timbers, coarse cobbles | Parallel rows of timbers are filled with cobbles. Log cribs are used to reinforce streambanks and are quite resistant to erosive flow, though not natural in appearance.<br>Triangular log crib deflectors are used to deflect current at a point on the streambank.<br>Susceptible to undermining.<br>Reference: Binns 1986. |
| Christmas Tree Fences/ Branch Boxes | Brush or trees, fencing material | Christmas tree fences act to reduce water velocities and wave action and facilitate sediment accretion.<br>Low energy environments - trees or brush can be tied into network of stakes<br>Moderate energy environments - a crib is constructed of parallel rows of fencing material, posts and hogwire. This is filled with Christmas trees, or brush.<br>The top of the cribs may be secured to prevent material from floating out.<br>Greatest accretion occurs with fencing in shallow water sites (< 1 meter) tied in to shoreline. Other siting possibilities: closure of a breach, enclosure of a corner of a pond.<br>Reference: Steller 1991, Allen 1992b |
| Slotted Wood Fences | Boards and pilings | A streambank stabilization structure. Pilings are driven at the toe of the bank and treated planks are bolted at intervals to the face of the pilings.<br>Slotted fences reduce water velocities and induce sedimentation behind the fence.<br>Utilized on bends with short radius of curvature and straight sections with high banks.<br>Susceptible to undermining.<br>Reference: Baker 1980. |
| Kellner Jacks | Long concrete beams or angle iron sections joined at centers to form hexapod | A streambank stabilization or training structure utilized to reduce flow velocities and induce sedimentation. Installed in single or multiple rows and anchored to pilings or deadmen.<br>Used with slotted fences in some cases to further reduce water velocities.<br>Reference: Baker 1980, Keown et al. 1977 |

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**Table 5-7 (continued)**
**Erosion Control Structures and Design Considerations**

| Structure | Materials | Design Considerations |
|---|---|---|
| Bulkhead | Filled concrete culverts, post and timbers, aluminum sheeting and stone | A retaining wall separating land and water<br><br>Reference: Coulombe et al. 1982. |
| Drop Structures | Earth, Soil-cement, Concrete Pipe, Riprap, Gabions, Sheet pile | Grade control structures to alter regime of stream from steep and eroding to stable.<br>1.5H to 1V embankment slopes possible with soil-cement structures. 2H to 1V or 3H to 1V typical drop slopes (Wulliman and Hanson 1990).<br>Reference: Roberson, Cassidy, Chaudhry 1988, Watson and Abt 1993, Wulliman and Hansen 1990., Soil Conservation Service (SCS) 1984, SCS 1989. |
| Diversion Terraces/ Detention Ponds | Graded earth | Demonstrated in halting gully development. Utilized to divert and capture sediment transported in surface flow. Potential for use in protecting wetlands from excessive sedimentation from overland flow.<br>Reference: Knighton 1984. |

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## Advantages

*a.* Vegetation and natural materials used for protection complement or become an element of the created and restored wetland.

*b.* Additional habitat can be created. Because the protection is often at the interface between open water and heavily vegetated water or land, it lies within the very productive portion of the wetland. Vegetated banks provide more appealing vistas for humans and more attractive habitat for wildlife that may otherwise be deterred by unnatural settings.

*c.* Vegetation is self perpetuating.

*d.* Vegetation will continue to strengthen and stabilize the bank assuming no destabilizing forces overcome the vegetation.

*e.* Successional or invasional species colonizing a site can add natural variety to the original protection scheme.

*f.* Vegetation minimizes the potential obstructions to the ingress and egress of organisms to the wetland, as well as the movement of water into and out of the wetland.

## Disadvantages

*a.* Vegetation takes one to three years to fully develop.

*b.* Vegetation often requires stabilization measures to protect it during development.

*c.* Vegetation is only successful when applied to mild erosional climates.

*d.* Vegetation requires continuous monitoring and maintenance.

*e.* Minimal guidance is available for designing vegetation erosion protection based on wave and current conditions.

## Common Reasons for Failure

*a.* Vegetation fails because there is no protection during the development stage.

*b.* Improper plant selection, handling, planting technique, or positioning may hinder development and propagation of plants.

*c.* The quality of the substrate was inadequate to support vegetation.

*d.* Opportunities to correct problems were missed due to inadequate monitoring and maintenance programs.

## Design Characteristics

The following information was derived from Knutson and Inskeep (1982), Knutson and Woodhouse (1983), Allen and Klimas (1986), and Knutson et al. (1990). Other useful references are Coppin and Richards (1990), Gray and Leiser (1982), Schiechtl (1980), Allen and Webb (1993), and Allen (1992b).

*Soil Type*. Marsh plants will grow in a variety of soils from coarse sands to clays. The soil characteristics that affect the success of marsh plantings are **substrate stability, nutrient supply** and **ease of planting.** The substrate must be stable while the plants develop root systems to anchor themselves. Plants may need several weeks to develop an anchoring system within their roots. Soil nutrients are required to help plants grow, but the nutrient concentrations also determine how quickly plants will grow. When nutrients are readily available in the soil, plants will grow more quickly. Soils should be tested for nutrients and a determination made as to whether nutrients (fertilizers) should be added. Hard clays are more difficult than loose sand to plant and newly placed dredged material is usually too soft for planting machinery to be used. The labor involved in planting depends on the difficulty in penetrating the soil and whether hand labor or machinery is used.

*Salinity*. Important for coastal marsh plantings. Regularly flooded areas will have salinities at 35 parts per thousand (sea strength) or less. Vegetation can be found that tolerate these levels of salinity. Most plants with a tolerance to seawater still tend to do better in areas where the salinity is below sea strength. Irregularly flooded areas or areas where waters do not flush significantly may have higher salinity values. Developing a successful vegetative stabilization scheme in these areas because of the stress on the vegetation is diffficult. If some doubt exists as to whether the vegetation will survive, locating existing stands of similar vegetation in similar (and nearby) areas will provide a good indicator for potential success.

*Sunlight.* Many emergent plants require maximum light exposure. For example, if emergents are planted near overhanging trees or bushes they will not survive. Water clarity and depth and duration of submergence during water level fluctuations affect the locations at which emergent vegetation will grow. Where an overhang is present, a recommended procedure is to clear the overhang back 3 to 5 m.

*Shore Width Planted*. Vegetation protects a bank by dissipating the nearshore current and wave energy. The broader the band of vegetation available for currents and waves to pass through, the greater the magnitude of dissipation. Based on observations, a practical planting width is 6 m. If the offshore slope is too steep to allow for this beach width, then the bank should be graded. (Grading should be done well in advance to allow for consolidation of sediments before planting.) Along the Atlantic coast where tidal fluctuations are less than 2 m, emergent vegetation can be found throughout the intertidal zone. Where the tidal fluctuations are greater than 2 m, establishment of vegetation in the lower part of the intertidal zone becomes more restrictive or impossible.

*Sediment Supply*. The loss of sediments from wetlands during storms or floods must be replenished during other periods. Sediment must be available through suspended or bedload transport. No guidelines are available for evaluating sediment supply.

*Survival by Fetch*. Survival of marsh plants is inversely proportional to the fetch length to the marsh. Knutson et al. (1990) found that 89 percent of projects exposed to less than a 2-km fetch were successful or partially successful (no erosion landward but some erosion at seaward edge of marsh). Conversely, 83 percent of the projects with fetches greater than 18 km were failures.

*Survival by Shore Configuration*. Projects located in narrow coves are exposed to waves only when waves are directed nearly perpendicular to shore. Projects located on headlands are exposed to waves from almost every direction. Hence, the likelihood of survival of a marsh in a cove is greater than that for a marsh established on a headland.

*Survival by Inundation Duration*. In the riverine environment, vegetation is generally unable to survive along the toe of the bank in streams having a continuous or base flow, or when there are strong hydraulic shear forces. For these reasons some form of structural protection is required up to the level at which vegetation can survive periodic inundation.

*Sediment Grain Size*. Sediment sizes in the intertidal zone are rough indicators of the wave-energy climate and so are potential indicators of planting success. Knutson et al. (1981) found that 84 percent of planted sites were successful or partially successful when the mean grain size was less than 0.4 mm. Conversely, they found that 82 percent of the sites failed where the mean grain size was greater than 0.8 mm.

*Offshore Depths.* Shallower offshore depths offer a better opportunity for successful shoreline stabilization projects. The shallower the offshore depths the smaller the wave heights for a given wind and fetch. For example, based on the methods in the SPM (1984) , a 13.9-m/s wind blowing over a 16-km fetch with a water depth of 1.5 m will generate a 0.5-m wave height. The same wind over the same fetch length but with a water depth of 12 m will generate wave heights of 0.8 m.

*Tidal Currents.* Marsh plantings as well as existing marshes are vulnerable to erosion by tidal currents. The proximity of tidal channels to the planting site and their tendency to migrate toward the plantings should be considered.

*Plant Materials (sprigs, pot-grown, plugs).* Sprigs are easiest to handle, transport and plant. They must be obtained from a field nursery planted at least one year in advance or from a nearby stable stand of vegetation. Pot-grown plants are easy to produce but cost 2 to 5 times that of sprigs to grow and plant. They are more difficult to transport and plant. Field-collected plugs are even more cumbersome to transport and plant and cost at least twice that of pot-grown plants.

*Planting Methods (hand planting and tools, power-driven auger, machine planting).* Hand planting with dibbles, spades and shovels is suitable for all types of plants. A power-driven auger is useful for difficult soils and for planting pot-grown seedlings and plugs. Machine planting is very efficient for large-scale plantings of sprigs and most can be equipped to handle seedlings.

*Intertidal Plants*. Several plants are available for stabilization projects. Two particular species are dominant in the intertidal zone. On the Atlantic seaboard and Gulf coast, smooth cordgrass (*Spartina alternaflora*) is dominant. On the West Coast, pacific cordgrass (*Spartina foliosa*) is more common. Notes on these emergent plants are provided in Table 5-4.

*Riverine Plants*. Plant species will vary up the bank depending on inundation frequency and duration and on their ability to withstand current attack. In the lower bank zone subject to frequent inundation, plants like reeds, rushes and sedges are recommended for planting. In the next zone up the bank grasses and woody plants are used which are flood tolerant and able to withstand inundation for up to several weeks. Various shrub-like willows such as peach leaf and basket are used in this zone. Alder and dogwood species have also been used in this zone. In the upper zone of the bank, inundation is much less frequent and grasses, shrubs and trees less tolerant to inundation are planted.

## Other Considerations

Vegetation used for bank protection must often be protected itself (or its foundation enhanced) until it has had time to develop root systems and a thick stand. Vegetation is sensitive to its environment, such as water depth, water clarity, water quality, sediment type and nutrients. A good indication of whether vegetation will survive at a given location is to look for similar conditions in the region where vegetation has survived.

No significant design guidance on allowable velocity or wave heights is available for using vegetation for shoreline and streambank protection. The references provided at the end of this section are a good resource for available techniques, but quantitative design guidance is lacking for designing vegetative protection for a given stream velocity or wave condition. A successful design depends on a thorough understanding of the physical and biological processes of the local environment and the protective vegetation and extensive experience with bioengineering techniques.

Vegetation can be protected initially by using some of the alternatives mentioned in the armor protection section below. Basically, anything that limits the intensity of waves and currents during vegetation development to an acceptable level is satisfactory. Additionally, you can apply techniques to strengthen the foundation in which vegetation is established. For example, natural or synthetic fiber mats can be sprigged with plants or the plants can be grown in fabric-sediment rolls. Vegetated mats and rolls can be grown offsite and transported to the project at construction. The mats and rolls provide a stable substrate for the plant roots. When vegetation is grown offsite, a significant lead time to construction is necessary so that the vegetation is ready for placement at the time of construction.

Vegetation has a limited range over which it is able to maintain sediment stability. That is, vegetation can only withstand a certain level of wave and current magnitude, before it is undermined or otherwise destroyed. However, even in cases where something other than vegetation is proposed for erosion control, you should always consider the possibility of adding vegetation to the design. For example, if rock revetment is necessary, it may be possible to plant vegetation between the rocks. The Natural Resources Conservation Service (NRCS) has established threshold levels for some vegetation protection techniques.

If a bank is too steep for vegetation to become established and thrive, the bank should be graded to an angle sufficient to support vegetation. If the bank previously contained vegetation but waves and currents have destroyed it and steepened the bank, then additional protection will be required after the bank is graded to prevent the bank from steepening again. The steepest bank slopes usually used for vegetation are 1:1. However, milder slopes of 1:2 or less are recommended.

## Fiber Mattresses

Fiber mattresses consist of intertwined natural or synthetic fibers. The mattresses are porous allowing water to permeate while retaining sediments. Fiber mattresses do not require the use of a filter fabric or layer. Fiber mattresses are strong but depend on the quality of the materials for durability. The success of a mattress depends on its strength, durability, and the system used to anchor it.

### Advantages

*a.* Biodegradable fiber mattresses can be used as temporary protection during the establishment of vegetation.

*b.* Vegetation can be sprigged in the mattress.

*c.* Mattresses are relatively inexpensive although, depending on the application, labor costs required to anchor the mattresses can be high.

*d.* Properly selected and installed mattresses are less noticeable and enhance aesthetic values.

## Disadvantages

*a.* Mattresses are sometimes difficult to anchor sufficiently because the broad surface may experience large uplift forces.

*b.* If the anchoring system is damaged, the mattresses that are free to move may damage wetland vegetation and create an unsightly appearance.

*c.* No design guidance is available for proper selection of mattresses for given currents or wave conditions.

*d.* No guidance is available for sufficient anchoring techniques for given currents or wave conditions.

## Common Reasons for Failure

*a.* Materials used in the mattress degrade too rapidly. For example, some glues used to hold the mesh together may soften in a wet environment.

*b.* Anchoring systems are pulled out by wave or current-induced uplift and drag forces on the mattresses.

*c.* Anchoring systems are undermined by currents or waves.

## Design Characteristics

*Mattress Overlap.* A recommended technique for connecting horizontal edges of the mattresses is to overlap them high bank over low bank. The overlap should be at least one foot and the overlapping pieces connected together as part of the anchoring plan. If more than one length of mattress is required for a project the mattresses should be overlapped upstream to downstream. The mattresses should overlap by at least one foot and be connected as part of the anchoring system.

*Mattress Thickness.* Fiber mattresses are usually limited to 0 to 5 cm. thick. No guidance is available to determine an appropriate thickness for a mattress placed in a given current or wave climate. In general, a thicker mattress might be better as it keeps currents further away from the sediment interface and will tend to trap sediments moving in suspension or as bedload.

*Other Considerations*. Manufacturers may present the high stress that the material can withstand before it fails, but failure is usually due to things other than material failure due to stress. For example, a poorly installed mattress may be easily undermined by allowing water to flow freely beneath the mat. Depending on the velocity of water as it flows over the broad surface of the mat, uplift forces will be exerted on the mat. The anchoring system is most important under those conditions.

The durability of the product in the climate of interest is a very important consideration as well. Natural materials should be slow to biodegrade. Synthetic materials should also degrade slowly especially in the presence of sunlight. In coastal applications, the materials should be resistant to the chemical and corrosive effects of seawater.

Also to be considered are the potential effects if failure should occur. The movement and littering of mattress material about the region should not present any serious ecological, economic, social or political ramifications. For example, large sections of geotextile fabrics, nylon mesh and ropes, and other synthetic materials may be difficult or costly to locate and remove.

## Cellular Concrete Mattresses (CCM) and Block Revetments

Erosion protection from wave attack or streamflow can be provided by man-made concrete blocks often labeled CCM for cellular concrete mattress. These interlocking or cable-tied blocks form a revetment similar to a gabion mattress. Cable-tied blocks are usually placed mechanically by crane and spreader bar, whereas interlocking blocks can be mechanically or hand-placed.

Most CCM blocks vary in size, shape, and thickness to accommodate velocities up to 7 m/s and wave heights up to about 2 m. A minimum thickness is about 10 cm. up to 20 cm. for all blocks with lengths and widths averaging about 35 to 45 cm.

Common to most concrete block or concrete mattress installations are these basic requirements:

*a.* Use a filter between the natural bank and the blocks.

*b.* Ensure the slope is stable under fully saturated conditions.

*c.* Ensure drainage of the soil to relieve hydrostatic pressures.

*d.* Ensure the CCM and block revetments are properly anchored.

*e.* The use of toe protection initially placed to the maximum scour depth is recommended, or a method that can adjust as scour occurs such as loose riprap or an apron of cable-tied CCM blocks.

*f.* Beware of inexperienced contractors and poor quality control. Attention to detail is critical with CCM blocks. Many of the failures that have occurred were the result of instability at the ends, edges, and transitions to other surfaces.

### Advantages

*a.* The CCM open area of 20 to 25 percent allows colonization by vegetation.

*b.* The alternative can be cost-effective for urban streams.

*c.* CCMs are flexible and durable and can conform to minor bank settlement.

*d.* CCMs require less tonnage than riprap with a thickness roughly less than one-third that of riprap for channel flow applications.

*e.* CCMs are easily maintained and can be mowed to control vegetation if necessary.

*f.* The revetment voids and hardened substrate can provide habitat for various biota.

## Advantages of Cable-Tied or Geotextile-Bonded Blocks

Blocks held together by cables or bonded to a geotextile to form a large flexible mat can have additional advantages over other types of block protection:

*a.* They offer greater flexibility, while retaining the advantage of interconnection to restrain blocks under extreme loading conditions.

*b.* They have a reduced risk of progressive local failure under extreme loading or deformation.

*c.* They are easily placed underwater and can be used as a flexible apron to address toe scour.

*d.* They can be placed rapidly including anchoring to subsoil.

## Disadvantages

*a.* Cable-tied and geotextile-bonded systems are usually proprietary.

*b.* They can be expensive in rural areas.

*c.* They are susceptible to vandals removing blocks (non-cabled).

*d.* Presently lacking design guidance on some CCMs.

*e.* Unnatural appearance unless vegetation is allowed to hide protection.

## Common Reasons for Failure

*a.* Toe scour undermining the revetment.

*b.* Excessive settlement leads to large hydraulic forces and an irregular block surface that can expose blocks.

*c.* Inadequate treatment and attention during design and construction to edges, ends, and transitions to other surfaces.

## Design Characteristics

*Block Type*. Avoid designs where small concrete protrusions subject to breakage make up the interlocking design. Use appropriate concrete strength as opposed to construction blocks that are weak and friable.

*Safety*. Consider safety if public has access to the revetment. The submerged portion of the mattress can become slippery which may be more of a problem if the slope is too steep.

*Block Size*. Available guidance is found in the manufacturer's literature and may or may not be based on actual stability tests. Where guidance is not available for current attack applications, use a block thickness equal to one-third the riprap thickness computed from EM 1110-2-1601 (USACE 1994b).

*Mattress Placement*. Concrete mattresses come in assorted widths depending on manufacturer and placement equipment. The mattress is placed on the bank with the top edge buried behind the crest of the bank to prevent overwash overbank drainage erosion.

*Toe Scour*. The bottom of the mattress should be buried below the toe of the slope to the expected scour or, if using cable tied mattresses, should extend horizontally twice the expected scour depth beyond the toe of the bank.

*Filter Layer*. A geotextile fabric must be used behind the CCM mattress to prevent bank material from filtering through and undermining the mattress.

*Bank Slope*. In general, a CCM mattress should not be placed on a bank steeper than 1V:1.5H.

## Riprap Revetment[1]

Riprap revetments are placed on a sloping bank and depend on the stability of the underlying soil for support. Fill material beneath a revetment must be adequately compacted prior to installation of the riprap. A riprap revetment, like the other revetments, consists of two or more layers. The first layer is a filter layer (or fabric). The filter supports the armor against settlement, provides drainage of groundwater through the revetment and prevents the retained soil from being washed through the armor layer by waves, currents, or groundwater seepage. The second layer is the armor layer which contains the larger stones that protect the filter layer and the bank. The armor layer maintains its position under wave and current forces either through the weight or interlocking of the individual units. Toe protection prevents displacement of the seaward or riverward edge of the revetment. Overtopping water must be controlled to prevent erosion problems at the top and behind the revetment.

[1] Much of the information in this section is taken from USACE (1981) (Low-cost shore protection, Section 54 study)

## Advantages

*a.* Riprap is self-adjusting to small amounts of substrate consolidation or movement.

*b.* Riprap may experience minor damage and still continue to function adequately without further damage.

*c.* The rough surface of riprap dissipates local currents and minimizes wave runup more than a smooth revetment such as a concrete block revetment.

*d.* Material is readily available in many locations and can be less expensive than other structural alternatives.

*e.* Aquatic organisms can use the riprap as suitable habitat.

*f.* Riprap can be repaired easily by placement of additional stone when needed (if access to the location is reasonable).

## Disadvantages

*a.* If material is not locally and readily available and easily transported to the site, costs can be prohibitive.

*b.* Riprap may present a barrier to organisms entering and leaving the wetland.

*c.* Riprap may not be aesthetically pleasing to some people.

*d.* Riprap may pose a hazard to people with access to the revetment.

## Common Reasons for Failure

*a.* Flanking, overtopping and undermining of the revetment.

*b.* Settlement of sections of the revetment due to poorly consolidated substrate material.

*c.* Improperly designed or installed filter layer or fabric.

*d.* Undersized stone riprap displaced by large waves or currents.

## Design Characteristics

*Bank Slope*. The underlying bank slope should be well consolidated and the steepest slope allowed should be 1 vertical on 2 horizontal (1:2) for waves and 1:1.5 for streamflow..

*Filter Layer or Fabric*. If a graded stone filter is used, it may be significantly more fine-grained than the armor layer. This may require the use of an intermediate layer of stone between the armor and the filter. This layer should consist of units about 1/10 the weight of stone in the armor layer. If a filter fabric is used, this intermediate layer is also recommended because it acts as bedding, helps to distribute the armor stones' weight and protects the cloth from punctures and tearing under the weight of the armor.

*Armor Stones for Waves*. The longest dimension of individual stones should be less than three times the shortest dimension. Avoid using plate-like or cylinder-shaped stones. Stones should be angular and blocky, not rounded.

The size of stone can be estimated with the following formula from the SPM (1984):

$$W = \frac{w_r H^3}{K_D (S_r - 1)^3 \cot \Theta} \tag{5-8}$$

where:

| | | |
|---|---|---|
| W | = | weight of an individual armor stone (N) |
| H | = | wave height (m) |
| $S_r$ | = | specific gravity of the armor stone, unitless, = $w_r/w_w$ |
| cot θ | = | slope of the structure expressed as horizontal units / vertical unit |
| $K_D$ | = | stability coefficient (from Table 5-8) |
| $w_r$ | = | unit weight of the rock ($N/m^3$) |

If uniform quarrystone is used, the individual stones should range from 0.75W to 1.25W with 75 percent of the stones weighing W or more. For graded riprap, W corresponds to the minimum value of $W_{50}$, referred to as $W_{50(min)}$, and the recommended gradation is 3.6 $W_{50}$ to 0.22 $W_{50}$.

**Table 5-8**
**Stability Coefficients ($K_D$) for Stone Revetments**

| Armor Unit | $K_D$ |
|---|---|
| Quarrystone | |
| Smooth Rounded | 2.1 |
| Rough Angular | 3.5 |
| Graded Riprap | 2.2 |

*Armor Stone for Streamflow*. Guidance for riprap in streamflow applications is found in EM 1110-2-1601, "Hydraulic Design of Flood Control Channels," dated 1991 with Change 1 dated 30 June 1994. This guidance uses a procedure based on local depth-averaged velocity.

From EM 1110-2-1601 the equation for determining stone size is

$$D_{30} = S_f C_s C_v C_T d \left[ \left( \frac{\gamma_w}{\gamma_s - \gamma_w} \right)^{1/2} \frac{V}{\sqrt{K_1 g d}} \right]^{2.5} \tag{5-9}$$

where

| | | |
|---|---|---|
| $D_{30}$ | = | riprap size of which 30 percent (by weight) is finer, m |

$S_f$ = safety factor, unitless ($S_f \geq 1.1$)
$C_s$ = stability coefficient for incipient failure, unitless
$C_v$ = vertical velocity distribution coefficient, unitless
$C_T$ = blanket thickness coefficient, unitless
d = local depth of flow, m
$\gamma_w$ = unit weight of water, $N/m^3$
$\gamma_s$ = unit weight of stone, $N/m^3$
V = local depth averaged velocity, m/s
g = gravitational constant, $m/s^2$
$K_1$ = side slope correction factor, unitless

Riprap thickness for most streambank protection projects is the greater of $1.0D_{100}$(max) or $1.5D_{50}$(max) and the blanket thickness coefficient ($C_T$) can be taken as 1.0. For riprap of this thickness and having a uniformity coefficient ($D_{85}/D_{15}$) between 1.7 and 5.2, the stability coeeficient for incipient failure ($C_s$) can be estimated as:

$C_s = 0.30$ for angular rock
$C_s = 0.375$ for rounded rock

The value for the vertical velocity distribution coefficient ($C_v$) should be:

$C_v = 1.0$ for straight channels or inside of bends
$C_v = 1.25$ downstream of concrete channels
$C_v = 1.25$ at end of dikes
$C_v = 1.283 - 0.2\log(R/W)$ for outside of bends ( or 1.0 for R/W > 26)

where:
R = centerline radius of bend, m
W = water surface width at upstream end of bend, m

Recommended side slope correction factors ($K_1$) based upon slope are:

| **Slope** | 1V:1.5H | 1V:2H | 1V:3H | 1V:4H or flatter |
|---|---|---|---|---|
| **$K_1$** | 0.71 | 0.88 | 0.98 | 1.0 |

A minimum safety factor ($S_f$) of 1.1 should be used in all cases.

For bank protection $V = V_{SS}$ where $V_{SS}$ is the depth averaged velocity at 20 percent of the slope length up from the toe. For natural channels typical of wetland applications, $V_{SS}$ is determined from Figure 5-3 using average channel velocity, R, and W.

*Toe*. In the wave environment, the toe of the revetment should extend to one design wave height below the existing grade line to prevent undercutting. In lieu of deep burial, a substantial sacrificial berm or apron of additional rubble (with filtering) should be provided at the toe. See the alternative below “Windrow and Trench-fill Revetments and Toe Protection” for guidance

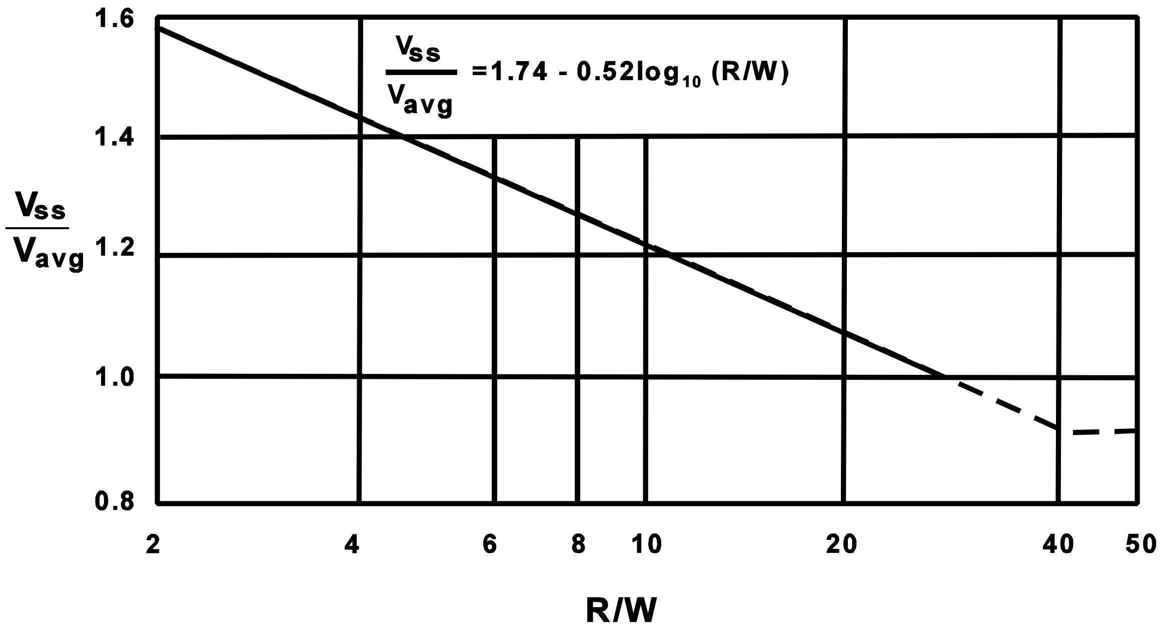


Figure 5-3. Depth averaged velocity as a function of R and W; $V_{SS}$ is the depth averaged velocity at 20 percent of slope length up from toe.

for toe design in the riverine environment. In the streamflow environment, reference USACE (1994b) for toe protection guidance.

## Dynamic Revetment[1]

A dynamic revetment consists of a larger volume of smaller stones as compared to a standard riprap revetment as described above. Because of the smaller stone size, the cross-sectional form of a dynamic revetment will be adjusted by the forces acting on it creating an equilibrium form. The larger volume of stone is required to ensure that the bank is fully protected even after the cross-sectional shape of the revetment is altered.

### Advantages

*a.* Smaller equipment is required to place the smaller stones.

*b.* Placement of stone requires less care than a standard riprap revetment.

*c.* Smaller stone may cost less than larger stones required for a standard riprap revetment.

[1] This section is based on the description and design guidance presented in Ahrens and Heimbaugh (1989)

*d.* The final cross-sectional shape is more natural looking than a typical revetment. The composition and form is similar to that of a pebble or shingle beach.

*e.* The smaller stone sizes present less of an obstruction to smaller organisms that need to enter or leave the wetland.

*f.* The smaller stone sizes present less of a hazard to foot traffic.

## Disadvantages

*a.* Smaller stones are not always less expensive than conventional riprap sizes. Without lower costs, the greater uncertainty in the performance of dynamic revetments (over conventional riprap revetments) may not be warranted.

*b.* Foot traffic and other activities may damage the equilibrium cross section obtained by the revetment. The cross section of a conventional riprap revetment is not likely to be damaged by foot traffic.

*c.* Less guidance and verification of guidance is available for dynamic revetments as opposed to conventional riprap revetments.

## Common Reasons for Failure

*a.* The stone size is too small to remain stable under the given wave conditions.

*b.* Insufficient volume of stone is placed on the bank.

*c.* The stones are not constrained from moving laterally along the shoreline.

*d.* The revetment is undermined by poor filter layer, fabric, or overwash.

## Design Considerations

*Stability*. The information presented here for determining stability should be used only for estimating the size and volume of stone required for a dynamic revetment. The references cited in this section should be consulted for a more detailed explanation for the appropriate use of the formulae provided.

Stone size can be related to wave height through the stability number given by Hudson and Davidson (1975) as

$$N_s = \frac{H_s}{D_{50}\left(\frac{w_r}{w_w} - 1\right)} \qquad (5\text{-}10)$$

where:

$N_s$ = stability number (lower value more stable), unitless
$H_s$ = significant wave height, m
$D_{50}$ = median stone diameter, m
$w_r$ = unit weight of the stone, $g/cm^3$
$w_w$ = unit weight of water , $g/cm^3$ (fresh water: 1.000 $g/cm^3$, seawater: 1.025 $g/cm^3$)

van de Meer and Pilarczyk (1986) used the stability number to classify structures and found that a dynamically stable rock slope has an $N_s$ between 6 and 20. Therefore, given a value for $H_s$ and selecting a value for $N_s$ between 6 and 20, you can determine an adequate median stone size ($D_{50}$).

Ahrens and Heimbaugh (1989) found that the most significant volume of rock affecting stability is the volume above the assumed still water line (swl). Assuming constant cross-sectional shape, the volume can be considered as the area above the swl per unit width of shoreline, A. The best parameter to use to determine the potential success or failure of the structure is

$$A' = \frac{A}{H_s L_o} \tag{5-11}$$

where:

A = area above the still water line per unit width of shoreline, $m^2$
$L_o$ = deepwater wavelength, m
$H_s$ = deepwater significant wave height, m.

All designs should have a value of A' greater than 0.1 to prevent failure.

## Gabions

Gabions are rectangular baskets or mattresses made of galvanized, and sometimes PVC-coated, steel wire in a hexagonal mesh, subdivided into approximately equal sized cells. At the jobsite, the baskets are unfolded and assembled by lacing the edges together with steel wire. The individual baskets are then wired together and filled with suitable diameter stone. The lids are finally closed and laced to the baskets, forming a large, heavy mass.

### Advantages

*a.* Smaller stone used in a gabion can offer protection equivalent to the much larger stone used in a riprap revetment. (Assumes no destruction of the wire baskets.)

*b.* Can support some vegetation.

*c.* Can be cost-effective when using locally available stone filler.

*d.* Requires less tonnage than riprap. Gabion thickness is roughly one-third that of riprap revetment.

*e.* Flexible and durable if properly maintained.

*f.* Can be stacked to obtain near-vertical side slopes where available right-of-way is limited.

*g.* The gabion baskets can be built without heavy equipment.

*h.* Gabions are flexible and can adjust to minor settlement of their substrate.

*i.* Gabions can be repaired easily by mending or replacing damaged baskets and refilling them as needed.

## Disadvantages

*a.* Wire mesh is subject to damage from strong waves, floating debris, corrosion, wear from high velocity sediments, and vandalism.

*b.* Labor intensive installation required.

*c.* Require monitoring and maintenance to identify wear before failure occurs.

## Common Reasons for Failure

*a.* Baskets are not filled completely or adequately allowing them to move, resulting in abrasion and fatigue failures of the wire.

*b.* Baskets are damaged by floating debris, wear or corrosion.

## Design Characteristics

*Wire Characteristics*. Wire is either galvanized or PVC coated for corrosive environments. See USACE (1993b) guide specifications for gabions.

*Thickness*. Expected flow velocities are required to determine the thickness of gabion structure required. Based on a smoothly graded bankline, design guidance in the Maccaferri Gabions publications (undated) suggests that gabion mattresses with thicknesses of 9, 12, and 18 inches will withstand velocities up to 10, 15 and 18 feet per second, respectively. Modular Gabion Systems guidance (undated) allows somewhat higher velocities. (Titles of undated gabion information publications are available from Maccaferri Gabions, Inc., Governor Lane Blvd, Williamsport, MD 21795: “Maccaferri Gabions; Gabions, Revet/Reno Mattress,” “Maccaferri Gabions; Maccaferri Revet Mattress,” “Maccaferri Gabions; Instructions for Assembly and Erection.”

*Placement*. The normal gabion mattress width is 2 meters and common lengths are 3 or 4 meters with interior diaphragms on 0.7- to 1.0-meter spacings along the gabion length. Special mattress sizes can be fabricated for extensive protection projects. All mattress gabion revetments are tied together side-by-side to form a continuous blanket of protection. Gabion revetments, as any successful protection, must be constructed on a stable bank with proper internal drainage.

*Bank Slope*. Mattress-type gabions should not be placed steeper than 1V:1.5H but box-type gabions can be stacked where near-vertical side slopes are required.

*Toe Scour*. Gabion mattresses are an effective method of providing toe scour protection that will adjust when scour occurs. If placed horizontally, the mattress should extend out from the toe of slope a distance equal to twice the expected scour depth.

*Filter*. Geotextile fabric should be used beneath gabions.

## Partial Bank Protection

On small to intermediate streams, most banks can be protected by a combination of structural protection on the lower bank and vegetation on the upper bank. As a general rule, the larger the stream, the greater the portion of the bank that must be protected with structures. Partial bank protection reduces the quantity of often costly structural protection and promotes vegetation in the riparian zone. An example is a willow post protection scheme that has performed satisfactorily in several applications. A minimal amount of structural protection such as riprap is placed along the toe of the eroding bank. The upper bank is graded to 1V:1H or flatter and 10- to 15-cm-diameter willow posts are augered vertically into the upper bank leaving 1.0 to 1.7 m exposed. The posts are sufficiently long to extend down into the water table to support the willow growth. The willow posts are placed along and up the eroding bank above the structural protection. While the willow and other vegetation is becoming established on the upper bank, the exposed posts provide flow resistance that reduces velocity on the upper bank. For high banks, the willow posts are often not long enough to extend to water that will support the willow, and other vegetation species are used on the higher regions of the upper bank.

### Windrow and Trench-fill Revetments and Toe Protection

Windrow and trench-fill revetments are armor methods used in the riverine environment in which the stream erosion places the riprap revetment. Initially the riprap is placed behind the eroding streambank along the desired alignment in a trench at top of bank for windrow revetments and at mid to lower bank for trench-fill revetments. As the stream erodes back to the rock-filled trench, the rock falls or launches down the eroded slope and armors the bank. One of the primary requirements for successful stone launching is that the eroding streambank material must be relatively noncohesive so that the bank fails in a uniform manner. Cohesive banks fail in blocks and the rock-launching process becomes uneven and uncertain. Design guidance for windrow and trench-fill revetments can be found in USACE (1994b) and Maynord (1995).

Riprap is the most common method for providing toe protection in the riverine environment. The riprap is either placed down to the elevation of the maximum scour or, similar to windrow and trenchfill revetments, placed in a section of riprap called a weighted toe to launch down as toe scour occurs. The weighted toe method is particularly useful in protection constructed underwater. Volume of stone in the weighted toe is more important than the shape of the before-launch section.

**Advantage**

*a.* Eliminates underwater excavation.

**Disadvantages**

*a.* Requires greater stone volume due to uncertainty in the launch process.

*b.* Requires noncohesive bank to properly function.

## Mild Offshore Slopes

In wave-dominated climates, a mild bottom slope (especially, when vegetated) is less likely to develop a serious erosion problem. A mild offshore slope helps to dissipate wave energy before it reaches the edge of the wetland. If the slope is vegetated additional energy losses occur. The slope must be made of material that can sufficiently resist breaking, propagating waves. If the wave climate is mild enough so that sand can be used, it will form reasonably submerged and subaerial stable bars and berms which help stabilize the sediment and dissipate wave energy.

A preliminary result of a test along the Gulf Intercoastal Waterway (GIWW), showed that a 1:15 slope fared better than a 1:10 slope for a dike exposed to boat wakes. After 2 years, the 1:10 slope shows an erosional scarp while the 1:15 slope does not. This result is not conclusive, however, as conditions offshore of the slopes have not been evaluated to determine whether they influenced wave conditions incident to the slopes.

## Sand

In some wave-dominated projects where wave heights are small, if a sufficient amount of sand can be placed offshore of the wetland, it can act to cause waves to break and dissipate their energy before reaching the wetland. This is similar to the idea of developing very mild offshore slopes as mentioned above. If the sand is contained within the project area (bounded laterally by land or structures), then it may shift around within the region due to wave action and eventually form an efficient energy dissipation zone. A low "backwall" and lateral boundaries are present to keep the sand from moving out of the system. While no guidance or examples are available, it is worth considering that sand is used for shore protection on the open coasts which are exposed to the full fury of storms. Sand is a good energy absorber. If the wave climate and water levels are too great, however, sand may be pushed into the wetland area being developed, destroying the new or existing vegetation. A "back wall" is needed.

## Sill

Sills are offshore structures with the crest usually submerged. The sill is designed to retain sediment and prevent it from migrating offshore. Design of a low-permeability structure is, therefore, important. A sill is often used in conjunction with other shoreward structures.

## Berm

Submerged linear mounds of sediment may be placed offshore from the project site. The purpose of the berms is to reduce wave energy incident to the site by causing waves to break as they pass over the berms. No design guidance is available for constructing berms in very shallow waters near a wetland creation or restoration project. No guidance is available to determine the amount of wave energy reduction that will occur.

The berms will generally erode due to sediment transport by tidal-, wind-, and wave-induced currents. The rate of erosion and the resulting change in the berm shape is also unknown. The coarser the sediments used in the berm the more stable the feature will be. The advantages of using berms as part of the shore protection for a project are that they add interesting features and variations to local bathymetry, they afford (at least temporarily) some protection against wave energy, they add sediment to the local sediment transport system, and they provide a useful means of using otherwise excess sediment from a restoration or creation project. The disadvantages occur when the advantages do not apply. That is, berms are a disadvantage when they do not add useful variations to the local bathymetry but rather cover existing bathymetry, when they add too much sediment to the sediment transport system, and when they require significant effort to construct but do not survive long enough to provide much protection against incident waves. Berms should be used in conjunction with other alternatives for bank protection.

## Stable Tidal Channel Design

Tidal wetlands must have a channel network that will provide the proper quantity of tidal water to achieve project goals of water quality and tidal circulation. While a channel network will form on its own in a created/restored wetland, initial sculpting of the wetland will cause channels to form in desirable locations that will meet project goals. The planform, channel cross section, and slope are determined by tidal characteristics, marsh sediment size, suspended sediment input, and biotic parameters such as the increase in stability that results from vegetation and the decrease in stability that results from burrowing animals. Because of the complex interactions of these variables, tidal channel dimensions are difficult to determine from first principles. Consequently, empirical methods are the best available method for small to medium tidal channel design in wetland restoration or establishment projects. The general form of these empirical relations are:

$$\text{Channel Width, Depth, or Area} = f(\text{tidal prism}) \qquad (5\text{-}12)$$

This relation is similar to regime theory for upland channel design that is a function of discharge rather than tidal prism. Coats et al. (1995) provides empirical data and relationships applicable to California marshes and outlines a procedure to apply results to other areas.

# Section 5
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**Wetlands Research Program**

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# Wetlands Engineering Handbook

## Section 6

## Wetland Ecosystems and Vegetation Establishment

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# 6-1 Introduction to Vegetation Establishment Considerations[1]

## Decision Sequence for Establishing Wetland Vegetation

Wetland restoration and establishment project development and implementation encompasses many disciplines such as hydrologic engineering, geotechnical engineering, plant specialists, and others. Plant establishment, however, integrates many aspects of the project. Not only do the conditions need to be created to support growth of desired plant species, but also the conditions need to be in place at the appropriate season for planting as well as within project management time constraints. The process of wetland vegetation establishment plan development can become very complicated if it is not approached systematically.

There is a logical sequence of decisions that must be made to effectively plan for wetland vegetation establishment (Figure 6-1). Once the project goals, design criteria, and site assessment have been completed, the site hydrology and soils can be investigated or planned. Vegetation establishment considerations should then be reviewed in light of the anticipated soils and hydrology. In some cases, the targeted vegetation will have to be altered because the anticipated hydrology or soil may not be compatible with that goal. The need for erosion control plantings or seedings should be assessed. Planting decisions should be made by a plant specialist coordinating with the site hydrologist, soil scientist and/or geotechnical engineer.

The first consideration for wetland vegetation establishment is to determine during the site assessment (see Chapter 2-5) whether the site will naturally colonize with desirable species or planting will be required. For natural colonization to be viable, there must be sources of seeds or vegetative propagules nearby that have access to the site (Anderson and Brown 1991; Reinartz and Warne 1993). Seeds can be blown by the wind, carried by water, or transported by man or animals (Brown et al. 1992). Wind dispersed species are likely to quickly colonize a site. However, it must be recognized that many of the more obnoxious weeds are wind dispersed. With heavier seeds, colonization may be slow, especially if the site is isolated. Fluvial sites with nearby donor wetlands will be quickly colonized via water transport. Plant fragments of some aquatic species may be adequate to colonize a site. If the natural soils are left in place in a restoration project, there may be an adequate seedbank and residual plants to recolonize a degraded site when conditions are improved. Since there is little effort involved, natural colonization is the least expensive method to establish vegetation. Successful natural

[1] By Mary M. Davis

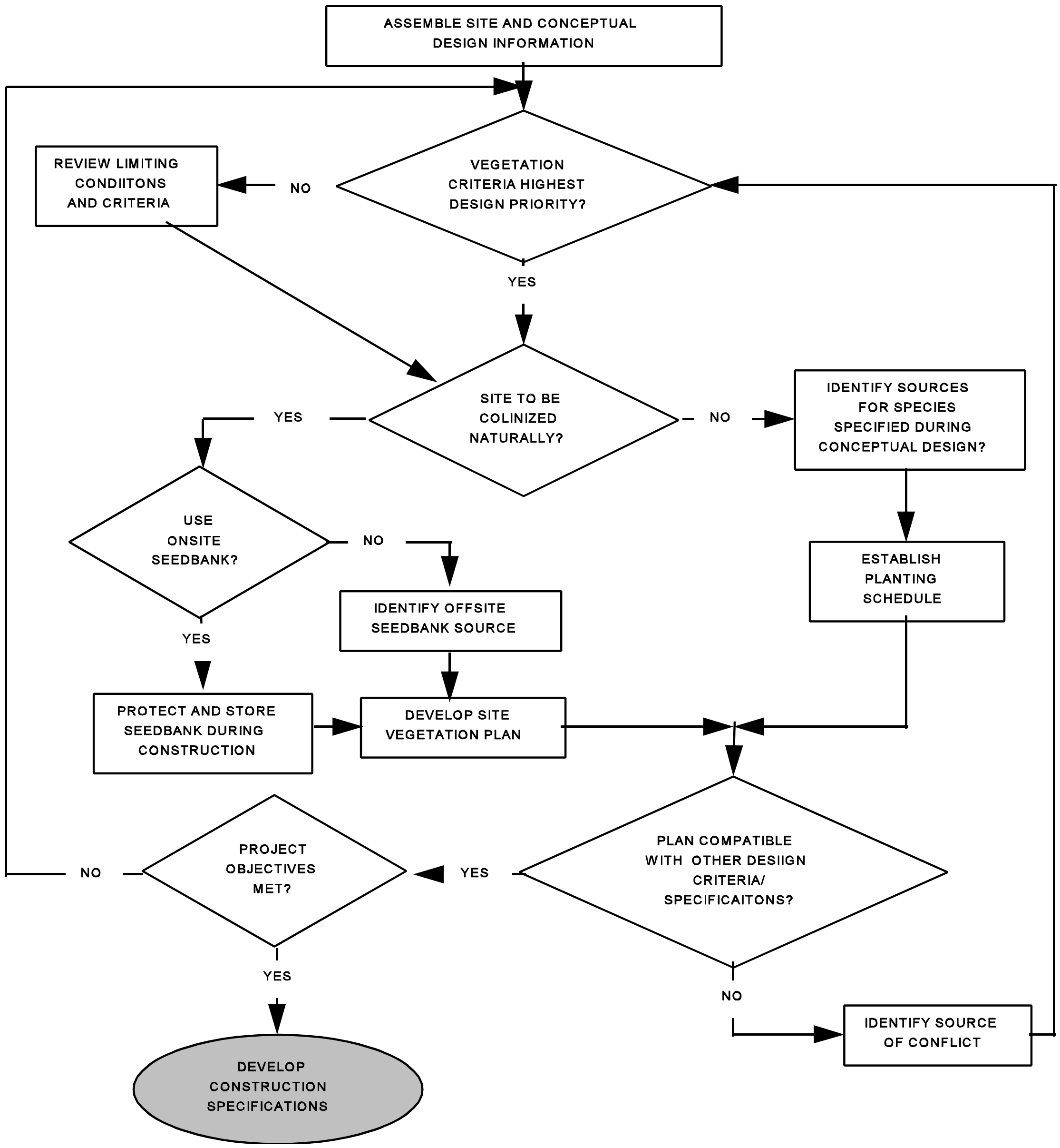


Figure 6-1. Decision sequence for planning wetland vegetation restoration.

establishment of desirable species, however, depends on many factors specific to the site and seeds (van der Valk 1987; Allen and Kennedy 1989), and consequently, is the most unreliable.

If planting will be necessary to establish the desired community or to accelerate the development of plant cover, species must be selected that will meet project objectives and be competitive under the site conditions. The plants must be available in adequate supply and in good condition during the planting time window. Plant material acquisition can be made through a commercial nursery, contract grown, or collected from natural populations. There are trade-offs in cost, labor, and quality of plant material in choosing among the plant material sources. Site preparations must be made prior to arrival of the plant material onsite to minimize the time plants are out of the ground. Timing is equally important if plants are established by seeding. Once acquired, plants must be installed in the proper location using methods appropriate for the type of material used. Maintenance of plants through control of nuisance species, erosion, and water level in managed systems can be crucial to the survival and growth of the vegetation.

The body of the wetland vegetation establishment plan consists of a project description. This may be in a variety of forms, such as maps, figures, and tables. With creation, it should include information regarding the ground surface elevations, water levels, soil strata, and planting areas. Some of this information may not be necessary for restoration. Species of plants to be used, placement, and planting techniques should be specified. Scheduling of plan implementation should take into account seasonality of plant growth and water levels.

A monitoring program is an integral part of a successful vegetation establishment plan. Once a plan is implemented there are no guarantees that the project will be successful. Differences between actual project construction and plan design can lead to poor plant survival and growth. For example, if the site was evaluated during wet or dry years, water levels may not reach designed levels, leaving plants too dry or too wet. A monitoring program that periodically and systematically evaluates the health of the plantings, either quantitatively or qualitatively, aids in the detection of problems and in the development of mid-course corrections, and in identifying "mistakes" to be avoided in future projects.

The following chapters in this section and Section 7 discuss species selection (Chapter 6-4), plant acquisition (Chapter 6-5), planting methods (Chapter 7-3), planting schedule (Chapter 7-4), site preparation and maintenance (Chapter 7-5), and costs for revegetation (Chapter 6-6).

# 6-2 Wetland Vegetation Establishment Considerations[1]

## Characteristics of Wetland Vegetation

Besides being the primary biomass producers, wetland plants are critical components of the wetland ecosystem because they provide cover for breeding, refuge from predators, and resting sites for aquatic (Poe et al. 1986, Rozas and Odum 1987) and many wildlife species (Roth 1976). In addition, wetland plants contribute to other desirable wetland functions that have considerable value for society (Table 6-1), such as sediment management (Lowrance et al. 1984) and nutrient removal (Kitchens et al. 1975, Tilton and Kadlec 1979, Hammer 1992). Recreational and landscape aesthetic values are improved by the successful management of wetland vegetation.

Wetland plants are commonly referred to as hydrophytes — “any plant growing in water or on a substrate that is periodically deficient in oxygen as a result of excessive water content” (Cowardin et al. 1979). Except for the strictly aquatic species, hydrophytes are tolerant of a wide range of alternating inundated and drained conditions (Tiner 1991, Bedinger 1978). These plants must be able to maintain themselves under anaerobic conditions (Hook and Scholtens 1978, Barclay and Crawford 1982) and regenerate in spite of periodic inundation or saturation (Fredrickson and Taylor 1982, Huenneke and Sharitz 1986).

Flooding has three basic detrimental effects on plants: (1) oxygen diffusion to the root zone is restricted; (2) toxic by-products of respiration accumulate in the root zone; and (3) nutrient availability in soils is altered (Mitsch and Gosselink 1986). Wetland plants have anatomical, morphological, and physiological adaptations that enable them to survive the stressful conditions imposed by inundation (Hook and Scholtens 1978, Kozlowski 1984). Wetland plant adaptations generally involve

- increasing oxygen transport to roots (e.g., hypertrophied lenticels, swollen buttresses, aerenchyma)

- physiological mechanisms for tolerating anaerobic respiration (e.g., production of less toxic end products such as malic acid) (McKee and Kelvin 1993)

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[1] By Mary M. Davis and Lisa C. Gandy

**Table 6-1**
**Mechanisms by Which Vegetation Contributes to Wetland Functional Capacity**

| WETLAND FUNCTION | MECHANISMS |
|---|---|
| Sediment Stabilization | Diffuse energy impinging on shorelines and soil surface<br>Anchor soil in root mass |
| Sediment/Toxicant Retention | Increase sedimentation rates by providing resistance to current and wave energies<br>Bury sediments and toxins under accumulated organic matter<br>Reduce metal solubility through chelation with organic matter |
| Nutrient Removal/ Transformation | Reduce metal solubilities in oxidized root zone<br>Provide colonization substrate for microfauna<br>Provide organic matter for decomposition<br>Uptake and retention |
| Carbon Production Export | Produce organic matter |
| Aquatic and Wildlife Diversity/Abundance | Provides structure for refuge, nesting, and colonization<br>Provides plant matter for herbivores<br>Provides organic matter for decomposers |
| Recreation | Improves aesthetics<br>Improves aquatic and wildlife habitat quality<br>Improves water quality |
| Uniqueness/Heritage | Provides basis of ecosystem dynamics not found elsewhere<br>Provides peat as an energy source<br>Rice is a food staple for the majority of the world's population |

For example, root systems of most woody plants that have developed under saturated conditions are succulent and poorly branched (Hook and Scholtens 1978). As a result of low oxygen conditions, the roots and stems of many different types of wetland plants develop aerenchyma (air spaces ) either through cellular breakdown or separation. A honeycomb-like structure results with thin cellular partitions between the pockets of aerenchyma. The thickness of the partitions does not limit gas diffusion, and oxygen is able to diffuse from the aerial segment of the plant to the roots. Aerobic respiration in the roots continues, and the plant avoids low energy supplies and toxic end products of anaerobic respiration. In addition, oxygen from the aerated roots diffuses from the roots into the soil atmosphere. This benefits the plants by oxidizing reduced compounds such as ferrous and manganous ions, which are abundant in flooded soils and are toxic to roots (Kozlowski 1984).

Plants in a functioning ecosystem must be able to regenerate. In many wetland systems, wetland plants regenerate by seed during periods of exposure long enough to allow germination and establishment of the seedling (van der Valk and Davis 1978, Huenneke and Sharitz 1986). In others, exposure and subsequent re-wetting of the seed will key dormancy release. A wet-cold period may also be part of dormancy release. Continued survival and growth of the seedling depends on the ability to tolerate total submergence or for the plant to grow tall enough for leaves to extend above the water surface (Weisner *et al.* 1993). Putnam (1952) demonstrated that dormant tree seedlings were generally more tolerant of submergence than actively growing seedlings.

# Primary Limiting Conditions for Establishment of Wetland Vegetation

Development of wetland vegetation communities involves processes and mechanisms that interact with and can be limited by many physical, chemical, and biological factors (Figure 6-2). The result of these limitations is that each plant species is capable of growing under a characteristic range of environmental conditions that the species can tolerate. Successful establishment of plants in wetland restoration and establishment projects depends on an understanding of whether site conditions are within the species tolerance range and how target species will interact with project site conditions and with each other. Not only must the plants be tolerant of the anticipated environmental conditions, they must be competitive under those conditions and within the species mix. The following are important considerations for establishing vegetation in wetland restoration and establishment projects.

## Water

Three general aspects of the hydrological conditions and hydraulics of a wetland site affect the type and success of vegetation establishment. Hydrologic regime, water quality, and wave and current energies are all important determinants of wetland plant distributions.

### Hydrologic Regime

The depth, duration, timing, and flow of water primarily determine the availability of oxygen and the consequent biogeochemical processes described above. The longer and deeper an area is inundated, the longer and more intensely the site is likely to be anaerobic (Hook and Scholtens 1978). Plant productivity rates in wetlands with flowing water are generally greater than in stagnant water primarily because of increased oxygen exchange across the surface of moving water (Mitsch and Ewel 1979). Moreover, inundation during the growing season when oxygen demand is greatest further limits the establishment and growth of emergent and woody plants.

Natural hydrologic regimes vary widely with region of the country and hydrogeomorphic setting of wetlands. Short- and long-term variations in water levels determine the period of exposure of wetland soils. This has a direct effect on all aspects of plant community development (Figure 6-2), including seed banks, vegetative propagules, germination and establishment of plants, competition for limiting resources, growth, and reproduction. Acknowledgment that the hydrologic regime will vary is critical because of the large influence this variation will have in the development of wetland plant communities.

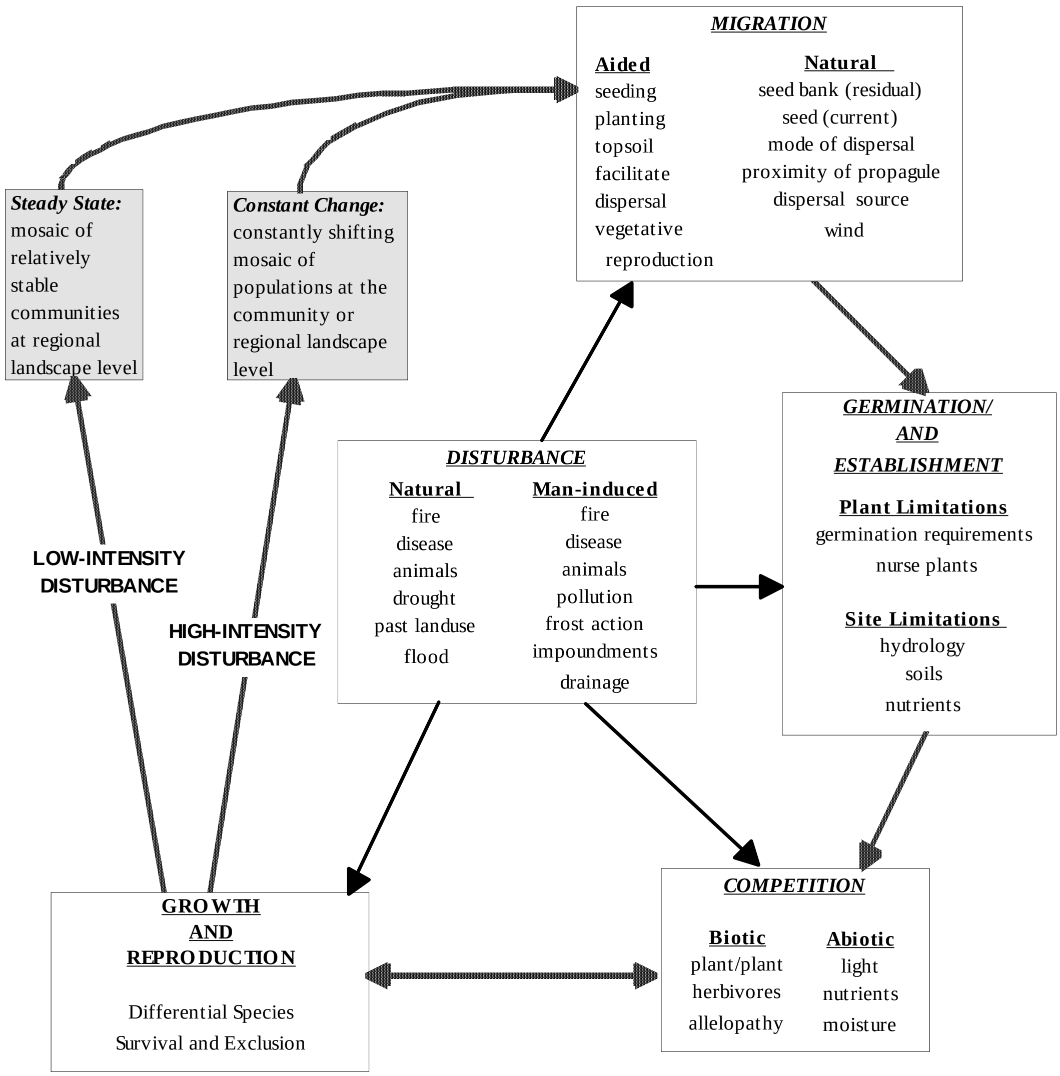



Figure 6-2. Processes, mechanisms, and interactions affecting wetland vegetation. Vegetation tends to evolve in a cyclic pattern where plant community development goes through processes towards a natural state of population and community dynamics. That dynamic may be characterized by constant change or a relatively steady state. Natural and man-induced disturbances, however, can alter the development process at many points in the cycle (after Niering 1987).

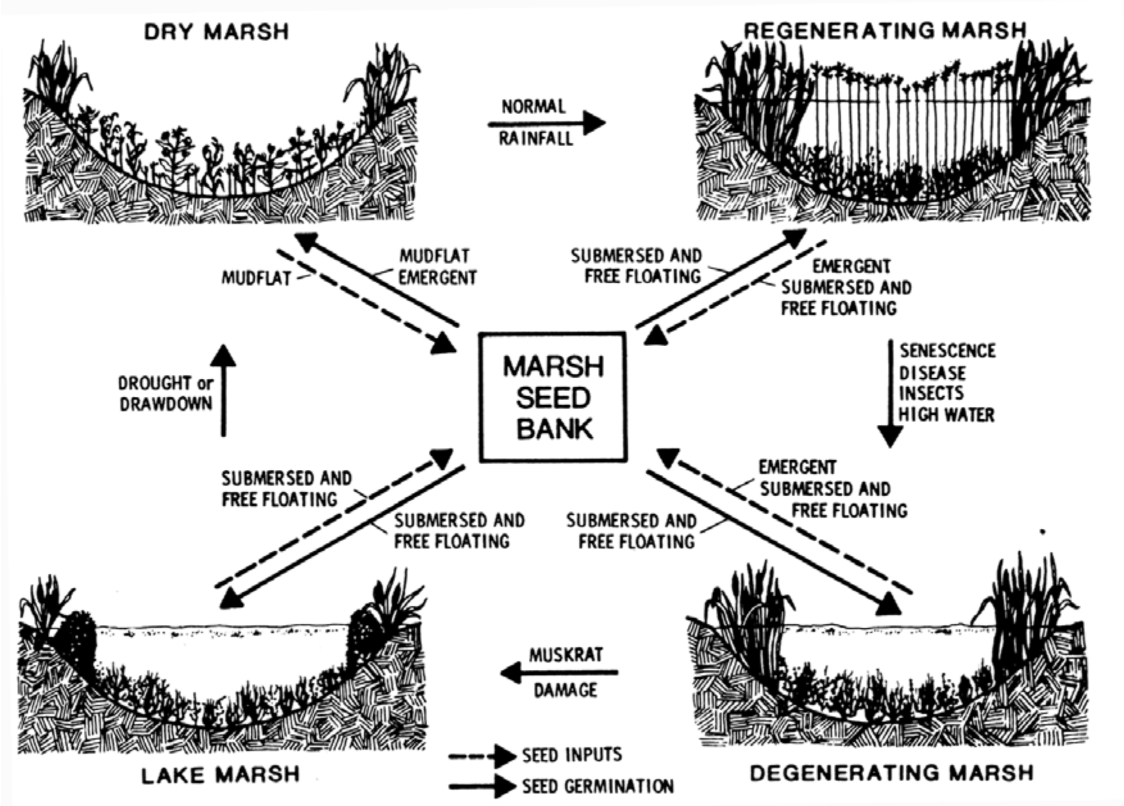


Figure 6-3. The importance of seed banks in prairie marshes as illustrated by van der Valk and Davis (1978).

In flooded emergent wetlands, fluctuations in water level are necessary to maintain wetland seed bank and floristic diversity. van der Valk (1981) describes the presence or absence of standing water as an environmental sieve that determines the recruitment or extirpation of species in wetland seed banks. The importance of seed banks in wetland community dynamics has been illustrated by van der Valk and Davis (1978) for prairie marshes (Figure 6-3). During droughts, water levels drop so that mud flat annuals (annual species with long-lived seeds) and perennial emergent species are recruited to the seed bank. With normal rainfall, deep standing water eliminates mud flat species, stops germination of emergent species, and triggers germination of submersed and floating species. If periods of high water continue or the water deepens further, intolerant emergent species decline. The degenerating marsh and lake marsh have abundant submersed and free-floating plants. Intense herbivory pressure will cause the development of a lake marsh. At each stage the seed bank contributes to the vegetation and, in turn, the vegetation contributes to renewal of the seed bank. Thus, in prairie marshes, at least in sites where drawdowns occur, the seed bank contains elements of each stage of the vegetative cycle. As drawdown duration and frequency increase, the chance for interactions with other plants increase as species richness and abundance increase (Leck 1989). As the potential for interactions increase, the similarities between the seed bank and standing vegetation decrease as well as the predictability of successful recruitment.

Complexities in relationships between species composition in the seed bank and standing vegetation increase with drawdown duration and frequency. In contrast to prairie marshes, the seed bank of a freshwater tidal wetland does not contain seeds of different successional stages.

The seed banks in these types of wetlands resemble the surface vegetation. This type of wetland is inundated daily and is not affected by drought; although changes in water level would direct vegetation change, such changes would not be cyclic. The importance of a species in freshwater tidal wetlands fluctuates in both the seed bank and in the vegetation over time (Leck and Simpson 1987, Leck 1989).

Seed banks have little influence on wetland plant community dynamics in permanently inundated areas and mature forested systems. Even in these areas, herbaceous species dominate wetland seed banks. Grasses and grasslike species usually comprise more than 50 percent of the seed bank, while woody species are not common even in swamps (Leck 1989). Lack of woody species may be related to high predation and decomposition rates, to delayed and variable reproduction rates (Harper 1977), or perhaps to a lack of dependancy on long-lived seeds by long-lived species (Leck 1989). Davis (1990) showed that the regeneration processes of many wetland tree species are dominated by vegetative regeneration, particularly under continuously inundated conditions. In wetlands with deep or stable water levels, seed banks may play little or no role in the recruitment of emergents (van der Valk and Pederson 1989, Wilson *et al.* 1993).

The success of seedling establishment is related to the timing, duration, and the depth of flooding. For example, studies in forested wetlands have shown that water oak (*Quercus nigra*) seedlings and saplings would not become established in areas where flooding was frequent and persisted for five (5) or more days. Seedlings of sycamore (*Platanus occidentalis*), red maple (*Acer rubrum*), shumard oak (*Q. shumardii*), sweetgum (*Liquidambar styraciflua*), hackberry (*Celtis occidentalis*), and cherry-bark oak (*Q. falcata* var. *pagodaefolia*) die if subjected to more than 20 days of complete submersion (Whitlow and Harris 1979). In comparison, if these same species are subject to water level depths up to the root collar, survival is significantly higher and reaches almost 100 percent. Survival of other species such as buttonbush (*Cephalanthus occidentalis*) and black willow (*Salix nigra*) during flood conditions was dependent on whether they were completely or partially submerged (Whitlow and Harris 1979). Permanent standing water (inundation, ponding) without seasonal drawdown inhibits the establishment of vegetation on a wetland project site. Sites where water is ponded year round may require some initial hydrological manipulation to allow vegetation to become established at the site (Southern Tier Consulting 1987).

Tolerance of seedlings to inundation is size related. Seeds that are exposed and germinate early in the growing season produce relatively larger seedlings than those that germinate after exposure in the late growing season. Weisner and Ekstam (1993) showed that the rate of emergence, height, survival, and reproduction of *Phragmites australis* was directly related to the size of the seedlings when submerged the previous spring. Similar results were found for alkali bulrush (*Scirpus maritimus*) and hardstem bulrush (*S. lacustris*) in moist-soil management experiments (Merendino and Smith 1991). Season of inundation, therefore, affects survival of inundated plants by limiting the effective length of the growing season.

Flood-tolerance of many established wetland tree species is also size related. Hall and Smith (1955) showed in an impounded lake in Tennessee that, with the exception of willow, the flood-duration tolerance of trees greater than 1 cm. in diameter at breast height was greater than the seedlings of most species. Harms *et al.* (1980) monitored mortality of floodplain forest trees in Florida that were permanently inundated up to about 1 m depth following impoundment of the

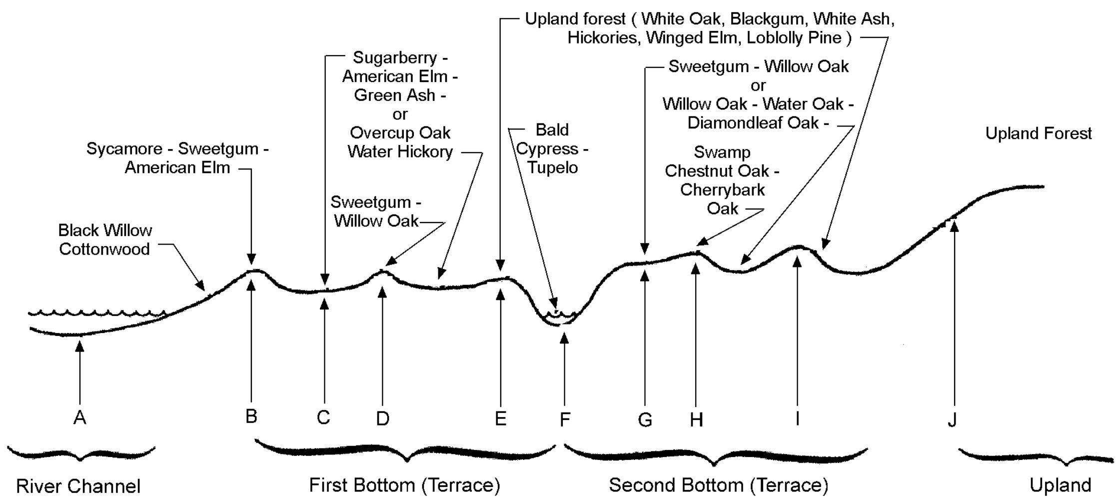
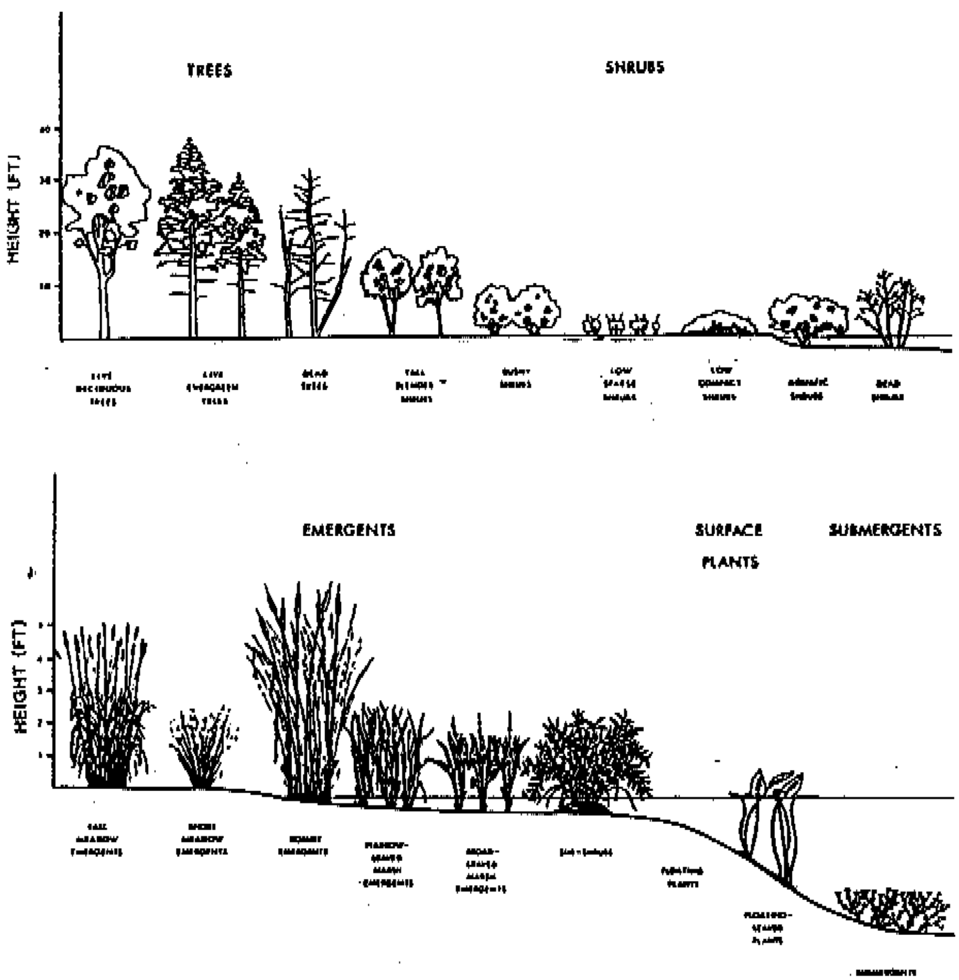



Figure 6-4. Example characteristic zones of wetland plants forming bands or concentric rings (from *Fine Gardening*, No. 20, July-August 1991).

river. Mortality of all tree species increased with depth of inundation, but mortality of smaller trees was greater than large trees for some species. For example, small trees (2 cm DBH) of Carolina ash (*Fraxinus caroliniana*) and swamp tupelo (*Nyssa sylvatica* var. *biflora*) had higher mortality rates than large trees (40 cm DBH). Mortality of red maple (*Acer rubrum*) and bald cypress (*Taxodium distichum*) following inundation, however, was not size related.

Despite the constraints on plant growth and survival, wetlands are among the most productive ecosystems in the world, as productive as estuaries and algal beds (Whittack and Likens 1973). Productivity is closely tied with the hydrologic regime. Of forested wetlands, flowing water swamps have greater net biomass production than either sluggish flow or stillwater swamps (Mitsch and Gosselink 1986). Riverine swamps with intermittent exposure and flowing water are most productive because of good root aeration during periods of exposure, elimination of flood-intolerant species by inundation, and continual supply of nutrients (Mitsch and Ewel 1979).

As a consequence of the limitations on vegetation development, hydrologic regime is a primary factor in determining the distribution of wetland plant species. This is a commonly observed phenomenon in marshes (Squires and van der Valk 1992) and lake fringe wetlands (Weisner 1991) where characteristic zones of plants change with depth of inundation, forming bands or concentric rings (Figure 6-4). Floodplain forests have mosaics of communities that are distributed along elevation gradients that correspond with duration and frequency of inundation (Figure 6-5) (Bedinger 1978, Fredrickson 1978).




**Subforms of vegetation used to classify wetlands of glaciated northeastern United States.** *(From Golet and Larson, 1974, p. 5)*

Figure 6-5. Floodplain forest communities distributed along elevation gradients that correspond with duration and frequency of inundation.

## Water Quality

Water quality (e.g., nutrient concentrations, pH, salinity, turbidity, hardness, heavy metals, and other toxic constituents) influences the type of plant species that can survive within a wetland and hence the establishment of vegetation at a wetland project site. The water quality will be reflected in the soils. Salinity and pH are probably the two most important water quality parameters relative to emergent wetland plant species distributions. Salinity, which is the concentration of total soluble salts in the water column, determines the osmotic gradient that the plant must tolerate. Halophytes are plants tolerant of saline conditions and are commonly found in salt marshes, estuaries, and other saline environments. Plants typically found in freshwater marshes, however, are very susceptible to exposure to saline water. Increased cypress and palm tree mortality along the Gulf Coast, for example, has been attributed to exposure to salt water intrusions (Conner and Askew 1992 and Williams[1]) that probably results from a combination of land subsidence, sea level rise, and drought. The pH affects the availability of both plant nutrients (Figure 6-6) and toxins. Extreme pH levels damage plant membranes, which becomes a major limiting factor in restoration with acidic runoff from coal mines. Although many wetland plant species have wide pH tolerance ranges, characteristic associations of plant species differ between acidic wetlands, such as cypress domes and bogs, and less acidic wetlands.

Submerged aquatic vegetation is sensitive to several water quality parameters. The distributions of many submerged aquatic macrophytes are related to turbidity, total alkalinity, pH, dissolved organic matter, total nitrates and nitrites, and phosphorus (Pip 1979, 1988). Turbidity is a measure of the total suspended solids, dissolved matter, and color within the water column and is a very important factor in freshwater systems. In these systems, the transmission of light is decreased by turbidity which in turn decreases photosynthesis and survival of plants at deeper water depths. In addition, suspended solids that settle on submerged plant surfaces block light and gas exchange for photosynthesis (Korschegen and Green 1988). Turbidity values are likely to increase during the first few years following wetland creation as the amount of suspended organics in the water column increases. Concentrations of toxic constituents, such as metals, herbicides, pesticides, and organics, at concentrations above certain threshold levels can affect physiological processes in seeds, seed viability, and germination.

## Energy

The physical action of currents and waves may preclude seedlings from becoming rooted in wetlands being restored within exposed coastal, riparian, and fringe areas. Even though the seed may be viable, seedlings cannot become established under energy conditions sufficient to move seeds and soils. Movement of seeds as they are germinating prevents roots from reaching and penetrating soils. Rates of successful seed germination and survival are reduced when deposition of sediments buries seeds and erosion washes seeds away. Currents, however, can be an important mechanism of seed dispersal in wetlands. If shoreline topography and water levels are appropriate, seeds brought by currents to a wetland can naturally colonize the site (Wein et al. 1994).

Currents and waves damage established submergent and emergent plant species and can erode soils away from plant roots. The plants are stressed by loss of leaves and stem breakage,

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[1] Personal Communication. Kimberly Williams, University of Florida.

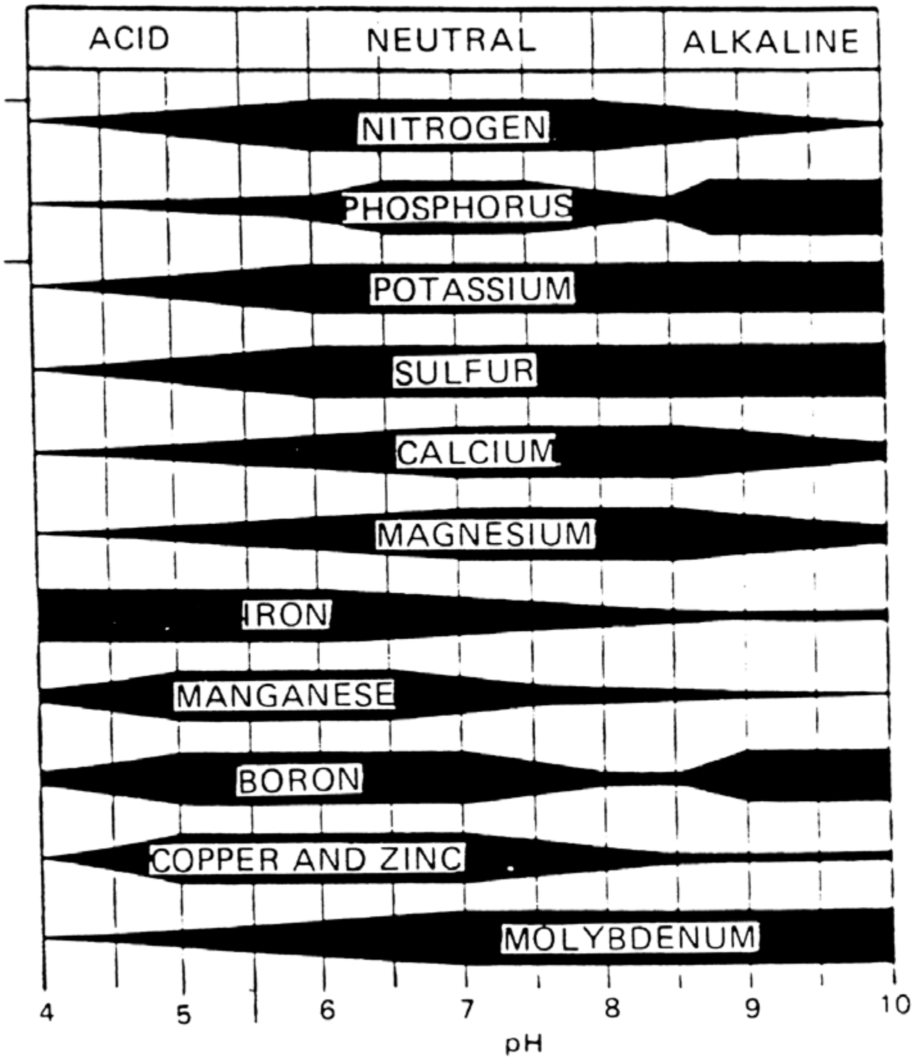


Figure 6-6. Effect of water pH on the availability of nutrients to plants.

and recovery of healthy plants is limited by continued exposure to high energy. Floating leaved species are particularly vulnerable, because they are often carried by waves and currents and can only become established in calm and sheltered environments (Kadlec and Wentz 1974). The scouring action of high flows and currents in riverine systems can displace and remove well established vegetation. Moving ice grinds, plows through, or overruns any vegetation in its path (Kadlec and Wentz 1974). With coastal shoreline restoration, the fetch distance and the shoreline geometry are among the most important factors in determining whether the site will be stable in the expected wave energies. Guidelines for determining the feasibility of utilizing salt marsh plantings of *Spartina alterniflora* in shoreline stabilization can be found in Knutson and Innskeep (1982), Knutson and Woodhouse (1983) and Sharp et al. (undated).

## Substrate

Wetland substrates provide moisture and nutrients for vegetation as well as structural support to anchor the plants in place. Overall substrate characteristics such as texture, structure, density, compaction, fertility, salinity, pH, and permeability influence vegetation establishment by influencing rooting volume and water and nutrient availability. Appropriate substrate conditions are a critical precondition for successful vegetation establishment at a site. A discussion of substrate characteristics that impact vegetation establishment is provided in the following sections and in Section 4.

### Compacted Soils and Soil Pans

Excessively hard substrates are thought to be one of the chief causes of failure of establishment of natural or planted marsh and aquatic vegetation (Kadlec and Wentz 1974). Compacted soils or the presence of hardened soil pans:

1. inhibit or limit root penetration
2. inhibit the exchange of gases into the atmosphere produced by root respiration
3. inhibit fresh oxygen from entering the soil
4. slow infiltration of water into the soil
5. allow surface erosion to increase

Notable reductions in vegetative growth will occur as a result of reduced rooting volume in compacted soils (Environmental Laboratory 1986). Reduced infiltration rates through plow pans in old agricultural fields of the Mississippi Delta result in long periods of standing water. Mortality rates are high for tree seedlings planted in these fields, particularly when high water temperatures exacerbate the stress caused by standing water.[1]

### Soil Fertility

Fertility is the ability of a soil to supply the nutrients essential to plant growth and directly affects plant growth and establishment at any site. Soil fertility is related to texture, pH, organic matter content, and past land use. For example, sandy soils in general have lower fertility status than finer textured soils that have weatherable minerals (Environmental Laboratory 1986). Organic matter has a high cation exchange capacity (CEC) that effectively binds and retains many plant nutrients such as phosphorus that would otherwise be lost from the system. In addition, organic matter contributes to increased friability and nutrient availability as it decays over time. Soils containing toxins or contaminants from past land use will limit vegetation establishment on a site if the concentrations of the available constituent is above a threshold level that causes a toxic response. Toxic chemicals may include fertilizers, pesticides, and heavy metals.

Infertile soils such as the subsoils exposed during grading for wetland restoration and establishment projects may initially support plant establishment and growth when fertilized, but the effects may not last if the soil does not retain the nutrients. Plants may grow until fertilizer

[1] Personal Communication. R. Haynes, U.S. Fish and Wildlife Service.

effects are lost and then languish or die. In such cases, soil treatments such as application of topsoil can enhance revegetation success and promote establishment of a persistent vegetative cover (Claassen and Zasoski 1993, but see Garbisch 1986). Reapplication of topsoil to subsurface materials enhances the re-establishment of vegetation by increasing nutrient availability, water-holding capacity, and microbial activity (Hargis and Redente 1984).

In contrast, soils of too high fertility can adversely affect the plant species composition of a target community in wetland restoration and establishment projects. There is an inverse relationship between fertility and species richness; more fertile sites support fewer species (Grime 1979, Grubb 1977). The mechanism seems to be that some plant species are capable of utilizing excess nutrients, primarily nitrogen, and thereby increase growth rates. Most native species, however, are adapted to low nutrient conditions and are less capable of responding to fertilization. In a restoration or establishment project, plants representative of relatively low nutrient wetlands that are placed in high nutrient soils do not all respond equally and grow bigger faster. The species capable of responding to fertilization, often considered weeds or undesirable species, grow faster than the other species. Available space and soil water, which now become limiting resources, are completely utilized by the faster growing species, and the smaller, slow-growing species are out-competed. What was intended to become a species rich and diverse community because of seeding and planting efforts becomes dominated by a few species, which are usually grasses. The project objectives are not met. This has been a problem during attempts to establish and maintain many semi-natural plant communities on agricultural lands with excessive fertilizer residues.

## Soil Salinity

Soluble salts often present a problem in vegetation establishment, growth, and survival in arid western regions (Environmental Laboratory 1986) and are a critical factor in coastal and estuarine systems. High rates of evaporation can increase soil salinity in arid regions due to previous practices such as fertilization and pesticide application. Accumulated salts may limit vegetation establishment on a site at least temporarily until the salt is leached from the soil or may restrict vegetation establishment to salt-tolerant species such as saltgrass, alkali cordgrass, prairie cordgrass, and *Atriplex* (Environmental Laboratory 1986). Neill (1993) found that spring flooding or irrigation reduced soil salinity in northern prairie marshes and resulted in increased plant productivity in comparison with nonflooded marshes. His results suggested two mechanisms by which spring flooding controlled soil salinity. Flooding decreased soil salinity during the spring and buffered surface soils against large increases of soil salinity after mid-summer water levels declined. Soluble salts should also be monitored in projects that have the potential for exposure of acid-producing soils. The presence, but not the identity of these acids, will be detected as part of standard agricultural testing for soluble salts.

## Soil pH

The ratio of acidity to alkalinity in the soil is expressed as soil pH. Soil pH is a key factor in the availability of many mineral elements to plants (Figure 6-6). While a neutral pH is optimum for the major plant nutrients, several of the minor nutrients are more available at a lower pH. Generally, a slightly acidic or neutral soil pH is satisfactory for most plants and will not create nutrient deficiencies or plant toxicities (Environmental Laboratory 1986).

## Soil Texture

Soil texture is that soil property describing the proportions of different size particles. The direct effect of soil particle size on plant establishment is of a mechanical nature in that plant roots may be restricted or prevented from penetration as a result of fine soil texture. For example, finely textured clay soils tend to be more restrictive to plant root penetration than more coarse loamy or sandy soils. Soils with more than 30 percent volume of rock or other large objects reduce root penetration. Soil texture also affects plant establishment through its influence on soil aeration (Table 6-2). Large soil particles help maintain pores through which gases can exchange with the atmosphere.

In addition, soils containing high percentages of montmorillonite clay have high potential for shrinking and swelling. These soils crack as they dry allowing air into the soils and desiccation of exposed roots. This has become a problem, for example, in planting oak seedlings in bottomland hardwood restoration projects in the Mississippi Delta. These soils have high clay content and shrink-swell capacities. Tree seedlings are economically planted with a tractor and plow apparatus that slits the soil, places the seedling in the slit and then closes the slit around the seedling. As the soil dries around tree seedlings planted in this manner in the Mississippi Delta, it can shrink away from and expose the seedling roots.[1]

**Table 6-2**
**Soil Texture Influence on Permeability and Water Holding Capacity**

| Texture Class | Infiltration Rate[a] Structure Strength: Weak | Infiltration Rate[a] Structure Strength: Strong | Available Water (% volume ) | Approx. Air Capacity at Saturation[b] (% volume) |
|---|---|---|---|---|
| Sand | rapid | | 0.02-0.13 | 10 |
| Loamy sand | rapid | | 0.15-0.23 | 15 |
| Sandy loam | rapid to moderate | | 0.22-0.30 | 15 |
| Loam | | moderate | 0.19-0.30 | 6-12 |
| Sandy clay loam | | moderate | 0.21-0.23 | |
| Sandy clay | slow | moderate | 0.21-0.23 | |
| Clay loam | slow | moderate | 0.30-0.37 | 5 |
| Clay | slow | slow | 0.16 | < 1 |
| Silt loam | | moderate | 0.30-0.50 | |
| Silty clay loam | slow | moderate | 0.13-0.50 | |
| Silty clay | slow | | 0.13-0.28 | |
| Silt | | | 0.26 | |

[a]Infiltration rate is categorized as: Rapid-> 7.5 cm/hr, Moderate- 0.5-7.5 cm/hr, Slow-< 0.5 cm/hr
[b]Taken from Oosting 1956.

[1] Personal Communication. Harvey Kennedy, U.S. Forest Service.

This leaves the seedling to desiccate and die. Sand and silt, in contrast, do not crack to such a detrimental extent.

Soil texture also affects plant establishment and growth through its influence on permeability and water holding capacity (Table 6-2). Water infiltrates more rapidly through the large pores in coarse soils then fine texture soils. There is, however, more water available for plant growth in moderately fine textured soils, loams, and clay loams than in coarse textured soils such as sand (Table 6-2) (USDA Forest Service 1989).

## Soil Structure

Soil structure is defined as the arrangement of soil particles as a result of soil particles bonding into structural units. There are six recognized soil structure shapes (Figure 6-7). When soil structure is weak or has been destroyed, plant growth and establishment becomes restricted and infiltration rates are reduced (Table 6-2). Soil structure can be lost through disturbances such as removal of native vegetation, passage of an implement through or over a soil, intensive trampling by animals, off-road vehicles or people, all of which result in soil compaction. Natural physical processes, such as ice formation, freezing/thawing, shrinking/swelling, and frost heaving that change the physical structure of soils and affect the establishment and survival of plants onsite.

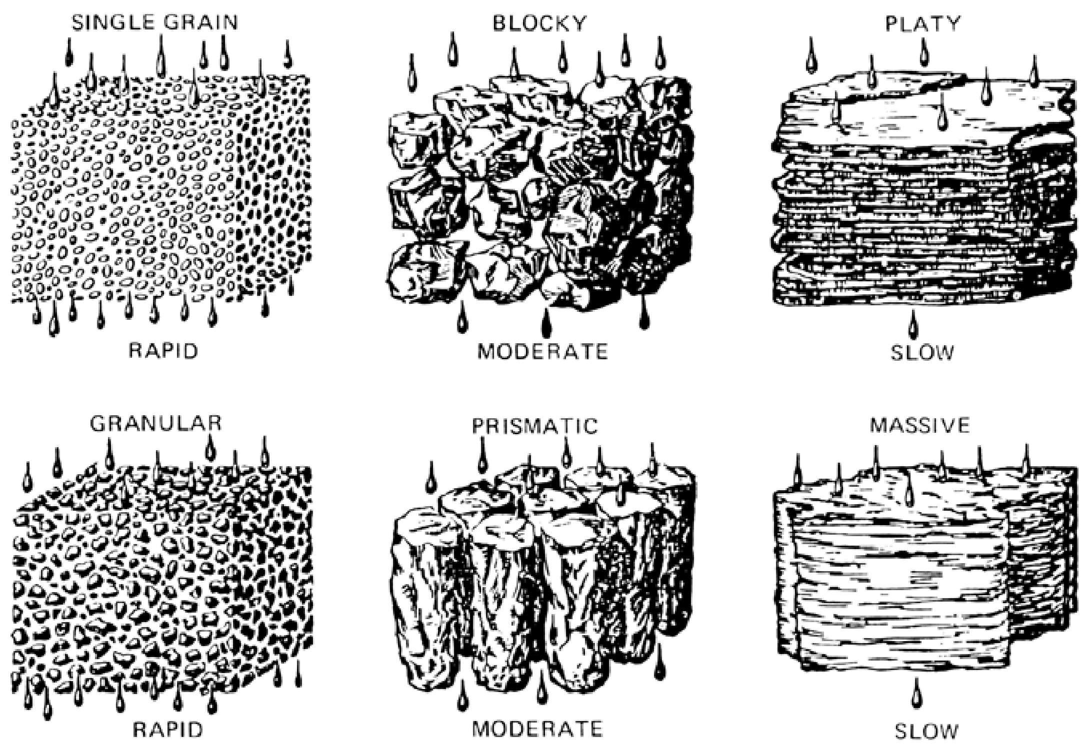


Figure 6-7. Recognized soils structure shapes.

## Soil Density

Soil density varies depending on the texture of the soil, the compaction of the soil, and on how much organic matter is present. In general, sands will have a higher bulk density than clays. Silts are intermediate. Changes in soil density influence root penetration. For example, roots penetrate most rapidly and easily into soil that is composed of loose granular materials. Organic matter interspersed with mineral soil particles lowers soil density by limiting settling and maintenance of pore spaces between particles.

## Soil Moisture

Soil moisture content and water retention are important physical properties to maintaining seedling germination, survival, and growth. Viable seeds of wetland plants readily germinate in moist habitats when favorable conditions occur, that is, usually when moisture is at or slightly below field capacity (Fredrickson and Taylor 1982). Soil moisture is directly influenced by soil characteristics such as texture, permeability, infiltration, elevation, precipitation, and evaporation. Figure 6-8 shows the ranges of soil water retention for sandy loam and silt loam soils. Silt loam soils contain more available water because of their finer texture whereas sandy soils hold less available water due to less surface area and larger pore spaces (Environmental Laboratory 1986).

## Topography

Site topography, including elevation, slope steepness, aspect, landscape position, and overall terrain, can be an important physical limitation to the establishment of vegetation at a site. These elements can directly affect vegetation establishment and indirectly affect the development of soil structure and soil moisture.

## Elevation

Generally, elevation relative to sea level is a minor factor in vegetation establishment; however, in some wetland types, such as in tidal landscapes (Lewis 1982) and forested bottomland hardwoods (Bedinger 1978, Fredrickson 1978), slight and almost indiscernible changes in elevation exert a profound influence on the species that can be established in these communities. Sharp elevational changes can be a barrier to species dispersal and establishment onto a site; however, the extent to which elevation hinders dispersal of propagules to a site is dependent on species dispersal mechanisms. Elevation also plays an indirect role in vegetation establishment in its influence on and relationship to climate, site runoff, and soil drainage.

## Slope Gradient

The slope gradient is defined as the inclination of the soil surface from the horizontal. Slope gradient is important because it influences the rate at which surface and internal water will flow. The potential for soil erosion increases as the slope gradient increases, which directly and indirectly affects vegetation establishment and maintenance of vegetation on a site.

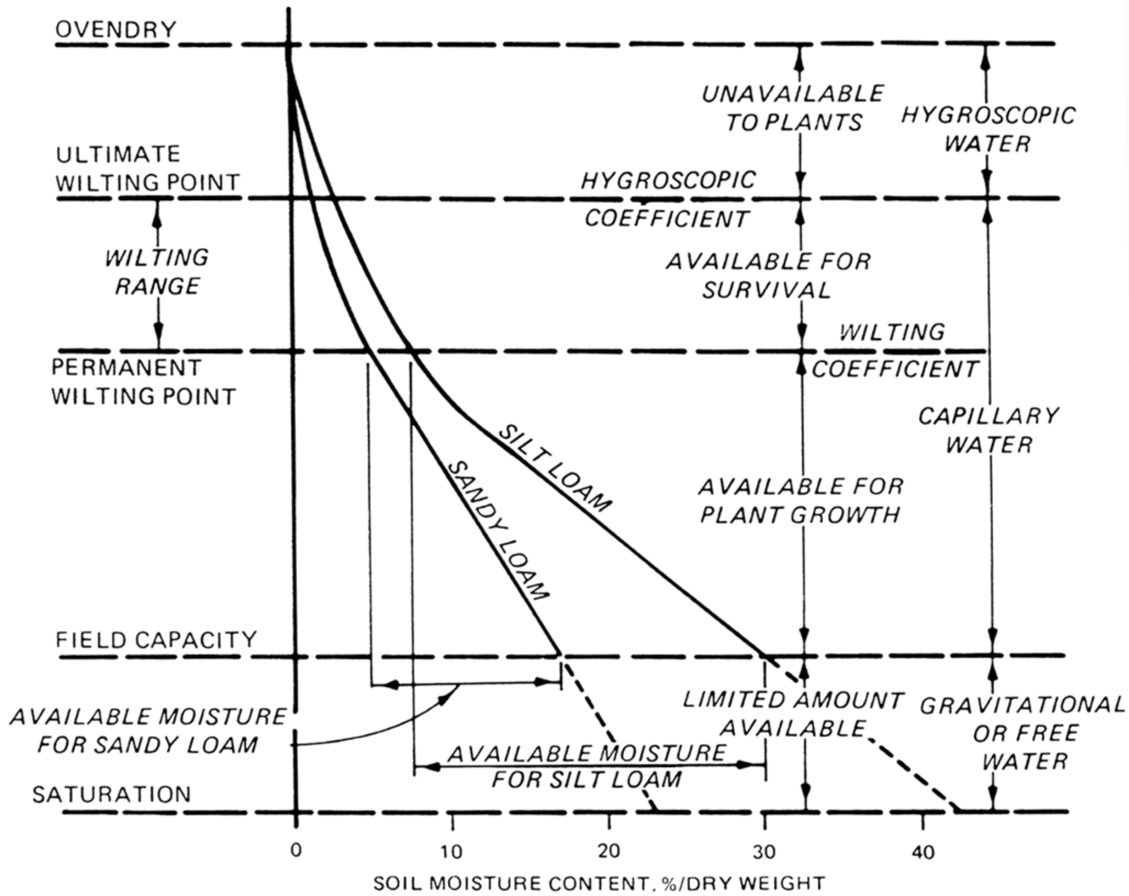


Figure 6-8. Ranges of soil water retention for sandy loam and silt loam soils.

Plant establishment and growth requires stable substrates for anchoring root systems and preserving propagules such as seeds and plant fragments, and slope is a primary factor in determining substrate stability. Establishing plants directly on or below eroding slopes is not possible for most species, and any such plantings must be considered high-risk. In such instances, plant species capable of rapid spread and anchoring soils should be selected or bioengineering techniques should be used to aid the establishment of a plant cover (Environmental Laboratory 1986).

Ground surface slope interacts with the site hydrology to determine water depths for specific areas within the site. Depth and duration of inundation are principal factors in the zonation of wetland plant species. A given change in water levels will expose a relatively small area on a steep slope in comparison with a much larger area exposed on a gradual or flat slope. Narrow planting zones will be delineated on steep slopes for species tolerant of specific hydrologic conditions, whereas gradual slopes enable the use of wider planting zones.

In addition, soils on steep slopes generally drain more rapidly than those on gradual slopes. This means that soils remain saturated longer on gradual slopes with falling water levels, and roots remain in anoxic conditions even after aerial plant parts are exposed. If soils on gradual slopes are classified as poorly drained, care should be taken that plant species are selected for planting that are tolerant of saturation for longer periods of time than would be determined from surface water levels alone.

## Slope Shape

Slopes can be concave, convex or linear in shape. Each of these shapes has benefits and limitations to the establishment of vegetation. Concave slopes, saucer-shaped depressions, are generally moist and are sheltered from the wind which may be beneficial to the trapping of propagules from adjacent sources, to the protection of seedlings and young plants from wind, evapotranspiration, and loss of soil moisture. Concave slopes, however, can be detrimental to the establishment and growth of vegetation, particularly in cold climates, because cold air settles into these pockets and they tend to be frost pockets (Environmental Laboratory 1986). Sedimentation also occurs in concave slopes which can bury vegetation and propagules that have been dispersed to the site. Convex slopes, slopes that are inverted saucer-shaped, are exposed to high winds which may cause desiccation of young seedlings and young plants and drying out of the soils. Also wind and water erosion also take place at these sites. Linear-shaped slopes are slopes with a level plain. Depending on the soil texture, these shaped slopes will influence soil moisture. For example, sandy linear-shaped slopes tend to be droughty, whereas fine-textured soils may have restricted internal soil drainage. In either case, these slopes in combination with soil texture may influence soil moisture and plant establishment and growth (Environmental Laboratory 1986).

## Aspect/Orientation

Slope orientation with respect to sun, shade, and wind is also another factor or characteristic that can influence vegetation establishment, growth, and survival. In some regions of the U.S., this factor has a significant effect on the quality of site for the establishment of forested wetlands. In northern latitudes, southerly exposed slopes are generally warmer and drier and the vegetation exhibits summer moisture stress during the late summer months compared to northerly exposed slopes. In contrast, vegetative growth and budding of vegetation is delayed on north facing slopes. Frequently, there is a sharp contrast in the species mix between north and south facing slopes. In the Northern Appalachians, oak dominates many southern exposures with maple dominating north facing slopes.

## Landscape Position

Landscape position refers to the spatial location of a site or a site component relative to other sites or site components within its geographic setting. The landscape position of a wetland restoration site directly influences site hydrology, soil conditions, and climatic factors, all of which affect vegetation establishment at a site. For example, the landscape position of a soil will influence its depth, texture, structure, and internal and external soil drainage. If a site is located in the upper portions of a watershed and does not receive water or runoff from other areas within the watershed, then the site conditions and climatic factors most likely will exert the controlling influences on the establishment of vegetation at that site. Alternatively, if its position in the watershed is such that it receives surface runoff or groundwater from upstream or up-gradient areas, activities or conditions at those upstream/up-gradient sites can directly affect vegetation establishment at the site. For example, agricultural runoff often carries heavy silt, nutrient, and chemical loads. Heavy siltation is a major cause of vegetation mortality in lowland forests because aeration to root systems is reduced (Fredrickson 1978; Reid *et al.* 1989). Therefore, a site positioned in a watershed where it may receive agricultural runoff from numerous upstream sources may be subject to sedimentation and degraded water quality. Similarly, vegetation establishment may be directly affected by runoff, groundwater, or sediments from municipal sewage/wastewater treatment facilities, dairy or confined animal farms, mining areas, smelters, timber stands, and industrial facilities such as oil refining, pesticide and fertilizer, landfill, wood treating, and other facilities. These characteristics in turn will have an impact on the species that can become established on a site and hence on the overall species composition of the site (Environmental Laboratory 1986).

## Topography

Site topography affects maintenance of plant species diversity. Small irregularities in the ground surface (e.g., hummocks, depressions, logs, etc.) are common in natural systems. More species are found in wetlands with many micro-topographic features than in wetlands without such features. Raised sites are particularly important because they allow plants to escape inundation that would otherwise die while flooded.

A second topographic feature that promotes increased species diversity in littoral wetlands is a convoluted shoreline. Littoral drift along a straight shoreline carries seeds and plant fragments along with sediments, with little opportunity for the propagules to be captured and become established. Concave portions of shorelines trap sediments and propagules enabling the natural establishment and growth of more species and protection from erosive wave and current energy.

## Competition

Competition is an interaction between two or more organisms that utilize a common resource in short supply that results in mutually adverse effects to the organisms (Barbour *et al.* 1980). Competition can occur between individuals of the same species or between individuals of different species. Plants compete for sunlight, water, nutrients, and space. For example, tall plants often out-compete short plants in their shade, deep-rooted plants obtain water from depths greater than shallow-rooted species can access, and fine-rooted species access a greater volume of soil and more plant nutrients than more coarsely rooted species. In all of these cases the plant that is most successful in obtaining the resource is the plant that will most likely survive. Competition is an important mechanism regulating a plant's ability to survive in a particular location, and is a primary limiting factor in successful plant establishment in wetland restoration and establishment projects.

Competition may arise from several sources in wetland projects. Existing vegetation can effectively out-compete newly planted target species. Established vegetation in a relatively mature ecosystem is resistant to invading species because it is utilizing resources to the extent that new vegetation has difficulty accessing adequate resources for survival. For most projects, the seed bank and seed rain will have a very strong influence on community development. Especially where the soil has been turned, competition may occur between aggressive and fast-growing species that are present in the seed bank, such as cattail, willow and wet-tolerant annual grasses, and the planted or seeded materials. Such "aggressive" species can rapidly dominate resource acquisition to the detriment of the target species. Competition from indigenous populations can be a significant factor in vegetation establishment because indigenous populations are often readily adapted to a site and out-compete planted species, particularly plant material from distant sources.

Overall, competition between individuals planted in an area can affect the establishment of vegetation at a site and ultimately result in a change in species composition of the site. Evaluating the potential effects of competition on vegetation establishment can be very difficult, unless obvious aggressive species are present and potential problems. In the latter case, site preparation and maintenance will be necessary to reduce the area influenced by these species.

## Allelopathy

Allelopathy is the direct or indirect harmful or beneficial effect of one plant on another through the production of chemical compounds that are released to the environment (Environmental Laboratory 1986). These chemicals often have inhibitory effects on the establishment or growth of other plant species in its local area; however, the effect is dependent on the chemical compound being released into the environment. A number of inhibiting chemicals have been found including organic acids, terpenoids, steroids, luctones, guinones, phenolic compounds and other compounds such as tannins, alkaloids, and flavinoids. These chemicals are released from the plant by volatilization, leaching, exudation from the roots, or decomposition of plant roots (Environmental Laboratory 1986). Allelopathic effects are somewhat difficult to distinguish from other inhibitory effects such as the buildup of litter and shading.

## Exotic Species

Exotic species are species that have been introduced from other areas. Because of the elimination of natural mechanisms that keep these species under control, exotic species often become nuisance species and become quite difficult to control, especially when they reach the seed producing stage. For example, water hyacinth has become a major nuisance species in wetlands and waterways in the Southeast. Purple loosestrife (*Lythrum salicaria*) is a hardy, eurasian perennial that is widely distributed on numerous wetlands throughout North America, particularly in the northeast. The dense growth of these species chokes wetlands, prevents other species from becoming established, and reduces the wetland values for wildlife. Canary reed grass (*Phalaris arundinacea*) is native to segments of North America, but is an example of a native species that is expanding in range and is now considered an undesirable, aggressive species in some areas, particularly in the northwest.

## Disturbances

### Diseases and Insects

Diseases are disorders of plants caused by fungi, bacteria, and viruses. Some diseases affect newly germinated seedlings while others weaken the mature plant and affect its continued growth and survival. Others completely kill plants. Some diseases persist while others are influenced by climatic factors and disappear with a change in the climate. In regions of high humidity, such as the Southern region, incidence of disease is higher and may be an important limiting factor in vegetation establishment on wetland restoration/creation sites. Incidence of diseases will be lower in regions of low humidity and dry weather (Environmental Laboratory 1986). It is important to note, however, that diseases are often secondary stresses induced by a previous environmental stress (e.g., unfavorable light, high humidity, etc.).

More than 850,000 insect species are known throughout the world. Insects have the capability to affect vegetation establishment through the decimation of young seedlings, weakening of saplings or mature trees, and defoliation of vegetation.

## Herbivory

The ability of vegetation to become established at a wetland restoration site depends on the number of propagules at the site, the condition of the propagules, and the growth of the plants at the site. Herbivores can directly affect all of these aspects. Herbivores can reduce the number of propagules at a site by consuming large numbers of seeds and vegetative propagules, by damaging seeds so that seed mortality occurs, and by destroying newly established, tender vegetation. Rodents, such as mice, rabbit, muskrat, beaver, nutria, squirrels, raccoons, etc., can affect successful vegetation establishment at a site. Seed tests in bottomland hardwood forest restoration projects in Stoneville, MS were unsuccessful when the restoration was completed under full canopy. However, when small clearings were made in the forested areas, or when seeding was conducted in open agricultural fields, restoration by seeding was far more successful than under full canopy (Johnson and Krinard 1985). The success in the latter trial was attributed to less herbivory by rodents.

## Climate/Microclimate

Climate is defined as the prevailing regional temperature, precipitation, wind and other environmental factors. Examples of climatic factors that influence vegetation establishment are:

- temperature
- shade
- precipitation
- wind
- frost
- humidity
- drought
- solar radiation
- photoperiod

Changes in these climatic factors occur both spatially and temporally. Temporal changes occur on a daily and seasonal basis; spatial changes occur with changes in latitude and elevation. Figure 6-9 illustrates the climatic regions or major plant growth regions of North America. Establishment of vegetation at a site may be restricted by climatic extremes, for example, either too much or too little rainfall, and the duration and frequency of conditions. For example, if the number of consecutive days of freezing temperatures exceeds species tolerances, establishment and survival of those species at a site will be affected. The frequency, duration, and severity of a drought during the growing season may affect germination, growth, survival, and reproduction of plants. For example, in forested wetlands, extended drought periods during the growing season lower seedling establishment compared to establishment during periods of normal rainfall. Most established oak seedlings will survive at least six to eight rainless weeks during the growing season (Johnson and Krinard 1985). Severe climatic conditions may preclude natural revegetation of an area or the survival of transplants without the implementation of proper controls.

Not only are there regional differences in temperature, moisture, photoperiod, and other climatic factors, but also local horizontal and vertical differences in these factors exist in the immediate area of wetland plants on the surface of the ground or in and beneath vegetation. These immediate differences in environmental conditions are termed microclimate and are often a function of both biotic and abiotic conditions of the immediate environment. For example, plant height and density influence air movement within and around plants and may change over a short distance. Microclimate variations in temperature, precipitation, humidity, light, shade, wind or air movements, and other environmental factors are influenced by slope, soils, and vegetation of the immediate area. Therefore, the establishment of plant species and species composition at any site is greatly influenced by the climate and the microclimate of the area.

## Previous Site Activities and Operations

A knowledge of previous operations and activities at a site chosen for restoration is critical in identifying potential factors that can affect vegetation establishment at a site. For example, use of agricultural fields for moist soil management or as wetland restoration sites for forested wetlands requires the consideration of herbicide and pesticide residues in the soil and overall soil condition. In a bottomland hardwood restoration project in the South, less than 5 percent of sown acorns produced seedlings in two old fields where milo had grown the year before. The authors suspected that a chemical used for weed control may have killed the germinating seeds, especially because the leaves of the new seedlings that did appear were chlorotic (Johnson and Krinard 1985).

Similarly, sites that may have had previous industrial uses, municipal uses, or other uses may include heavy metals, mineral salts, organic compounds, municipal sewage, or other contaminants that can prevent seedling germination, growth, and vegetation establishment.

Previous operations at a site may also include heavy equipment operation, plowing or soil aeration, etc. If practices have been undertaken that result in soil disturbance, the soil may be compacted which inhibits root penetration and seedling survival. It has been found that most soil compaction takes place with initial soil disturbance rather than later use (Environmental Laboratory 1986).


Figure 6-9. Climatic regions or major plant growth regions of North America.

## Interacting Site Factors That Limit Plant Establishment

Restoration of wetlands requires consideration of the wetland ecosystem as a whole. Using an ecosystem approach, one needs to look not only at the individual system components (i.e., soil, plants, water quality, etc.), but also at the relation between these individual components. For example, the productivity or nutrient availability of a marsh is directly related to the hydrologic regime, specifically the water cycles within the wetland (Fredrickson and Reid 1988). Soil texture and compaction limit the retention of water and root aeration. Soils that are coarse grained are more subject to frequent shifting and instability, and poor anchorage of plants especially in areas affected by waves or currents. Therefore, the combination of soil substrate and energy is important in effecting substrate stability and in the establishment and growth of plants. Soil texture influences water quality, for example, fine clay soils are notorious for contributing to turbidity. In general, fine particles sink more slowly than coarser particles and are more easily stirred into the water column. Turbidity is often related to energy characteristics of the system. In freshwater systems, turbidities are often the result of waves or currents that resuspend fine particles from the sediments (Kadlec and Wentz 1974).

Evaluating the direct and indirect relation between a number of environmental components and limiting factors is important. Often a factor may become a limiting factor as a result of a direct relationship with another variable.

# 6-3 Natural Vegetation Colonization and Establishment[1]

Even though earth-moving and hydrologic structure construction are commonly the most expensive facets of a wetland creation, vegetation establishment can also be an expensive and time-consuming endeavor. This is in contrast with restoration, where vegetation establishment is often the largest single expense. If wetland vegetation establishment is unsuccessfully planted or a great deal of vegetative maintenance is necessary, project objectives usually cannot be met within budget nor in a timely manner. Thus, natural plant colonization and establishment processes should be utilized to the greatest extent possible. Project costs and involvement will be minimized with natural colonization, and the likelihood of establishing a sustainable plant community is enhanced.

Natural plant colonization is the result of several processes that must all occur within the same time frame. First, seeds or vegetative propagules must be produced. Seeds and/or vegetative propagules must be dispersed to a site by some sort of conveyance mechanism, such as wind, flowing water, or animals. The migrants must arrive on site in viable condition and in sufficient numbers to become established. Site conditions must be adequate for seed germination and plant growth. Finally, site conditions must be conducive for plant growth for a long enough period of time that the new plants become well enough established to be able to tolerate subsequent disturbances such as inundation, grazing, or fire.

For natural colonization to be a viable alternative to planting for vegetation establishment on wetland restoration and establishment projects, the following conditions must exist:

- desirable plants already exist on site **OR** a natural source of plants and propagules is available
- no barriers to migration exist
- project site conditions are adequate for the germination and establishment of desirable plant species.

The objective of this chapter is to provide a general decision framework that will identify the major conditions limiting natural vegetation colonization and establishment at a specific restoration site and aid in deciding whether to plant or not to plant. Under certain conditions,

[1] By Mary M. Davis

desirable vegetation already exists at a site but is inadequate in species richness, density, or areal coverage. Planting may not be required, but some degree of vegetation or site manipulation may be necessary to ensure that the desired assemblage of species becomes established and remains viable. The decision framework also guides the user to practices and methods for continued vegetation management and site maintenance (see Section 7).

## Nuisance Plant Species

If nuisance species are identified in the onsite vegetation and seedbanks, it is advisable to incorporate a management technique to control the undesirable vegetation prior to further vegetation management (Figure 6-1). Vegetation management techniques target different life history stages of the plants. If seeds of undesirable species are present in appreciable densities, management techniques should target seedling emergence. For example, a site can be lightly harrowed after seeds have been allowed to germinate to strip the seedlings from the soil. Multiple harrow treatments will deplete the seedbank and reduce the potential of nuisance species invasion from the seedbank, but do not turn the soil or you will expose additional seedbank. Alternatively, if seeds are intolerant of inundation, the site can be temporarily flooded until the seeds rot and viability is lost. Pre-emergent herbicides that are approved for aquatic systems can be applied to eliminate seedlings as they emerge. Vegetation management techniques can also target plant growth. Mowing and fire reduce plant biomass of existing nuisance plants. One of these treatments may be necessary to allow more desirable species to grow and become dominant. More extensive techniques are, however, usually required to control existing vegetation. Preferred vegetation management methods should have as little impact on the desirable vegetation as practicable to minimize the need to plant the site later.

## Adequate Composition, Density, and Cover of Desirable Species

Wetland restoration and establishment project objectives should include an indication of desired vegetation, preferably a species list, and the density or percent areal coverage the vegetation should attain within a specified time frame for the project to be considered successful. It is necessary at this point in the project planning decision framework (Figure 6-1) to decide whether adequate vegetation already exists onsite, if inadequate coverage of the desired vegetation will increase to adequate coverage within the project time frame, or if further management may be required. Information gathered during the initial site assessment should provide a basis for this decision.

The first aspect to consider is whether the composition of desired species that already exists on the site and in the seedbank (if a seedbank study was conducted) is adequate. If an adequate species complement is not already present, possibilities of natural colonization should be investigated and, barring colonization, selected species may have to be introduced via planting or seeding. If the species complement is adequate, the volume and coverage of the anticipated dispersal rain needs to be considered in determining whether to introduce plant materials.

The potential for existing plants and seeds to grow and increase their coverage on the project site depends on several factors. The first is whether the designed conditions are optimal or marginal for plant growth. Rates of spread of healthy plant material can be estimated from the rate of spread of stock planted in optimal conditions. If hydrology, nutrients, competition, and herbivory are not limiting to plant growth, it is not uncommon in wetland projects for rhizomatous grasses, other herbs, and some shrubs planted to less than 5 percent coverage to reach 100 percent cover in less than 3 years by spreading vegetatively. Nonrhizomatous species such as tufted grass and grasslike species planted as sprigs, however, spread more slowly. The radius of the tuft increases slowly as new culms are produced. In the case of single stem plants, like trees, growth is in height and crown radius. If, for example, 50 percent cover of a tree species is required within 10 years, to estimate whether adequate tree cover will be attained one needs to estimate 1) the canopy area required at the end of the project, 2) the density of trees onsite that are likely to survive at the end of the project time period, and 3) the likelihood that the trees will attain the required size. Assume the required tree coverage equals 5,000 $m^2$ (one half hectare) by year 10. If 110 trees/ha are onsite and 100 are expected to live 10 years, then the trees must average 50 $m^2$ cover at that time. This is a crown radius of 4 m (about 13 ft). The project biologist would have to estimate whether this coverage would be easily attained by the existing trees or whether additional trees should be established to ensure project objectives are met.

The second factor affecting potential growth of the plants onsite is their present state of health. Inspection of the plants should indicate whether they are capable of growth under present conditions. If the plants look weak (i.e., yellow or sparse leaves), severely damaged (i.e., excessive loss of leaves, branches, or roots), or suppressed (i.e., no indication of recent growth), there is little likelihood that the existing plants will recover and grow without some management intervention. Poor growth may be a reflection of poor site conditions. Onsite analyses should be made to determine the factors limiting growth of existing vegetation. Management such as exclusion of grazers, fertilizer or pH amendments, erosion control, and altered hydrology are among the possible techniques (Fredrickson and Taylor 1982) that can be used to improve plant growth conditions on the wetland restoration or establishment project site.

It is more difficult to assess the development of vegetative cover from seeds. Often reasonable agreement is found between plant composition and numbers of plants that emerged from seedbank studies in greenhouses and from the respective natural sites, but this is not always the case, particularly in forested systems (Pickett and McConnell 1989). More importantly, the ability and accuracy of predicting the future postrecruitment vegetative composition and structure from a known seedbank has been rarely investigated (van der Valk and Pederson 1989). Although many site factors, such as erosion, inundation, and drying, will affect emergence, results of the seedbank study can be used with caution to estimate the amount of vegetation that will emerge on the project site. Effects of the site-specific conditions on seed germination and seedling growth of the species of interest must be carefully evaluated.

The direction of successional development is very dependent on the timing of the release into succession. In much of the mid-Atlantic States, a spring or fall abandonment of farmland will favor the establishment of *Ambrosia artemissifolia* (ragweed), whereas a summer release into secondary succession will favor *Setaria faberii* (foxtail) to the near absence of the *Ambrosia* (Squiers 1989). Managers of waterfowl basins can strongly influence the composition and structure of the drawdown releases via the selection of different release dates (van der Valk and

Pederson 1989). Determining the most advantageous release date for the targeted species mix will be important in directing the successional development toward the targeted community and away from unwanted compositions.

## Colonization from Natural Sources of Seeds and Plant Propagules

If inadequate species and/or cover of desirable plants exist on the wetland restoration or establishment project site, natural colonization of the site by vegetation from nearby sources may be a viable method to vegetate the project site. The objective of this point in the planning decision framework (Figure 6-1) is to 1) determine whether sources of desirable vegetation capable of colonization are available, 2) identify barriers to migration, and 3) determine if site conditions are adequate for germination and establishment of colonizing species.

At a minimum, the following information will be required to assess the potential for natural colonization at a project site:

a. At least one site visit will be required during a period of the year when onsite and surrounding vegetation can be identified to species. Plant species identification should always be made by a qualified expert familiar with local flora.

b. The dispersal mechanisms and specific germination requirements of the desired species need to be determined. Germination requirements can be determined to different degrees of certainty using one of the methods discussed in the next section.

c. Distance to seed/propagule sources and presence of barriers to dispersal should be assessed with maps, onsite evaluations, and, if water dispersal is necessary, hydrological records or evidence.

d. Suitability of site conditions for germination and establishment of seeds and vegetative propagules can be determined from a comparison of potential colonizing species requirements and tolerances with site hydrology, soil conditions, and vegetation.

## Are Natural Sources of Desirable Vegetation Available?

Natural colonization of wetland restoration and establishment projects can be a highly successful method of revegetation if sources of seeds and plant propagules are nearby. Reinartz and Warne (1993) reported finding 142 species of vascular plants in naturally colonized created marshes of southeastern Wisconsin. They found that the diversity and richness of native wetland plants and the proportion of total plant cover that was comprised of native marsh plant species increased from one- to three-year-old wetlands. The diversity and richness of native wetland species increased with proximity to the nearest native marsh, with a marked decrease in species richness beyond 700 m to the nearest marsh.

Seeds of many woody species, however, have much shorter dispersal distances. Brown et al. (1992) evaluated a forested floodplain wetland as a source of windblown, bird-dispersed, and water-dispersed seeds to adjacent mined wetland areas. Windblown seeds decreased in densities as distance from forest edge increased. Densities ranged from $125/m^2$ to $380/m^2$ within the forest, $50/m^2$ to $120/m^2$ at the forest edge and decreased exponentially as distance from the forest edge increased. Bird-dispersed seed densities at the base of constructed perches and tree "snags" ranged from $100/m^2$ to more than $300/m^2$, but decreased rapidly beyond several meters from the perch. Water-dispersed seeds trapped in a creek flowing out of the mined area ranged from 0/day to 200/day, whereas dispersal rates downstream of the forest floodplain ranged from 200/day to 5000/day. Water dispersal of seeds, however, is highly dependent on distance to seed source as well as hydrology. Extensive tracts of agricultural land in the Mississippi Alluvial Valley are being restored to bottomland hardwood forest. Planting efforts have concentrated on heavy-seeded tree species with the assumption that lighter seeded species would be blown onsite by the wind or carried in by water. Natural colonization by additional tree species has been disappointingly low, due in large part to the great distance to natural seed sources and competing vegetation. In these cases, the restoration sites have been sufficiently large that the dispersal rain range of the mast species is not great enough to colonize the interior of the restoration sites, only the immediate periphery adjacent to existing forests.

Colonization of wetland vegetation from plant fragments is more limited than colonization from seeds, but can be an important form of colonization in some cases. Stem and root fragments of aquatic vegetation are capable of becoming established upon deposition. Hydrilla is a major aquatic nuisance species that is spread from stem fragments carried from one water body to another on boat propellers. Whole plants of wildcelery (*Vallisneria americana*) and sago pondweed *(Potamogeton pectinatus*) are ripped up by feeding migratory waterfowl in the Upper Mississippi River. These fragments can settle and become established in shallow areas with low energy and adequate light penetration. Geese feed on two sterile species common in saltmarshes throughout the Arctic, *Puccinellia phryganodes* and *Carex subspathacea*, and in the process tear up thousands of plant fragments that are carried to new areas by water currents. Soft sediments that are exposed by the feeding geese are recolonized by these plant fragments (Chou et al. 1982). Algae and bryophytes, although not commonly noted in the restoration literature, are also capable of colonizing new sites vegetatively.

Results of the studies described above indicate that sources of seeds of wetland species must be relatively close to the project site for dispersal of a diversity of species in adequate quantities to vegetate a site. The decision of whether adequate natural sources of seeds or vegetative propagules are available depends on the type of desired plants. For example, marshes containing desirable species that occur within 500-700 m (0.3-0.5 miles) of the project site are likely to be good seed sources of herbaceous plants, assuming the presence of dispersal vectors for the various seed types. Seed densities of windblown or animal-dispersed tree species decline rapidly with distance from the forest edge. Windblown tree seeds will be carried only a couple of hundred meters. Densities of bird-dispersed seeds can be increased in localized areas with the provision of perches. Perches can be old remaining trees, shrub piles, "planted" snags, or any other structure on which birds will perch. Water-dispersed seeds can be carried great distances, presumably for miles before they lose their buoyancy and sink. Sources of vegetative propagules and water-dispersed seeds must originate upstream of the project site.

# Barriers to Colonization

For natural colonization to occur, propagules (e.g., seeds, rhizomes, stolons) must be present at the site or must be able to disperse to the site. There are four primary agents of dispersal for wetland plants: wind, water, animals, or man. Propagules have numerous morphological adaptations that make them amenable to the various types of dispersal. Many of the common invader species that rapidly occupy a site are carried by wind (e.g., *Typha* and *Phragmites*). Currents, winds, and animal dispersal can account for some short range dispersal in riverine and fringe wetlands (Kadlec and Wentz 1974). A brief description of how each of the factors or conditions limit natural revegetation of a site is provided below.

*Topography:* Steep slopes may hinder the colonization of an area by a large number of species. The steep slopes increase runoff and may cause any seeds that have been dispersed to the site to wash off the slopes. A sudden and sharp increase in elevation between the site and its surroundings can present a physical barrier to dispersal of propagules to the site, particularly for those species that rely on wind dispersal. In riparian systems, floods occasionally carry seeds across land barriers (Kadlec and Wentz 1974).

*Currents and wave energy:* Colonization in riparian and fringe wetlands may be hindered by currents and waves that disrupt the establishment of seedlings and other propagules. Seeds and vegetative propagules must have stable sediments as roots develop to anchor the plant. Sources of energy that move soils or physically damage the plants will limit colonization.

*Dispersal rates:* On bare sites, such as sandbars, willow (*Salix* spp.) and aspens or cottonwoods (*Populus* spp.) frequently appear very rapidly because their wind-disseminated seeds reach new sites quickly and the seedlings are able to thrive on these wet, bare mineral soils. Assuming the presence of dispersal vectors, marsh and aquatic plants within the effective dispersal range invade most new environments within a few growing seasons because their means of dispersal are remarkably efficient (Kadlec and Wentz 1974).

*Competition from existing vegetation:* Competition from existing indigenous and aggressive undesirable species affects migration, growth, and survival of propagules that may potentially colonize a site. The existing vegetation physically limits delivery of seeds to a site, contact of the seeds with soil, and access of the developing new vegetation to light, water, and nutrients. Natural colonization may be an ineffective or undesirable method for establishing vegetation at a site when one or a few aggressive species are present and can exclude all others. (Southern Tier Consulting 1987).

*Soil condition:* Disturbances in soils at a site may significantly alter the soil condition at the site and prevent the colonization of original assemblages of species on the site or of species from surrounding areas. For example, if an area has been clear cut and has potentially been subject to a high amount of rainfall, leaching of soil nutrients may have occurred if the site has been left in a disturbed condition. If an area has been degraded by off-road vehicle use, changes in soil conditions, particularly compaction, may preclude the colonization of a desirable species mix and favor weedy colonization. Past land use practices can easily lead to the destruction of the mycorrhizzal and microbial communities, whose loss will strongly focus successional processes toward a weedy colonization.

*Modified hydrology*: A wetland site whose hydrology has been modified may require a review of the degree of hydrologic change prior to selecting natural colonization as the method of establishment. For example, a site that once supported an assemblage of forested wetland species that were tied to annual cycles of flooding and inundation throughout the growing season may not be able to support this same assemblage of species if the site timing, frequency, duration, and depth of inundation were greatly reduced at the site. A change in timing, frequency, duration, and depth of inundation can affect the survival of species in the seedbank. The ability of the species in the seedbank or propagules dispersed from adjacent locations to become established at the site will depend on the tolerances of the individual species to the new hydrologic regime and water budget.

*Time:* Natural colonization may require several years before the desired assemblage of species and cover is achieved. While many species may be established on a site without direct human intervention, the time required to achieve the desired assemblage of species at the desired coverages can be quite prolonged. This is especially true for sites in which the natural conditions of the site have been disturbed, modified, or regraded.

*Ecotypes:* Ecotypes are genetically different individuals of a species that are adapted to a specific set of local or regional environmental conditions. Because ecotypes have developed adaptations to a specific set of environmental conditions, they often will not grow well under a different set of environmental conditions. Colonization in wet conditions of ecotypes that are adapted to upland conditions can result in high mortality of propagules. Examples of wetland species that may have different ecotypes within the same area, such as within a watershed, are green ash (*Fraxinus pennsylvanica*), black gum (*Nyssa sylvatica*), and red maple *(Acer rubrum)*.

## Summary of Potential Site-Specific Conditions Limiting Wetland Vegetation

The following items can serve as a checklist for assessments of potential wetland project sites based on wetland vegetation.

*a.* Determine the physical limitations for dispersal of propagules onto the site and the establishment of plants on the site.

(1) What are the slope and soil characteristics of the site?

(2) Does the site have the potential for having poor drainage characteristics, i.e., for being either well drained or permanently flooded or inundated?

(3) What is the orientation of the slope with respect to the wind and the sun?

(4) Will this orientation have an effect on the potential success of establishment of natural vegetation?

(5) Are there any physical barriers to the natural dispersal of propagules to the site and if so what are these barriers?

(6) Can these barriers be removed easily and still meet the planned project goals?

(7) Are the soil conditions and characteristics adequate for the revegetation by local species?

(8) What is the soil condition including fertility and potential for productivity?

*b.* Evaluate the climatic limitations of the site. In which season will the site will be ready for vegetation to be established?

*c.* Determine the biological limitations to natural revegetation.

(1) Is there an abundance of nuisance animals in the surrounding communities that often feed on seeds and young seedlings?

(2) What are the dispersal mechanisms of the native vegetation in the area?

(3) Is there a natural wetland complex near the site to provide a source of propagules?

(4) Are there sufficient number of desirable species at the site or adjacent to the site?

(5) How far away are the nearest sources of natural propagules and are the propagules likely to be dispersed to the site?

(6) What is the composition of the seed rain that will reach the interior of the site?

(7) Is the seedbank a reliable source of a sufficient number of species?

(8) Are the sources of propagules in good, healthy condition, stress free, free of deleterious insect damage and signs of disease?

(9) Are there any undesirable species at the site or near the site?

(10) Are there any desirable species remaining on the site or adjacent to the site and what is the areal extent of the species?

*d.* Evaluate the site history and compare with current site conditions.

(1) Hydrology **-** Has the natural hydrology of the site been significantly altered so that local species or species indigenous to the area would be precluded from the normal course of revegetation because the species and the site conditions are no longer compatible?

(2) Soils - Have the soil characteristics of the site been significantly altered so that natural revegetation will be difficult without some site preparation or manipulation?

*c.* Identify any of the above problems that cannot be overcome.

*d.* Finally, determine if the site condition is compatible with the planned project goal if the site is not planted with transplants.

# 6-4 Species Selection[1]

## Introduction

Once the decision has been made to plant or seed the site, the next step is to select the wetland species that will be introduced into the wetland. The selection of species should not be conducted as an isolated task, but should be conducted in conjunction with the acquisition of information on the availability, cost, condition, and source of the plant materials. When selecting plant species for wetland projects, an iterative approach that continues to refine and narrow the list of potential species that will be introduced into the wetland should be used. This approach allows the selection of species that are not only compatible with the site characteristics but with the project goals, design criteria, and budget as well.

This chapter is targeted at providing:

- a brief overview of ecological concepts that are important to consider when selecting wetland plant species to be introduced into a site that will meet the project goals,
- species characteristics that are important for meeting project goals and objectives, and
- guidance for the selection of species that will meet the vegetation design criteria while being compatible with the site conditions.

## Ecological Concepts

The ideal basis for plant species selection is the natural assemblage of species found in natural reference wetlands. A reference wetland has characteristics similar to those that are to be restored or created. The reference wetland hydrology, substrate, energy levels, and biotic associations serve as a model for the restored wetland. If the restored or created wetland successfully recreates the physical, hydrological, and chemical conditions of the reference wetland, then selection of the same plant species for the project is desirable. Recreating the composition and distribution of the reference wetland species associations will not only meet project goals, but the survival and growth of the plants are likely to be more successful. There

[1] By Lisa C. Gandy and Mary M. Davis

are limits, however, to selecting species based only on the associations that occur in reference wetlands. Practical limitations exist such as the lack of plant material availability for many species.

Wetlands are dynamic ecosystems. As described earlier, the plants, animals, and chemical and physical environments in wetlands have complex interactions and self-regulating mechanisms. These interactions and mechanisms are the basis of wetland functions that have value for society. Successful plant species selection for wetland projects requires an understanding of how the new plants will interact with the ecosystem and the contribution of the plants to desired wetland functions.

There is a hierarchy of ecological considerations to be made when selecting plant species for a wetland project. At the simplest level are the individual plants to be installed in the project site. The species selection process must take into consideration the size, growth form, and flood-tolerance of the immature propagule for the individual to survive and grow under the site conditions. Species selection at the individual level must consider whether the species naturally occurs in the area and if the site conditions are within the environmental tolerance ranges of the species. Additional consideration must be made, however, during the species selection process at the population, community, and ecosystem levels to ensure that the species selected will be fully integrated into a functioning wetland ecosystem.

## Species Tolerance Ranges and Distributions

The fact that individual species have differing tolerances to flooding (depth, timing, frequency and duration), water quality, salinity, soil conditions, temperature, disease, insects, and other environmental conditions was introduced in an earlier section. Selecting the appropriate species to be planted at a site, therefore, is dependent on knowing the individual species tolerances and matching these with the site environmental conditions.

Differences in flood tolerance among wetland plant species is well established (e.g., Brink 1954; Broadfoot 1976; Hall et al. 1946; Hall and Smith 1955; Hosner 1958, 1959, 1960; Hosner and Boyce 1962; McDermott 1954; Theriot 1993; Williston 1959; Whitlow and Harris 1979; and Yeager 1949). For example, forested wetland species such as bald cypress (*Taxodium distichum*) and water-tupelo (*Nyssa aquatica*) are tolerant of flooding and are commonly found in wetlands with long periods of relatively deep inundation. In contrast, loblolly pine (*Pinus taeda*) and white oak (*Quercus alba*) are generally flood-intolerant and are found in drier portions of wetlands that experience infrequent and short periods of inundation (Theriot 1993; Whitlow and Harris 1979). Herbaceous species also have characteristic depth distributions that reflect their flood-tolerance. Squires and van der Valk (1992) report three ecological zones in northern marshes in which species were typically distributed. For example, *Carex atherodes* and *Phragmites australis* were commonly found in upper marshes that were only seasonally flooded. *Typha glauca* and *Scirpus acutus* were common in lower marshes that experienced permanent flooding.

Particular attention should be paid to flood-tolerance of young plants during the species selection process, because this is the life stage that is most critical for establishment in wetland restoration projects. Young plants are small and more likely to be completely submerged than their mature counterparts. Complete submergence blocks the leaves from sun and oxygen and is more lethal than partial inundation. Under greenhouse conditions, for example, seedlings of sycamore (*Platanus occidentalis*), red maple (*Acer rubrum*), shumard oak (*Quercus shumardii*), sweetgum (*Liquidambar styraciflua*), hackberry (*Celtis occidentalis*), and cherrybark oak (*Quercus falcata* var. *pagodaefolia*) all died after 20 days of complete submersion. Seedlings of these same species, however, showed either complete or significantly higher survival when subject to flooding just to the root collar. Survival of buttonbush (*Cephalanthus occidentalis*) and black willow (*Salix nigra*) under flood conditions was dependent on whether or not the plants were emergent or completely covered (Whitlow and Harris 1979).

Some wetland species are sensitive to water quality degradation. This is particularly true for freshwater marsh species such as *Najas flexilis*, many *Potomogeton* sp., and *Scirpus americanus*. On the contrary, other species increase in abundance or invade a site in turbid water, contaminated water, or at disturbed sites (Kadlec and Wentz 1974).

Soluble salts often present a problem in certain areas, especially in the more arid western states. Halophytic plant species such as saltgrass, alkali cordgrass, prairie cordgrass, atriplexes, and others are tolerant of high soil salinity conditions (Environmental Laboratory 1986). Halophytes are good candidate species for wetland projects where excessive evaporation will concentrate salts in the groundwater and at the soil surface and where water sources contain high salt concentrations.

Species distributions will be dependent on individual species abilities to tolerate the changing environmental conditions. Some wetland species are able to tolerate a wide range of environmental conditions. These species are often quite widespread in their geographic distribution and may be found in a number of wetland types. Widespread plants are those whose ranges encompass whole continents or hemispheres. Examples of widespread species are *Lemna minor, Phragmites australis,* and *Typha latifolia*. These plants are found in freshwater marshes throughout the world. Other species are able to tolerate only a very narrow set of environmental conditions and are typically more localized or restricted in their distributions. Species with limited tolerances often will have difficulty in becoming established at a site if the required conditions are not present. Alternatively, species with broad environmental tolerances can adapt to a wide range of environmental and site conditions and will often be more successful in becoming established at a site. Examples of regional or local species that are more restricted in their geographic range are *Sagittaria sanfordii* which is restricted to the Central Valley of California, *Najas ancistrocarpa*, found only in the southeastern U.S. and Japan, and *Cladium jamaicense*, found primarily along the U.S. Atlantic and Gulf Coasts (Kadlec and Wentz 1974). Therefore, a prime consideration in the selection of plant species for the wetland restoration/creation site is an understanding of the competitive tolerances and geographic distributions of the species involved.

## Plant Populations

*Maintenance.* Population dynamics are characterized by reproduction, growth, and death of individuals (Krebs 1978). To maintain themselves in an area, populations must be able to at least balance the number of births with the number of deaths. Even if the individuals of a planted population successfully become established and grow, the population will eventually die out if there is no reproduction. There are two basic methods of plant reproduction, which are vegetatively and by seed.

Many wetland plant species are capable of vegetative reproduction. Many shrubs, grasses, sedges, and herbs produce new individuals or clones with rhizomes, tillers, or stolens (i.e., prostrate stems). If conditions are good, they can spread over large areas without the benefit of seeds. This is a distinct advantage for wetland plant populations because the presence of water often inhibits germination of seeds and, hence, recruitment into the population. Selection of wetland plant species that are capable of clonal spread has advantages for increasing areal coverage of vegetated areas with limited planting effort. Clonal spread is usually most productive where there is adequate moisture and space for the plant to move into. Clonal spread of emergent wetland vegetation is usually limited by competing vegetation and excessive water depth. Aquatic or floating leaved plant species should be selected for areas that will experience permanent inundation.

As described earlier, reproduction of wetland species by seeds is often limited by the presence of water. Inundation of the ground surface blocks oxygen and light from reaching the seeds. The germination requirements of most seeds are not met while inundated, and if the water does not recede, the seeds often die underwater. Alternatively, the seed of some species may remain under the water column in a dormant state until a drawdown event cues germination. The consequence for plant populations dependent on seed reproduction that are subjected to long periods of inundation is limited periods for germination and successful recruitment. Individuals of seed reproducing species planted in areas that will experience long periods of inundation may survive and grow, but if they cannot reproduce, the population will eventually die out and the planting effort is wasted. For example, reproduction of most wetland tree species is by seeds and requires long enough periods of soil exposure for seeds to germinate and seedlings to grow large enough to tolerate subsequent inundation.

Similar to their natural counterparts, restored wetlands need to be self-maintaining for long-term sustainability. Species should be selected that will persist and reproduce at the site and thereby contribute to the long-term sustainability of the wetland and its functions. This does not mean, however, that the selection of species that will be temporary at a site is undesirable. In some instances, rapid growing annual grasses and forbs are important in establishing the temporary cover on a wetland site and in providing more acceptable conditions for perennial species on newly created or disturbed sites. These annual species, however, may only persist for a period of one season. In time, these species will be replaced by permanent cover species such as perennial grasses, legumes, and forbs and will provide cover for more than one season. Species can be selected that will aid colonization of species typical of later successional communities. For example, one might plant oaks in hope of establishing an understory environment that will foster the natural colonization of a suite of herbs typical of wet, acidic forests.

When selecting species that will be self-perpetuating in the restored wetland, careful consideration of the following characteristics should be made with regards to the wetland project site conditions:

- produce large numbers of rapidly germinating seeds and

- possess means of vegetative reproduction (e.g., suckers, sprouts, rhizomes).

*Resilience to stress*. Wetlands are subjected to many forms of disturbances that stress plants (see Chapter 1). Floods, drought, freezing temperatures, wind, waves, sedimentation, erosion, herbivory, pathogens, and other forms of stress are extreme events of naturally occurring conditions. In order for wetland plant populations to be maintained, they must be able to avoid or tolerate and recover from the stress imposed by these extreme events. There are several properties of natural plant populations that help increase resiliency to stress.

Local populations can be defined as the number of individuals of a species that occur together both temporally and spatially and are capable of gene exchange (Quinn 1978). Locally occurring populations are typically the most resilient to stresses imposed on an area by the various types of disturbances. Individuals that cannot recover from stress eventually die out leaving those individuals that can recover. As the surviving individuals undergo cycles of additional stress, recovery, reproduction, and growth, the population develops into what is known as an ecotype. Ecotypes often will not grow well under a different set of environmental conditions; therefore, species that commonly form ecotypes are not successfully transplanted into different conditions. Genetic fixation in local strains has often been overlooked in applied ecology and is particularly relevant to successful vegetation establishment at wetlands restoration and creation sites. The identification of ecotypes is important when selecting plant species and in materials acquisition for wetland restoration projects (Kadlec and Wentz 1974). Selecting local ecotypes of a species for a wetland restoration project helps ensure that the plants will be resilient to the type disturbances a site will most likely experience. Unfortunately, the term ecotype is used to imply almost any degree of genetic difference below the species level. Quinn (1978) argues against the use of the word “ecotype” in favor of “local population.”

Another important property of natural populations that helps increase resiliency to stress is genetic diversity. Not all individuals in a population are equally resilient to stress. Furthermore, an individual that is more tolerant of a particular type of stress than another individual may be less tolerant of a different stress. For example, an individual may have a high concentration of unpalatable compounds, but is not tolerant of prolonged inundation. The presence of these compounds would limit defoliation by insects, but the individual would die under an extremely long period of flooding. A nearby individual of the same species might be killed by repeated loss of leaves to herbivores, but would be able to withstand unusually long periods of flooding. There is a genetic basis to the mechanisms that enable these individuals to tolerate stress. Genetic variability in a population enables at least some individuals in a population to survive most disturbance events with recombination playing a key role. Selection of several locally occurring ecotypes further enhances the ability of the newly established wetland plant population to survive stress by increasing the genetic variation.

Wetland plant species have varying levels of tolerance or resistance to disturbance and should be considered when selecting species. Changes in water temperature, oxygen decrease, increase in turbidity, pollution, dredging and other physical disturbances, as well as biological disturbances, such as insect predation, herbivory, or trampling can cause changes in species composition of a wetland ( Kirkman and Sharitz 1994; Ellison and Bedford 1995). Many species show a low level of tolerance to these changes and will either greatly decrease in abundance or disappear altogether. Some species, however, will increase in abundance when other species disappear. In general, species with widespread geographic distributions and that are found in a wide variety of habitat types are more tolerant of disturbance. These species merit special consideration in establishment efforts (Kadlec and Wentz 1974) and particularly at project sites that have a high likelihood of being disturbed.

# Plant Communities

## Diversity

Establishing diverse wetland vegetation is a stated goal in most wetland mitigations. This is desirable for a variety of reasons. A relatively large number of species means an array of environmental tolerances is represented. As the new wetland experiences fluctuations in various environmental conditions over time, such as water level, temperature, and herbivory, some plants or species will not survive, but others may thrive. Any planting or seeding program is simply an additional input into the environmental seive of succession ( van der Valk, 1981). If the project is dominated by a few species, there is a possibility that the project will fail with the death of only one species. Planting a variety of species increases the chances for success of at least a few species.

A diverse array of wetland plant species is essential to a wetland's ability to provide and to sustain a number of functions. Monocultures, or communities with a single dominant species, are often considered to have limited value. The benefits of diverse communities are numerous. For example, establishment of a variety of desirable species will increase competition for resources and limit the potential for aggressive species to overtake a project site. In addition, the number of plant species and structural complexity of natural ecosystems generally correlate with wildlife species richness, particularly for birds (Wein and Pierce 1994).

A diversity of wetland types within a landscape increases wildlife value of an area. Various plant species association and hydrological conditions provide required habitats for different life history phases of animals, such as feeding, winter cover, and breeding (Heitmeyer and Vohs 1984, Frazer et al. 1990). Further, as fully functioning components of a landscape, a variety of wetland types in an area enables an exchange of genetic material among neighboring populations. Migration among populations helps maintain genetic diversity and repopulation of local extinctions.

Vegetative diversity can be increased at a wetland restoration/creation site in numerous ways such as by:

*a*. planting an array of different species in different amounts *b.* planting a variety of growth forms such as, herbaceous species, ground cover, shrubs, saplings and tree species, emergents, floating hydrophytes, submerged hydrophytes, or free-floating species

*c.* planting species with a variety of life histories (e.g., annuals, short-lived or long-lived perennials)

*d.* providing a range of site conditions (e.g., through elevational changes, creation of habitats with varying aspects/orientations) to support a diverse range of plant species

*e.* increasing margins or edges within a wetland (Davis 1995).

Determination of the optimal diversity for a wetland mitigation should be made when the project goals and design criteria are being set. The concept of in-kind replacement assumes that the natural landscape reflects the optimal diversity by virtue of natural developmental processes and the adaptation of organisms to those conditions. While this may often be the case, disturbed landscapes, such as urban, agricultural, or mined areas, require a different approach. Selection of an appropriate diversity of species is an important step toward meeting wetland project goals.

## Succession

Vegetative composition of wetlands, particularly those that are newly created or have been subject to disturbances, continually change over time. As discussed in Chapter 6-1, changes occur in species composition, diversity, structure, and function as a result of continual changes in site conditions. This is due to both factors originating outside the plant community (e.g., colonizing species, hydrology, etc.) and to factors arising from within (e.g., increased soil fertility, shading, etc.), which progressively change the habitat and, therefore, allow the plant community to develop a progressively greater complexity and biomass (Bradshaw 1989). For example, in forested wetland restoration sites on old agricultural fields, there is a rapid change in species composition of annual and perennial herbaceous species that colonize the relatively open site during the initial years following site establishment. These species are eventually out-competed as the surviving planted trees and other trees and shrubs that have colonized the site grow in height and shade out the early herbaceous vegetation. These woody species continue to grow into a forested community dominated by tree species and herbaceous shade-tolerant annual and perennial species. These changes are termed succession.

Recognizing that succession will occur regardless of any installed planting or seeding program is important because natural succession can create new communities of great value or negate the project goals and objectives. Wetland project site characteristics such as species diversity, soil fertility, and hydrology will influence the rate and direction of succession. If, for example, the habitat has been reconstructed to a higher level of fertility than is required by the planted or desired vegetation, there may be a fairly rapid change in the community, analogous to what occurs in the forested wetland example given above, until a new community develops. The new community may or may not meet project objectives. If, on the other hand, the habitat has been reconstructed to a fertility level which targets the planted vegetation, there will be less or slower change (Bradshaw 1989). Natural disturbance events may re-direct succession (Pickett and White 1985).

These considerations are particularly relevant when targeting an early successional wetland. For example, restoring a wet meadow that will naturally succeed to a forested wetland may be considered a failure with time, without some means to manage the succession. However, a goal of most projects will be minimal management and the sites will be allowed to enter secondary succession. Other considerations associated with natural succession include:

*a.* complete loss of species planted into a site to later successional species (e.g., high-light plants will not be competitive in low-light environments and vice versa).

*b.* change in functions that can be supported by the wetland; and

*c.* loss or replacement of specific habitat and environmental conditions for targeted plant or animal species.

When selecting species to be planted into a site, consideration should be given to the following:

*a.* the existing successional stage; specifically, to the species composition, structure, functions, and diversity

*b.* the desired plant community for the site

*c.* the natural mature plant community that will develop at the site with succession

*d.* whether or not the site will be planted/seeded, or whether only natural revegetation will occur

*e.* whether or not some management of succession will be necessary. For most projects, control of succession should not be required, nor is it desirable.

These parameters affect the plant species chosen for planting, if any. If the site is allowed to enter secondary succession without subsequent intervention, the composition of the plant communities that develop will be a function of the site characteristics and changes in site characteristics over time. The final composition of the wetland, however, may not be predictable nor may not meet the intended project objectives.

## Wetland Ecosystems

As briefly discussed in Chapter 6-1, wetlands provide a wide array of functions that are valuable to man and other organisms. Wetland plant species should be selected to:

*a.* achieve the desired function(s) of the wetland, *b.* maximize achievement of the functions, and

*c.* provide the functions at the appropriate time of year.

The selection of wetland species for waterfowl habitat, for example, includes the selection of appropriate species for nesting or overwintering food and for habitat for a number of waterfowl species, each with different requirements. A number of vegetative species should be selected that can meet the waterfowl species needs year round. The selection of species to be planted in a forested wetland restoration site that will provide habitat for wood ducks and other waterfowl should include high energy foods during their molting period (e.g., oak acorns, hickory nuts) yet these seeds should be small enough to be swallowed. Therefore, relatively small seeded oaks such as willow oak (*Quercus phellos*) or water oak (*Quercus nigra*) should be selected. Not only is a knowledge of the desired function necessary, but a knowledge of the biological requirements for survival for the target waterfowl species is important to select appropriate species that will maintain the desired wetland functions (Payne 1992).

When substrate stabilization is a desired function, plants selected should have an extensive underground system of roots and rhizomes and should be easy to establish (Kadlec and Wentz 1974). Grasses are particularly well suited for stabilizing problem wetland soils. They are highly adaptable to various site conditions and provide a quick dense and lasting ground cover. The dense, fibrous root systems of grasses securely anchor soil and allow surface water to infiltrate more rapidly. The ability of many grasses to spread themselves quickly by surface and underground runners (stolons and rhizomes) is another important feature to evaluate when selecting species for soil stabilization (Lee et al. 1985).

In selecting plant species to be planted into a site, both the ability of individual species to meet the desired function and the ability of the assemblage species to meet the desired function must be considered. Additionally, the selection of species should also be compatible for achieving or performing multiple functions. Wetland plant species that may be optimum for one function may be detrimental to achieving another function. For example, plant species that establish rapidly and dominate an area may be desirable for substrate stabilization functions. However, if the restored wetland also is to provide habitat for aquatic species, these same plant species may form monocultures and could prevent the establishment of other species that may have higher value for cover, food, or habitat.

## Low Maintenance

Species selected for wetland restoration also should require limited maintenance once planted into a site. While some level of maintenance is likely to be necessary at a wetland restoration/creation site to ensure that the desired goals and objectives of the wetland restoration/creation project are sufficiently met over the long-term, low maintenance species should be selected to reduce costs. Low maintenance vegetation involves plants that grow well and reproduce at a given location in a particular climate with minimum care and remain free of serious disease or insect pests. Contrasted with this concept is wetland vegetation that require irrigation, fertilizer for growth and reproduction, and pesticide applications against serious disease or insect pests. Vegetation requiring intensive care is considered high maintenance vegetation. For successful wetlands restoration to be achieved the selection of vegetation adapted to the site and its land use requirements must be recognized (Environmental Laboratory 1986).

## Rate and Ease of Establishment

Species have different abilities to become established at a site. These different rates or the ease of establishment are important criteria to evaluate when the competition from species from the surrounding plant communities or from exotic species may be high, when erosion at a site may be high, and when project goals need to be achieved in a short time frame. Some species of marsh and aquatic plants are very aggressive and may quickly become established at sites with bare mineral or organic soils (e.g., cattails *(Typha*) and common reed (*Phragmites*)). While rapid establishment may be a desirable characteristic for species for wetlands restoration, it must be weighed carefully against the potential consequences of planting these species. Species that rapidly become established on a wetland site tend to dominate an area and exclude other plant species from becoming established on the site for a long period of time.

Often phased plantings are more successful than a single planting. The initial planting or seeding provides for soil stabilization and the development of a vegetative cover to ameliorate osmotic stresses. This is followed by a second planting one or two years later. The Seattle District of the Corps reports better success with phase plantings of maple, alder, willow and poplar followed by a subsequent planting of hemlock, cedar and spruce than with a single mass planting.

Grasses are often considered desirable species if the objective is to establish a rapid vegetative cover on the site. They are highly adaptable to various site conditions and provide a quick dense and lasting ground cover. Rapid colonizers often have the following features:

*a.* Produce seeds every year

*b.* Produce a high number of seeds each year

*c.* Possess efficient seed and propagule dispersal mechanisms

*d.* Possess seeds that germinate under a wide range of environmental conditions

*e.* Possess a means of vegetative reproduction (e.g., tillers, rhizomes, stolons)

When selecting wetland species for rapid colonization of restoration sites, select species with these features. However, caution is warranted, as these plants may limit the overall diversity. For some projects, it may be possible to select short-lived perennial grasses that are not aggressive.

## Selection of Species Compatible with Site Characteristics

The selection of wetland plants for establishment on a restoration site should be based on a knowledge of the species native to the area, the specific characteristics of the site, the possible restrictions of local ecotypes, the potential for site preparation and control, the ease of establishment and maintenance, and the project objectives.

This section provides a list of steps that will serve as a framework so that the above considerations will be addressed. Background knowledge about the site and the definition of required conditions and the goals of the site are assumed. Specifically, information should be available for the following:

*a.* Site hydrology including timing, frequency, duration, depth, etc. of inundation, ponding, soil saturation, and source(s) of water, etc.

*b.* frequency and magnitude of waves or currents (i.e., energy), if any

*c.* fetch, if present

*d.* soil conditions including, substrate texture, structure, chemistry, productivity, pH, density, or organic content

*e.* water quality

*f.* topography including, elevations, slopes or gradients, aspect

*g.* climatic conditions including temperature ranges, averages, durations; total precipitation and duration of precipitation events; humidity, sunlight, shading, etc.

*h.* biotic characteristics, including presence of desirable and undesirable species onsite especially exotic species, aggressive species, and species that form monocultures

*i.* prevalence of potential predators

*j.* probability of man-made disturbances such as compaction from trampling, off-road vehicles, etc.

## Framework Approach

The framework approach provided in the following sections uses a process of elimination for selecting wetland restoration plant species followed by a species ranking process. Using this approach, species not compatible with the site environmental conditions, problem species, and exotic species are eliminated from further consideration. The remaining species are then ranked according to a set of specific criteria, such as availability, cost, etc. Those species with the highest score, should be acceptable wetland species for the restoration site. This framework should be utilized and species should be selected for each of the different habitat types that are proposed for the site. Several species will be found that can be planted into all of the habitats. Others will only be identified as being appropriate for one or two habitat types. The final decision with respect to the number and the cost associated with species acquisition is dependent on the project goals and budget, and the time frame of the project. The cost of the project increases as the number of species transplanted onto a site increases.

## Framework for Species Selection

Use the following framework for each habitat type or community type to be restored:

*Step 1:* List the most critical characteristics of the site that exert the most influence on the survival and growth of plant species. Add the desired wetland functions to be achieved, and project budget for materials and manpower.

*Step 2:* Develop a list of species that would be compatible with the site hydrologic conditions including site water quality, water depth and energy characteristics.

*Step 3:* Of the species identified in Step 2, identify those species that are also competitive under the local or regional climatic conditions.

*Step 4:* Of the species identified in Step 3, identify those species that occur in the surrounding areas.

*Step 5:* Of the species identified in Step 4, identify those that would be competitive on and tolerant of the site soil characteristics and conditions, and that would be able to become established within the constraints of the site and the special requirements or problems of the site.

*Step 5a:* Of the species identified in Step 5, identify shade tolerance and intolerance and match these with site conditions.

*Step 6:* Of the species identified in Step 5 and 5a, identify those with the potential to be aggressive, out compete other natural species, and/or to form monocultures. Go to Step 6A.

*Step 6a:* Determine if any of these species are desirable for use in this site. Go to Step 7.

*Step 7:* Of the species identified in Step 5, identify if any are exotic species. **Eliminate these species from the list.**

*Step 8:* Of the species remaining from Steps 6 and 7, highlight those species that meet the desired wetland functions.

*Step 9:* Identify any species incompatibilities and note.

*Step 10:* Identify those species that are less tolerant to disturbance or stress, that are susceptible to extirpation by animals, insects, disease or other stresses such as wind, drought, etc., and note.

*Step 11:* From the list, identify those species that are a) available locally either at nurseries or in the wild, b) require contract growing, and c) are available only from a different geographic area. Rank the species from those that are locally available first, those that are contract grown second, those that need to be purchased from elsewhere in the U.S. last.

*Step 12:* Note costs of a) available species, b) contract growing, and c) acquisition from a different geographic area. All costs should include acquisition, shipping, handling, and storage.

*Step 13:* Identify those species that will meet the desired objectives of the restoration project. Rank them from highest to lowest in meeting the desired objectives.

*Step 14:* Select an array of species that are compatible with the site and with each other, that are resistant to disturbance and that will provide the desired level of species diversity at the site.

*Step 15:* Rank the species according to their needs for maintenance with those requiring lowest maintenance first.

The following are considerations when selecting species for a site:

- Eliminate the selection of exotic species
- Minimize the selection of species that are invasive, aggressive, and tend to form monocultures
- Select at least five to seven species that are adaptable to all the habitat types on the restoration site, knowing that some species are expected to fail
- Select a large array of species that are specifically adapted to the individual habitat types

# 6-5 Plant Sources, Propagation and Handling[1]

## Introduction

Plant materials can be obtained from either commercial or natural (wild) sources or they can be propagated from local materials and grown locally. Great strides have been made in recent years with regard to both diversity of native species and types of propagules available from commercial sources. Many species, however, are unavailable from commercial sources and will have to be collected from the wild or propagated and grown from local materials. Soil Conservation Service (1992) provides an extensive list of commercial sources for plant materials that are commonly utilized in wetland restoration, enhancement, or creation projects. In some instances, a project schedule and budget may facilitate contracting with a commercial firm for propagation of desired native materials. In many instances, however, a project has neither sufficient lead time nor budget to allow this.

Holding plant materials (either commercial stock or collected materials or locally grown materials) until planting time will necessitate special handling procedures. It should be determined during the initial project planning phases whether it is more advantageous to provide the special handling or to select species for planting that have minimal handling requirements in storage.

## Advantages and Disadvantages of Commercial versus Natural Sources

The advantages and disadvantages of commercial versus wild collection are discussed in Allen et al (1989). In general, natural (wild) sources of plant materials tend to provide certain advantages relating to genetic diversity and adaptation to local environmental conditions that are less available from nursery grown stock, but there are exceptions. This advantage is reduced or eliminated when local plants are propagated and grown for a specific project, but local growers are relatively few in many areas. The chief advantage of commercial propagation is mass availability of easily plantable stock. The type of propagule available is an important variable to consider in determining advantages of materials from the wild over those from commercial sources. A number of different forms of propagules are available for plant establishment in most

[1] By Janet Grabowski and Gary E. Tucker

wetland types, which tends to allow for some degree of flexibility. Cost considerations between wild collection and commercial propagation are region-specific. In some regions and for some plant types, commercial prices are rapidly dropping due to increased competition between nurseries and better expertise and efficiency in propagating the plants.

## Natural Sources

Advantages of stock from local natural sources may include:

*a.* Beneficial soil biota (including mycorrhizae) are usually present.

*b.* Better genetic diversity (except in those species that form large asexual clones) in plants.

*c.* Vegetation can better adapt to local conditions.

*d.* Plants can be collected as needed, reducing the need for extended storage.

*e.* A wide diversity of species is available.

Disadvantages of stock from the wild include:

*a.* Species must be accurately identified to ensure attainment of project goals. Identification difficulties will increase when collecting dormant herbaceous stock.

*b.* Dormant materials may not be available.

*c.* A suitable donor area must be located and permission obtained for harvesting whole plants or seeds.

*d.* Weedy species may contaminate the donor area and may be transplanted inadvertently.

*e.* Special expertise in collecting may be required and the plants may be damaged due to improper handling.

## Commercial Sources

Benefits of nursery grown stock generally include the following:

*a.* Propagules are usually more uniform in size and quality.

*b.* Potentially less labor required to obtain and maintain materials.

*c.* Avoids imposing environmental pressure caused by collecting in natural populations of wetland species.

*d.* Does not require the restoration team to have specialized expertise in collection, handling, and storage of materials.

Disadvantages of nursery grown stock include the following:

*a.* Plants may not be adapted to the local environment (contract growing can eliminate this problem).

*b.* Selection of species available and quantities may be limited.

*c.* Plants may arrive in poor condition or at wrong time.

## Availability of Propagules

Commercial wetland nurseries are becoming much more widespread, but while the list of species being propagated is ever increasing, many plant materials are still largely unavailable. Also, particularly in the case of species that are propagated from seed, variations in seed production from one year to the next affect the availability of nursery stock. For that reason, it pays to have a contingency plan for alternative plant materials in the event certain desired species are unavailable.

## Restrictions on Collection from Natural Sources

Collection of seeds or transplants from donor wetlands ultimately affects the health and vigor of the donor stand. This is true regardless of the amount of care taken in spacing and location of impacted areas and in the interval of harvest activities. For this reason, many states stringently regulate the collection of materials from the wild except in removal of plant materials from sites that are slated for total destruction by other activities. The state Department of Agriculture and local District Office of Army Corps of Engineers should be consulted for regulations and permits before collection. Written authorization will be required from landowners when scouting or collecting plant materials on private land.

Where commercial sources of plant materials are not available, the use of donor stands may be the only alternative. In those instances, particular care should be taken to prevent degradation of the donor site from excessive collection.

## Adaptability to Local Conditions

A project site should be vegetated with plant materials that are adapted to local climate and photoperiodic conditions. For the most part, dominant wetland plant species are widely distributed and across their geographic range contain a number of different ecotypes (ecological variants adapted to local conditions). Although the various ecotypes of these dominant species may be very similar in appearance, their physiological adaptability to local wetland conditions may be limited. For that reason, plant materials used in restoration, enhancement, or creation activities should have their origins as close as possible to the project site while at the same time coming from similar environmental settings as the targeted mitigation site. Proximity, however, is no guarantee of ecotypic similarity. Plants that are grown too far beyond their normal latitudinal range often represent ecotypes that are not in sync with the new environment and lack the potential to ever truly establish.

Local edaphic conditions often provide additional problems in the adaptation of plants from a distant site to a new habitat. The presence or absence of certain soil biota may play a significant role in determining whether or not a species establishes. A major factor in the high success rate with the use of transplants from local wetland sites is the presence of necessary soil biota (including but not limited to mycorrhizae).

## Source of Propagules

The successful establishment of a plant species at a restoration site greatly depends on the source of planting materials (propagules). The source of a propagule can be a limiting factor in two ways: 1) inability of propagules from one site to adapt to a different set of environmental conditions (ecotypes), and 2) limited gene pool diversity when the source is not varied.

Plant species often develop adaptations to local conditions. These adaptations frequently result in the formation of genotypic and phenotypic populations, especially in species with wide geographic ranges (Kadlec and Wentz 1974). Local genotypes or ecotypes, while being well adapted to local conditions, often do poorly when planted at a restoration site whose conditions are unlike those to which the species is adapted. A further discussion of ecotypes is provided in Chapter 6-3.

Obtaining propagules from a single source (i.e., a single plant or population) can decrease the genetic diversity of the wetland plants established at a site. Limited genetic diversity can affect a population's ability to survive under adverse conditions and can be subject to widespread losses of vegetation at a site. For example, in a bottomland hardwood restoration project, a group of large acorns from a single water oak *(Quercus nigra)* parent were sown in an old field in February. Acorns from other water oak trees were also sown at the same time. Initial germination tests indicated that acorns from all trees were viable. In mid-April, however, the large acorns were rotten and all subsequent samples of the large acorns were dead. Consequently, none of the large test acorns produced seedlings whereas under the same environmental conditions, over half of the acorns from the other parent oak trees developed into seedlings. The authors concluded that the sudden demise of the large acorns was due to some genetic or physiologic characteristic (Johnson and Krinard 1985). This example demonstrates the need for the sources of propagules to vary to increase genetic diversity of the species and to ensure the successful establishment of vegetation on a restoration site.

Consequently, the source of propagules can have a significant effect on the success of vegetation establishment at a restoration site. Ensuring that local ecotypes are obtained, utilizing widespread species with wide tolerances, and having several sources to maximize gene pool diversity will increase the likelihood of successful vegetation establishment.

Each of the propagule types can be obtained either through collection from the wild, large commercial operations, or under contract growing. In general practice, most individual species are typically established with only one or a few propagule types although several may be available. Those species that are annuals (capable of living a single season) typically can be established only by seed (e.g., *Polygonum lapathifolium*, nodding smartweed), while perennial species (capable of living for several to many seasons) can be established with at least several different types of propagules (e.g., most willows can be established from cuttings, transplants, rootstock, or container-grown stock). Commercial sources often provide only one or two propagule types for an individual species, however, even though the species may potentially be established with any one of several propagule types.

Propagule types can be grouped into two different categories: sexual and asexual. When a seed is used as a propagule, for example, it usually represents a sexual propagule that has been produced on the plant through a process involving genetic recombination. Seeds, therefore, are generally a potential source of tremendous variability. Plant a handful of seeds, and you have the potential of getting many different degrees of adaptability to variable site conditions among the seedlings. An asexual propagule, on the other hand, is a fragment of some plant part: root, stem, or leaf. A rhizome (e.g., *Iris pseudacorus*, yellow flag) is a part of an underground stem system, and often it is one that has been long established and is continuing to increase vegetatively in the absence of genetic recombination. In many shrub species (e.g., *Alnus serrulata*, common alder) an entire colony of plants may be connected together underground by a system of rhizomes, with each individual part genetically identical to the other. Asexual propagules are a source of uniformity and not variability, and in that sense may be less capable of providing a desired degree of adaptability to variable site conditions.

Project goals, site characteristics (e.g., susceptibility to erosion or amount of water onsite), permit requirements (e.g., percent cover requirements within a specified time period), amount of propagules needed, budgetary considerations, season, etc. are all factors to be considered in determining which type of propagule to use.

## Quantity

When determining quantity of required plant materials, one needs to consider the desired cover values and the amount of time allotted for reaching the desired condition. Additional factors will include an evaluation of site-specific conditions, including potential for erosion, damage from herbivores, etc. More propagules should be obtained than the estimate needed because of the possible loss of some propagules or death of some plantings.

Depending on project objectives, cover can be obtained by more or less intensive plantings. A planting established on 1-m centers, for example, requires 10,000 plants/ha. A 0.5-m spacing requires 40,000 plants/ha, and 2-m spacing requires 2,500 plants/ha.

# Costs

Vegetation costs are discussed in Chapter 6-6.

# Plant Propagation

The focus of the remainder of this chapter is plant propagation. The materials presented assume a nursery environment and are not directed at a discussion of mitigation site planting or seeding techniques.

## Seeds and Fruits

In an attempt to broaden the genetic diversity of a planting or seeding program, it is best to collect seeds from a number of individuals from several populations with differing phenotypic traits. Geographic origin (provenance), ecotypic variation, and other site factors of the seed source may affect the potential for successful establishment and growth of the offspring produced. Latitudinal differences in distribution are more critical in determining adaptability of provenances than longitudinal differences (Dirr and Heuser 1987). Correct identification of the parent plant is crucial. Fruits can be collected from seed orchards or production fields, from wild stands, from trees felled for timber, or from the water surface. Some plants do not produce an adequate quantity of seed yearly, so pre-planning and scouting of seed crops may be required. When collecting seeds, consider the effects of cross-pollination with neighboring plants. Fruits must be collected at the proper stage of maturity. Maturity indices have been documented in various references for many species, particularly economically important plants (Stein et al. 1974). Many seeds will disperse from the fruit and be lost if collection is delayed too long; others may enter a more pronounced state of dormancy making germination difficult (Hartmann and Kester 1975; Dirr and Heuser 1987). Collection dates for a species can vary annually due to weather conditions and variety or ecotypic characteristics. Some tree species mature their fruit over two years or longer and provide no sure indication of maturity, increasing the likelihood of collecting immature fruit. Experience and record keeping will increase success. Fruits or seeds can be harvested by hand - from the plant or from the ground after dispersal - or they can be harvested mechanically. Plant identity and collection information must be maintained throughout collection and processing. Dry fruits and cones can be shipped and temporarily stored in a variety of rigid or nonrigid containers prior to processing. Care must be taken to prevent heating and fungal growth (refer to the sections on shipping and storage for additional information) (Stein et al. 1974).

Fruits are processed to extract the seeds and to prepare the seeds for storage or planting. The seed of dry, indehiscent fruit often cannot be extracted and the fruit itself is usually sown as a “seed.” Processing methods have been designed for three general types of fruits: cones (strobili), fleshy fruits, and dry fruits. Seeds are generally extracted from cones by drying the cones to open them and shaking or tumbling the seeds out. In some cases, the cones are crushed to release the seed. Seed is then separated from foreign matter by screening. To aid sowing, wings and other adhering structures may need to be removed from the seed by rubbing. A final screening will produce clean seed. Fleshy fruits include berries, drupes, pomes, and fruits of gymnosperms with a fleshy aril surrounding the seed. Processing fleshy fruit involves macerating the flesh, separating the seeds with water, drying, and screening to remove dried flesh and other debris. Empty seed can usually be removed by flotation during the separation process. Processing should begin soon after collection and seeds should be dried quickly after separation to avoid fermentation; however, certain high moisture requiring seeds will not tolerate drying during the processing. Some fruits with a thin layer of flesh can be dried and sown with the fruit coverings intact; however, many seeds will become dormant if handled in this manner. Dry fruits may require little processing other than cleaning to remove debris. Others may require drying and additional processing to remove fruit structures, wings, or other appendages that interfere with planting. Fragmentation of large fruit clusters is often required (Stein et al. 1974).

Seeds often need to be preconditioned by various treatments to overcome dormancy mechanisms and allow germination. It is not unusual for seeds to have multiple dormancy mechanisms, each requiring a separate treatment method (Dirr and Heuser 1987; Hartmann and Kester 1975).

Some seeds have hard, impervious seed coats that must be altered to allow germination. Sometimes all that is required is fall planting and allowing natural processes to abrade the seed coat (Dirr and Heuser 1987). Soaking seeds in water or even in hot water (77 to 100°C) can also be used to soften seed coats of some species. The most common method of treating hard seed coats is scarification. This can be done mechanically by rubbing with sandpaper, filing, or cracking the seed with a hammer or a vise, or in machines made especially for this purpose. Care must be taken to avoid damaging the embryo when mechanically scarifying seed. Seeds can also be scarified by soaking in concentrated sulfuric (occasionally nitric) acid. These acids are very caustic and will react violently with water, so protective clothing should be worn during treatment. Propagation references include recommended treatment durations for most hard seeded species; however, lot characteristics and treatment conditions can affect seed response. The mixture must be carefully stirred occasionally to avoid clumping. Periodically, seed samples should be removed from the acid and cut open to check seed coat thickness. End treatment when the seed coat becomes paper thin. The acid should be decanted and washed from the seeds and the seeds dried before use. Scarified seeds will not tolerate storage for extended periods of time, so the seeds should be used soon after treatment (Bonner et al. 1974).

Moist chilling or cold stratification allows the embryo to undergo a period of after-ripening that allows germination. Stratification can be done naturally by fall planting. It can also be done by storing the seeds in a refrigerated storage area. The seeds must be fully hydrated for after-ripening to occur, so impermeable seed coats must be scarified before stratification. The seed lot is then mixed with one to three times its volume of a moist, but well aerated medium, such as peat moss, sphagnum moss, sand, or vermiculite. Fungicides may be added to the medium. Storage temperatures should be 2 to 7°C. Some species can be stratified at higher temperatures, but longer storage periods may be required and premature sprouting may occur. After-ripening will cease at temperatures above 15.5°C. Each species will have different requirements; however, stratification for 1 to 4 months is usually sufficient. Seeds should be checked frequently for radicle emergence and planted promptly if this occurs. Various containers can be used for the seed mixture, including boxes, jars with perforated lids, cans, and plastic bags or they can be planted directly in flats providing the medium can be kept constantly moist (Bonner et al. 1974). Oxygen is required for the physiological processes of after-ripening to occur, so thick plastic bags and other containers that restrict air movement are not acceptable. Seeds should not be allowed to dry during stratification or the after-ripening process will be adversely affected. The seeds should be planted immediately after removal from stratification without drying (Hartmann and Kester 1975).

Some seeds have rudimentary embryos requiring a period of warm, moist exposure, often referred to as warm stratification, for embryo maturation. Seeds are handled using the same methods as described for cold stratification, but the temperatures should be 20 to 30°C. Temperature fluctuation does not appear to be as critical as for cold stratification and may be required for some species; however, more or less constant temperatures are usually best. Seeds that require warm stratification often require a subsequent cold stratification treatment for germination to occur. In this case, outdoor planting will require less management; however, these treatments can also be done under more controlled conditions (Hartmann and Kester 1975).

Since stratification can be a time-consuming process for some species, chemical stimulants have been tried to overcome dormancy and enhance germination. Chemicals such as gibberellic acid, cytokinins, ethylene, potassium nitrate, thiourea, and sodium hypochlorite have been shown to stimulate germination of some seed, but response is very species-specific and widespread nursery use may not be possible (Hartmann and Kester 1975).

After collection, cleaning, and application of the appropriate pretreatments, viable seeds must be exposed to the proper environmental conditions for germination to occur. Species can have various responses to temperature. After cold stratification, some seeds will enter secondary dormancy if exposed to high temperatures. Germination temperatures for these species should be 10 to 17°C. Other stratified seeds will not germinate without warm temperatures. Seeds of these species should be germinated at 20 to 30°C. Other species, including those with stratification and non-stratification requirements, will germinate over a wide temperature range from 15 to 32°C. Temperature requirements of the seeds being sown will affect planting schedules. For example, temperature insensitive species sown in the fall may germinate prematurely and be damaged by winter temperatures. Moisture is another requirement for germination. Seeds must be hydrated to germinate, so the medium must provide constant moisture, but if too wet, diseases such as damping-off and physiological problems can affect the seed. Exposure to light is required for some seeds to germinate. Light requiring seeds will not germinate if deeply covered; however, shallow planting will make them more susceptible to drying. Seeds generally do not require fertilization for germination and high soluble salts around the seeds can inhibit germination and damage seedlings. After germination and root growth has occurred, moderate levels of fertilizer should then be applied for vigorous growth. Seeds can be sown in greenhouses, cold frames, hot beds or other structures or they can be sown outdoors. Temperature and environmental conditions are easier to control in structures, but they are more expensive to maintain and the crop will require more labor. Outdoor sowing can also provide the appropriate germination pretreatments under natural conditions (Hartmann and Kester 1975).

Plants grown in structures (greenhouses) can be sown in seed flats for later transplanting, or direct sown into containers. More greenhouse space is required for direct sowing, but the plants will not experience the growth checks associated with transplanting. There are many types of containers that can be used; tall, bottomless containers are becoming popular, especially for tap-rooted species because they provide air pruning and promote root branching. Growing media for flats and containers must be sterile and well aerated, but still have high moisture holding capacity. The media should be low in soluble salts. Various mixes of peat moss, vermiculite and perlite or other types of artificial mixes have been used successfully. Mixes containing field soil are not widely used today due to the necessity for sterilization and variability of supply. Fungicides may be applied to the seeds or the growing medium to protect against diseases. Protection must be provided against insects and small rodents that can damage seed or seedlings. Seeds are sown and covered by 2 to 3 times their minimum diameter. Small seeds and those with a light requirement should be placed on the surface and not covered. Artificial lighting may prove beneficial for light-requiring seeds. Proper germination temperatures must be maintained. Cool conditions will promote damping-off, and high temperatures increase drying and may force some seeds to enter secondary dormancy. Moisture can be maintained by the use of an intermittent mist system or by covering the flats or containers with plastic or glass. Coverings can increase temperatures so shading may be required. All coverings must be removed following germination. After germination and root growth, temperatures can be reduced and moisture levels decreased somewhat. High light is important for good growth. Seedlings in seed flats must be transplanted before they crowd each other. They can be transplanted after the first true leaves (not cotyledons or 'seed leaves') appear until 4 to 6 leaves are present. Root pruning during transplanting is often desirable. Before greenhouse-grown seedlings can be moved outdoors, growth must be hardened-off by a gradual reduction in temperature, water and fertilizer levels.

Seedlings grown outdoors can be planted in seed beds for transplanting into the field or containers, or direct sown in nursery rows, wet cells or containers. As discussed for greenhouse production, direct sowing saves labor and plant stress, but the increased growing area is more difficult to maintain. It is important to plant at the proper time of year so that environmental conditions are appropriate for germination. Soils should be well drained and thoroughly tilled before planting. Addition of organic matter can improve water holding capacity and friability. Preplant soil fumigation may be desirable to reduce weed and disease problems. Container media should also provide adequate aeration and water holding capacity. Bark-based media have become very popular for container culture. An irrigation system is required to provide the necessary moisture. The seeding rate depends on species and germination percentage. In seed beds, seeds can be planted in rows or broadcast on the bed, which allows closer spacing. For direct field sowing, seeds should be planted in rows at a spacing of 10 to 20 cm apart depending on species. Direct sowing in containers often requires several seeds to be planted and subsequent thinning to ensure a seedling in each container. Seeds are planted using the same techniques covered under greenhouse production. Planting depth should be two to four times the seed diameter. Light-requiring seeds will need to be planted near the surface. Weed growth must be controlled to prevent competition with the seedlings. Fumigants and herbicides are chemicals that can be used to control weed growth. Mulching seed beds or nursery rows will also help control weeds as well as conserve moisture, control soil temperature fluctuations, and prevent erosion. Crusting of the soil surface following rains or irrigation can prevent seedling emergence. Careful irrigation, mulches, or an application of vermiculite above the seed will help alleviate this problem. Some species will require shading during early growth. Plants in seed beds will need to be transplanted before crowding occurs.

## Vegetative Propagules

Transplants can be vegetatively produced from cuttings, divisions, by grafting or budding or by tissue culture, often referred to as micropropagation or *in vitro* propagation (Hartmann and Kester 1975).

### Cuttings

Propagation by cuttings is the most commonly used vegetative propagation method, especially for woody plant species. Cuttings can be taken from all parts of the plant, and each species of plant will be best suited to one or several cutting methods. Cuttings should be taken from vigorously growing plants of known identity that are free of disease, insects, and other damage. Virus diseases are particularly troublesome. Callus, an undifferentiated proliferation of tissues, is usually produced at the point of wounding and is involved in root formation. For woody species, juvenility or age of the wood from which the cutting is made has an effect on the ease of rooting. Juvenile tissue will form roots more easily than mature tissue. Some species, varieties, or individuals will root more easily than others placed under similar conditions, leading to a great deal of variability in the success of cutting propagation. Another factor that affects rooting is polarity. All types of cuttings must be planted in the same physical orientation as they were growing on the stock plant (the basal end down). Often the basal cut is made at an angle to mark its polarity. Girdling or etiolation of the tissue prior to cutting removal can increase root formation. The time of year that cuttings are taken, nutritional status of the stock plant, and whether or not the plant is flowering can also affect rooting ability (Hartmann and Kester 1975).

### Stem Cuttings

Stem cuttings can be classified as hardwood, semi-hardwood, softwood, or herbaceous, depending on the type of plant, stage of growth, and time of year that cuttings are taken. The cutting itself consists of a segment of the shoot containing lateral and/or terminal buds. The cut is generally made just below a node. Cuttings that have leaf growth must be kept from drying while handling and rooting. The cuttings should be taken early in the day when temperatures are low and processed quickly. Lower leaves that interfere with placing the cutting in the rooting medium should be removed. Rooting of several woody species is enhanced by wounding the base of the cutting (making cuts through the bark) before placing in the rooting medium (Hartmann and Kester 1975). Willows (*Salix* spp) are commonly established from tip cuttings of stems.

Hardwood cuttings are taken from deciduous woody species during the dormant season. Cuttings consist of wood from the previous season's growth. They can range from 10 to 76 cm long and should contain at least two nodes. The cut can be straight across the stem or it can be made so that the base of the cutting contains a “heel” or “mallet” of older wood that can promote rooting of some species. Cuttings can be stored until spring, or planted when taken. Because the cuttings are dormant, they are not as sensitive to environmental stress as cuttings of actively growing tissue. That makes hardwood cuttings the least management-intensive type of stem cutting; however, difficult-to-root species generally will not root from this type of cutting due to the age of the wood used. Hardwood cuttings are often rooted in outdoor beds with little environmental control. Many conifers can also be rooted from cuttings. Cuttings are made from terminal growth (10 to 20 cm long) of the previous season's wood. Although not actively growing when taken, these cuttings have leaves attached and must be rooted under conditions that prevent drying. These cuttings are rooted in greenhouses or other structures in conditions of moderate to high light and high humidity (Hartmann and Kester 1975).

Semi-hardwood cuttings are taken in the summer from broad-leafed evergreen or deciduous species. The cutting is taken from the current season's growth after the spring flush of growth has taken place and the wood has partially matured. The cuttings should be 7.5 to 15 cm long and should contain at least two nodes. If the leaves are large, those to be left on the cutting should be cut to reduce water loss and, as for all leafy cuttings, humidity should be kept high during rooting (Hartmann and Kester 1975).

Softwood or greenwood cuttings are taken from the soft, new spring growth of deciduous or evergreen species. Softwood cuttings consist of the terminal 7.5 to 13 cm of the shoot with two or more nodes. These cuttings are from extremely juvenile tissue and will generally root more quickly than other cuttings, but the succulent nature of the tissue makes them more difficult to handle. Strict environmental control is required to successfully root softwood cuttings (Hartmann and Kester 1975).

Herbaceous stem cuttings are made from plants without woody stems. They should be 7.5 to 13 cm long and will also require strict environmental control (Hartmann and Kester 1975).

## Leaf Cuttings

Leaf cuttings are most commonly used for herbaceous species. Cuttings consist of the leaf or leaf blade and petiole. Adventitious roots and shoots form from the leaf base. Some species will not spontaneously form shoots and will require a small piece of stem with the attached axillary bud to form a new plant. This type of cutting is called a leaf-bud cutting. Both types of cuttings will require high humidity conditions for rooting and growth (Hartmann and Kester 1975).

## Root Cuttings

Root cuttings are taken in the dormant season when roots are well supplied with stored food. Plants with small delicate roots are cut into 2.5- to 5-cm sections and planted horizontally on the surface of the rooting medium. They are subject to drying, so they must be planted in the greenhouse, generally under mist. Plants with fleshy roots are sectioned into 5- to 8-cm pieces and planted vertically. These are also best planted in the greenhouse. Plants with large, less succulent roots can be planted outdoors. These cuttings should be 5 to 15 cm long and may benefit from a curing period at 4.5°C in damp sand, sawdust or peat moss before planting vertically in the rooting medium (Hartmann and Kester 1975).

## Techniques

Rooting media must be well drained. Soil (preferably sandy loam), sand, peat moss, vermiculite, and perlite can be used alone or in combination for rooting various types of cuttings. Soil should be sterilized to prevent diseases. Sanitation of the propagation area is very important to prevent diseases. Workbenches, tools, flats and anything else that touches the cutting should be treated with a disinfectant solution and hoses should be kept off the ground. Fungicides can also be used to prevent disease development. Treating the basal portion of stem cuttings with root-promoting chemicals is standard practice for species that are difficult to root. It is generally not economical to treat easily rooted species. The most commonly used chemicals are the synthetic auxins, indole-3-butyric acid (IBA), and naphthalene acetic acid (NAA). Recommended rates of application will be expressed as percentages or parts per million (ppm). It is important to use the proper rate, because these chemicals can be toxic at higher concentrations. They can be applied in a powder or talc formulation, often with other chemicals, such as fungicides. This formulation is easy to apply, but results are often variable since differing amounts of powder may adhere to the cutting. A liquid dilute soak, usually 24 hours in length, can also be used but is very time consuming. Quick dips of more concentrated solutions for 5 seconds is less time consuming, but has the potential for burning the cuttings if not done properly. When using hormone formulations to treat cuttings, transfer a small amount into a separate container to avoid possibly contaminating the entire stock solution or powder. Proper environmental conditions for rooting all types of non-dormant cuttings include ample light for photosynthesis and high humidity to reduce moisture loss. High humidity can be maintained by coverings (glass, plastic, etc.), by applying water to greenhouse surfaces, or automatic mist systems that apply water to the leaf surface. Nutrients can be applied with mist and will be beneficial for some species and disadvantageous for others. After growth begins mist can be reduced and cuttings can be fertilized at moderate levels. Temperatures in the greenhouse or other structure should be 21 to 27°C during the day and 15°C at night. Heating the growth medium (bottom heat) to 24 to 26.5°C is often beneficial for many types of cuttings. Cuttings may require one or more year's growth before being lined out in the nursery or potted in containers. Container media should be similar to that used for container-grown seedlings. All cuttings grown in the greenhouse must be hardened-off gradually before moving them outdoors (Hartmann and Kester 1975).

# Division

Division is the separation of one parent plant into two or more individuals. Plants can be divided in various ways depending on their growth habit. Many plants produce specialized underground organs such as rhizomes, corms, tubers, and bulbs whose main function is to store food reserves. These structures are modified stems, and as in aerial stems, they contain nodes with meristematic tissue that can be divided to produce new plants (Hartmann and Kester 1975).

## Crowns

The crown is that part of a plant near the surface of the ground where new shoots are produced. Herbaceous plants, especially those with rosette growth habits, are readily propagated by dividing the crown; woody plants with several stems can also be divided. Parent plants are dug during the dormant season and cut into several sections. Each section should contain one to several shoots, several roots, and possible rhizomes or other structures. If plant material is not limiting, it is best to use the younger sections around the outer edge of the clump and discard the older, center part. Shoots and/or roots can be trimmed to decrease water loss and facilitate planting. The sections are then grown until large enough to survive planting in the landscape (Hartmann and Kester 1975).

## Suckers

A sucker is a shoot which arose below ground, from adventitious buds on the roots or stem base. Suckers can be cut from the parent plant and grown to plantable size. Digging will usually be done in the dormant season (Hartmann and Kester 1975).. Examples of species that are commonly established from suckers include corkwood (*Leitneria floridana*) and Virginia willow (*Itea virginica*).

## Rhizomes

Rhizomes are modified stems that grow horizontally at or just below the soil surface. They can be thick and fleshy or slender with long internodes. Rhizomes can be propagated by cutting the rhizome into sections, with each section containing at least one node. Sections are laid horizontally in a well-drained growing medium. Another method involves removing and planting lateral offshoots from the rhizome. These offshoots already contain shoots, stems, and roots and merely need additional growth to reach plantable size (Hartmann and Kester 1975). Examples of species that can be established from rhizomes include smartweeds (*Polygonum*), softstem bulrush (*Scirpus validus*), and creeping spikerush (*Eleocharis palustris*).

## Corms

A corm is a modified stem, consisting of a swollen base, enclosed by dry, scale-like leaves. Corms are food storage organs, but they are also a reproductive structure that contains a flowering shoot. When a corm flowers, its reserves are used up in flowering and it disintegrates, but it produces one or several corms in its place. Propagation involves digging the new corms in the dormant season. Smaller corms, called cormels, will require one to two year's growth to reach plantable size. Corms can also be propagated by cutting the corm into sections with each containing at least one bud. Each section should produce a new corm. Pieces need to be treated with a fungicide to prevent decay (Hartmann and Kester 1975).

## Tubers

Tubers are modified below-ground stem structures that are swollen to accumulate food reserves. The parent plant will produce several tubers each growing season. Species with large tubers can be propagated by cutting the tuber into sections that contain an “eye” or bud. The sections should be stored at high temperatures (20°C) and high humidity for two to three days to allow the cut surfaces to heal before planting. They can also be propagated by planting the entire tuber (Hartmann and Kester, 1975). Duck potato or wapato (*Sagittaria*) and chufa (*Cyperus esculentus)* are typically established from uncut tubers.

### Bulbs

Bulbs are specialized organs consisting of a short, fleshy stem axis enclosed by thick, fleshy scales. They have storage and reproductive functions similar to corms. Some bulbs disintegrate after flowering, and others do not. Bulbs produce several smaller bulbs (bulblets or offsets) that can be removed from the mother bulb, and grown to plantable size. Some plants will produce aerial bulblets in the leaf axils or inflorescence that can also be grown to produce plantable bulbs. Other propagation methods are scaling, or removing and planting scales from the bulb or by sectioning the bulbs in a similar fashion as corms (Hartmann and Kester 1975).

## Layering

Layering is a propagation method where shoots are rooted while still attached to the parent plant. Since the shoot still receives nutrients from the parent plant, layering is generally a more successful propagation method than rooting cuttings, especially for plants that are difficult to root. However, layering is a labor-intensive propagation method. Many plants produce layers naturally, or layering can be induced by artificial methods (Hartmann and Kester 1975).

### Stolons

Stolons are modified, horizontally borne stems. They will root and produce shoots at nodes along the stem. New plants can be removed from the parent plant and grown to larger size (Hartmann and Kester 1975).

### Induced Layering

Rooting depends on a breach in the downward movement of organic materials (carbohydrates, auxins, and other growth-regulating materials) through the stem, creating an area where these materials accumulate. Root formation is promoted by elimination of light in this area. The breach or movement typically is accomplished by bending, cutting, or partially or completely girdling the stem. Application of a root-promoting substance, such as IBA (3-indolebutyric acid), can be applied to the rooting area to speed rooting. Light can be eliminated by placing soil or a rooting medium around the rooting area. Root formation requires optimal moisture, aeration, and temperature levels in the rooting medium. Younger shoots will layer more easily than older material. Layering will generally take at least one growing season. Tip layering involves bending the tip of the shoot to the ground and burying it into the soil. Natural growth will cause a sharp bend as the shoot attempts to grow upwards and is impeded by the soil. Rooting will occur at the point of bending. Simple layering involves bending a stem to the ground, and partially covering it with soil or rooting medium, leaving the terminal end exposed. The stem is bent or cut to induce rooting and often requires a peg, wire, or stone to hold it in place. Serpentine layering is similar to simple layering, but a long, flexible stem is alternately buried and exposed along its length to produce several plants. In air layering, rooting is accomplished on stems above the soil surface. The stem is girdled close to the tip and the rooting area is wrapped in a damp medium, such as sphagnum moss, and generally is contained in a moisture-proof covering. Frequent monitoring is required to maintain the proper moisture and temperatures in the rooting medium. Mound or stool layering is done by cutting a plant to the ground when dormant. Soil or rooting medium is then mounded around the base of the newly developing shoots to eliminate light and encourage rooting. Rooted plants can be removed from the parent plant and grown to plantable size. Trench layering is a similar method where plants or branches are grown in a horizontal position in the base of a trench. Soil is placed around the new shoots as they develop, encouraging rooting at their bases (Hartmann and Kester 1975).

## Grafting and Budding

Grafting and budding are methods of propagation where two woody plants are united together to form one. The scion is a short piece of shoot, or in the case of budding, a bud and surrounding tissue, that will form the shoot of the grafted plant. The rootstock is the lower portion of the graft which forms the root system for the grafted plant. Several techniques of grafting and budding have been developed. Grafts occur when the scion and rootstock are compatible (usually genetically related), the cambium of the rootstock and scion are properly aligned, and environmental conditions are correct. Grafting and budding are very labor intensive, and are mainly used for high value, ornamental or fruit trees. Planting large areas with grafted trees is usually not economically justified.

## Tissue Culture

Tissue culture, also known as micro- or *in vitro* propagation, is the production of new plants under aseptic conditions from small pieces of the parent plant (referred to as explants). Embryos, seeds, shoot tips, root tips, callus, ovules, anthers, pollen grains, and single cells can be used as explants. These plant parts are only able to regenerate a new plant when externally supplied all nourishment (water, carbohydrates, hormones, vitamins, and other growth factors) in the culture medium. The propagator can control the growth and development of the cultures by varying constituents of the medium. Methods used are usually quite specific for an individual plant species. Common aspects of tissue culture for all species include using pathogen-free explants and maintaining freedom from disease during culture, controlling the amount of mutations that occur, and proper hardening after culture to allow the plants to survive nursery or greenhouse conditions. Tissue culture can produce large amounts of vegetative propagules quickly and is especially suited for plants that are difficult to propagate by other means (Hartmann and Kester 1975).

## Transplants

The term “transplants” is perhaps better used in a discussion of planting methods than as a propagule type, but it has been used both ways in the literature (Environmental Laboratory 1978; Allen and Klimas 1986). When used as a propagule type, the term typically is applied to an entire plant that is removed from the wild and replanted in another site. The “transplanting method” makes little distinction between bare-root seedlings, rooted or unrooted cuttings, balled-and-burlapped plants, containerized plants, sprigs, plugs, rhizomes, and tubers (Allen and Klimas 1986). When removed during the dormant season, a transplant may be moved with or without soil, but during the growing season a transplant typically is moved with its soil intact to reduce shock from root loss and disturbance. The term sprig generally refers to smaller transplants, often very young, that are removed and planted in the same fashion. Transplants and sprigs are the most common type of propagule used in marsh establishment. Examples of woody species that can be established with transplants include arrow arum (*Peltandra virginica*), arrowhead (*Sagittaria* spp.), and cattails (*Typha* spp.).

# Storage

## Seeds and Fruits

Seeds of each plant species have inherent characteristics that impose limits on the capacity for long-term storage. Species with short-lived seeds include those with large fleshy seeds or nuts, and certain wetland or aquatic species (most of which cannot tolerate seed drying), as well as those species adapted to immediate germination following dispersal. Short-lived seeds cannot be stored for periods longer than one year. Species with medium-lived seeds, which include most crop seeds, will retain viability for two or three and perhaps up to 15 years, provided proper environmental conditions are maintained during the storage period. Long-lived seeds have hard, impermeable seed coats that will retain viability for at least 15 to 20 years without environmental modification (Hartmann and Kester 1975).

Within these limits, retention of viability during storage for each seed lot depends on the stage of maturity during collection, pre-storage care and handling, initial viability, seed moisture content, storage environmental conditions, and degree of infestation with pathogens or other pests. Fully ripened seeds will maintain viability in storage longer than seeds collected when immature. Seeds with high initial viability can be stored more successfully than seeds of that species with low initial viability. Viability should be tested before placing seeds in storage. There are references that explain testing procedures, or seed can be tested by a seed testing lab. Only the best seeds should be used for long-term storage. Seeds physically damaged during collection and processing or with insect or disease damage will quickly lose viability during storage (Stein et al. 1974).

The goal of seed storage is to slow respiration and other metabolic processes without injuring the embryo. This can be accomplished by reducing temperatures, reducing seed moisture content, and reducing the relative humidity of the air. Some medium-lived seeds can be stored for short periods of time exposed to ambient environmental conditions; however, the reduction in viability will generally be unacceptable for long-term storage in this manner. Under these same conditions, long-lived seeds will not lose viability. Short-lived seeds cannot be exposed to ambient conditions or viability will be quickly lost (Hartmann and Kester 1975).

Storage temperatures can be controlled by placing the seeds in refrigerators, walk-in coolers, or refrigerated storage buildings. Seeds can also be stored through the winter months outdoors on or in the ground or in sheds; however, temperature fluctuations and drying may reduce viability or result in premature germination. Storage temperatures should be between 0 and 10°C. Some species will tolerate subfreezing temperatures; however, it is often not feasible to maintain these low temperatures for long periods of time or for large seed lots (Hartmann and Kester 1975).

Except for wet-stored species, the ideal seed moisture content for storing medium-lived seeds will be between 5 and 12%. Seeds should be dried to this moisture level during processing. This low moisture content can be maintained in storage by placing the seeds in moisture-proof containers or in dehumidified storage areas. Short-lived seeds that are intolerant of such drying may require up to 40% moisture. This high moisture can be maintained during storage by mixing with a damp medium (sphagnum or peat moss, sawdust, etc.), by storing in aerated water (fresh or brackish), or for larger seeds, by coating in paraffin or latex (Hartmann and Kester 1975).

Seed moisture content and the relative humidity of the air are at equilibrium. Storage at high relative humidity will increase moisture content and reduce viability of most seeds. For long-term storage, the relative humidity should be between 20 and 25%. Additional modification of the storage atmosphere, such as reduced oxygen levels, is also beneficial for some seeds (Hartmann and Kester 1975).

Seeds should be containerized to facilitate handling and environmental control. Containers that can be used for seed storage include burlap or cloth sacks, cardboard drums, metal cans or drums, glass jars, plastic or paper bags, and plastic-lined foil pouches. The type of container used depends on storage conditions and species requirements. Moisture-proof containers, such as plastic bags, will prevent water gain for dry seeds and water loss for seeds with high moisture requirements. If the seed moisture content is higher than desired, do not place the seeds in a moisture-proof container or the seed will be damaged. In this case, a container that allows air exchange should be used. Some seeds are easily damaged by handling and should be placed in rigid-wall containers. Water-absorbing chemicals (silica gel beads, charcoal, calcium chloride) can be placed in the seed container to maintain low moisture content; however, care must be taken to not over-dry the seed. All seed containers should be labeled to indicate species, source, and collection date. Some substances will give off fumes toxic to seeds. All storage areas and containers should be checked for this before use, and potentially harmful substances should not be allowed in a seed storage area. The amount of entrapped air and associated humidity can be minimized by completely filling the container. Container shape and stacking pattern should facilitate handling, aeration, and proper temperature control (Stein et al. 1974).

Seeds must be protected from pest attacks while in storage. Rodents will be a problem unless the storage area is screened or otherwise tightly enclosed, or the containers are designed to exclude them. Traps or poisoned bait can be used as a control; however, some damage will occur before control is achieved. Insect and disease activity is reduced or eliminated at low temperature and low seed moisture content. If proper environmental conditions cannot be maintained during storage, insecticide, fungicide, or fumigant treatment may be necessary.

## Woody Species

To successfully store whole woody plants, respiration and transpiration processes within the plant must be kept to minimum levels and the action of fungal disease organisms reduced. These activities will be slowed when storage temperatures are reduced, as long as kept above critical plant damage levels. Storage temperatures should be between -2 and 1.5°C. Most deciduous plants are best stored nearer the upper limit of the range and coniferous plants at the lower end of the range. Temperatures must be monitored regularly and should not be allowed to fluctuate or plant damage may occur. The relative humidity of the storage area must be high to reduce transpiration and ensure survival. When plants are stored at the recommended temperature levels, relative humidity should be kept at approximately 90%. Relative humidity can be increased by humidifiers or by applying water to the storage area floor. Do not apply water to the plants themselves or disease activity will be enhanced. Relative humidity should be checked frequently using a hydrometer, a sling psychrometer, or electronic sensors (Davidson and Mecklenburg 1981).

Various methods can be used to store plants. In areas with cold winters, plants can be stored outdoors with the roots heeled-in a damp medium such as peat moss, sawdust, or finely ground wood chips. They should be planted or shipped before the onset of growth in the spring. More commonly, plants are overwintered in structures such as cold frames, shade houses, or plastic houses. Within these structures, the roots must generally also be heeled-in for protection. A disadvantage to these outdoor storage methods is the lack of environmental control which can result in plant injury due to low or high temperature exposure and increased disease. The common storage method uses natural ventilation to cool an insulated building. Since cool air is heavier than warm air and will sink to the bottom of the building, the storage area can be cooled by opening vents in the wall or drive-through doors at night and warm air can be expelled by opening vents in the roof. This method requires a great deal of monitoring to be successful and is not acceptable when outside temperatures are high. The most uniform storage method is the use of refrigerated storage areas. There are several refrigeration methods available and the storage area can range in size from a walk-in cooler to whole buildings depending on the amount of nursery stock to be stored. Temperatures and humidity can be precisely controlled using refrigeration and stock can be successfully stored for a longer period of time. Controlled atmosphere refrigerated storage, where the carbon dioxide levels are increased and oxygen levels reduced, will further reduce respiration rates, but is not economical for most nursery stock. Good air movement is important for maintaining temperature levels during storage; however, high velocities will increase plant transpiration. Storage areas should have circulation fans installed to provide air movement of approximately 15 meters per minute. Plants are usually stacked in bins or boxes or on ricks, pallets, or frames to facilitate handling. Proper stacking and spatial arrangement of plants and containers will ensure proper air movement; there should be air passages between the stacks and the walls and ceilings of the storage area (Davidson and Mecklenburg 1981).

Potential problems that may be encountered in nursery storage areas are desiccation, freezing, fungi, rodents, and exposure to damaging gases. Desiccation will be minimized if proper environmental conditions are maintained throughout storage. Some dormant, bare-root plants can be coated with paraffin wax to further reduce moisture loss. The root system of plants is usually more prone to freezing damage than the shoots. Damaging temperatures depend on species and stage of maturity; however, most plants cannot tolerate root exposure to temperatures less than -3°C. When low temperatures are expected, plants stored outdoors will need to have their root system protected by mulching with wood chips, sawdust, or shredded polystyrene, or the entire plant covered with a thermal blanket (microfoam). Fungal diseases can be prevented by good sanitation of the storage area, use of fungicides, and maintaining proper environmental conditions. Rodents will damage plants severely in storage if not controlled. Control methods are discussed under seed storage. The most prevalent gas that damages nursery stock is ethylene. Fruits, vegetables, and decaying plant material all generate ethylene. Fruits and vegetables should not be allowed in storage areas and the area should be cleaned regularly to prevent ethylene release. Ammonia and carbon monoxide can also damage nursery stock and sources of these gases should be eliminated. Plant identity must be maintained during storage (Davidson and Mecklenburg 1981).

## Bare-Root Seedlings

Bare-root plants are dug with no ball of soil around the root system. The seedlings are dug beginning in the fall and must be fully dormant for proper winter storage. Natural hardening processes that take place in the fall precondition plants for storage. Steps that can be taken to speed the onset of dormancy include withholding water and nitrogen fertilizer in late summer, root pruning in early fall, and avoiding top pruning after midsummer. Deciduous plants that have not defoliated naturally can be defoliated by hand stripping, using rubber-fingered mechanical beaters, or using chemical defoliants (potassium iodide, Bromodine, Ethrel). These methods are time consuming and can inflict considerable damage to nursery stock if not used properly. Plants are graded and bundled before storage. Plants packaged for marketing (e.g., with roots wrapped with peat moss or sphagnum moss, or plants with clay or gel) will often be packaged before or during storage. Bare-root stock is best stored in refrigerated or in common storage, to protect against freezing injury and desiccation. However, many dormant, bare-root deciduous plants have been stored successfully in outdoor heeling-in grounds when the root systems were adequately protected. Storage temperatures should not fluctuate 1.5°C above or below recommended levels or plant damage can occur (Davidson and Mecklenburg 1981).

## Containerized and Balled and Burlapped

Containerized plants are grown in some kind of container that holds the root system and growing medium. Soil-balled plants are field grown and dug with a ball of soil around the roots which is retained with burlap for ease of marketing (balled and burlapped or B&B). Boxes, pots, and baskets can be used instead of burlap. B&B and containerized plants can be grown to larger sizes than is possible for bare-root stock. These plants can be harvested throughout the year. Plants harvested during the growing season may require refrigerated storage for short periods of time before shipping. Desiccation will severely damage actively growing plants if proper storage conditions are not maintained. To increase storage life, the field heat should be removed before moving these plants into the storage area. This can be done by placing them in a precooling room with temperatures of 1.5 to 4.5°C or by keeping the plant material outdoors overnight if conditions are cool and dry. Containerized and fall-dug B&B stock often require long-term storage over winter. Generally, heeling-in grounds and outdoor structures are used; however, refrigerated and common storage can be used for high value stock. Insulating properties of the soil or growing medium can afford a degree of freeze protection that bare-root stock does not possess. However, containerized stock often requires root protection by mulching with sawdust, peat moss, or wood chips before the onset of freezing temperatures (Davidson and Mecklenburg 1981).

## Rooted Cuttings

As a result of marketing schedules and limited propagation space, rooted cuttings may require storage. After rooting, the mist in the propagation area should be reduced and the cuttings hardened gradually. Some species will not tolerate disturbance and need to be left in the rooting bed until the following year. These species are generally overwintered in the structure in which they were rooted. Rooted cuttings will need to be protected from temperature extremes. Species that can tolerate disturbance can be lifted from the rooting beds, bundled, labeled, and placed in plastic bags. Many species can be stored bare-root. Those that cannot will require that sufficient rooting medium be left around the roots or a damp medium, such as sawdust, sphagnum or peat moss, be included in the bag to ensure moisture for the root system. Rooted cuttings can be treated with a fungicide to prevent disease development. Storage temperatures should be 0 to 4.5°C; however, the requirements of each species and variety must be determined by trial and error. Maximum storage should not exceed five months (Dirr and Heuser 1987).

### Unrooted Cuttings

Softwood and semi-hardwood cuttings generally cannot be stored for more than a few days. Hardwood cuttings collected in the dormant state can be stored if kept moist, and at temperatures low enough to prevent bud development. These propagules have been stored successfully outdoors during the winter; however, refrigerated conditions are more dependable. Cuttings should be bundled with the basal ends clearly indicated and labeled. A small amount of a damp packing material, such as sawdust, wood shavings, or peat moss, should be sprinkled through the bundle with heavy, waterproof paper wrapped around the bundle. If plastic wrapping will be used instead, the packing material is generally not required because the internal moisture of the plant material is usually sufficient. If the storage period will be less than one month, storage temperatures of 5 to 10°C are satisfactory. For longer storage (1 to 3 months), temperatures should be approximately 0°C to ensure continued dormancy. Some species will begin growth after several months storage even at this temperature. Cuttings should be examined frequently and if the buds show signs of swelling, they should be used or stored at a lower temperature (Hartmann and Kester 1975).

## Herbaceous Species

### Seedlings

Most herbaceous plants cannot be stored bare-root and will need to be containerized or planted in outdoor planting beds to ensure survival. Outdoor beds should be constructed so that water levels in the bed can be controlled. Some species may be difficult to dig from planting beds, especially if they are rhizomatous and they are to be held for a long period of time, which will make containers more desirable (Environmental Laboratory 1978). Hardier species can be held bare-root for short periods, if temperatures are cool and the plants are not allowed to desiccate. Plants will store better when hardened-off, by reducing irrigation and growing temperatures, before being placed in storage. Proper storage temperatures have not been determined for most species. Generally, temperatures should be in the range of 1 to 5°C; however, species adapted to warmer climates may not tolerate temperatures this close to freezing. To prevent desiccation, the relative humidity of the storage area should be kept high by use of humidifiers or irrigating the storage floor. Roots must be kept moist by placing a fully saturated packing medium around them and enclosing in a plastic bag. The plants should be examined frequently and planted at the first sign of deterioration or disease incidence.

### Containerized Seedlings

Containerized seedlings include plants grown in containers and plants potted in containers for storage after harvest or collection. Plastic or peat pots can be used; however, if the plants are going to be held longer than 6 months, peat pots may become too degraded to handle easily. Proper water levels for the species must be maintained within the pots. Plastic pots with drain holes drilled at approximately half the container height and no holes at the bottom will allow waterlogging of the lower part of the medium column. Peat pots will need to be maintained in a bed where water levels can be controlled (Environmental Laboratory 1978). When storing the plants over the winter, unless trying to force faster growth, it is generally best to place them outdoors to allow normal dormancy. The medium and the moisture levels within the container should provide frost protection, although additional measures may be needed in areas with extremely cold temperatures. Unrooted cuttings, if not used immediately on the planting site, must be placed in a greenhouse and rooted. Then they can be treated as seedlings or containerized seedlings, as applicable.

### Rhizomes, Tubers, Corms and Bulbs

Rhizomes will need to be potted or planted in soil beds if they are to be held in storage for several months (Environmental Laboratory 1978). They can then be treated in a similar manner as other containerized or bedded herbaceous plants. Rhizomes of most species can be stored cool and moist to wet. They should be placed in plastic bags with a damp or wet medium (peat or sphagnum moss, sawdust, etc.) and refrigerated at close to 0°C. At the first sign of sprouting, deterioration or disease, they should be removed from storage and used immediately. Tubers, corms and bulbs need to be kept moist, not wet, during storage. Large-sized propagules can be economically overwintered in outdoor planting beds. Smaller-sized propagules can be stored in planting beds or in refrigerated storage areas. If they are refrigerated, they should be placed in a container or bag. Damp media may or may not be required in the container, depending on the species. The requirements of all species are not known, but, as a rule of thumb, temperatures should be 1 to 5°C and relative humidity of the storage area 70 to 80% (Hartmann and Kester 1975). Fungicides may be necessary to combat disease problems.

## Packing and Shipping

Most states require inspection and certification before shipping seed and nursery stock to other states. The identity of all plant materials must be maintained throughout the shipping process. Shipping by air freight is cost prohibitive for all but the most perishable products. Most shipping will be by common ground carrier, preferably with refrigeration capabilities. Railroad and ship are other carriers that may be used. Carriers will have shipping container size and weight restrictions. When shipping as part of a mixed load, potentially hazardous chemicals, especially herbicides, should not be included in the load. Shipping containers should be labeled to indicate contents and shipping requirements. Live plants should be labeled as such. Time spent in shipment should be as short as carrier limitations and economics allow.

## Seeds and Fruits

Seed quality can be reduced by improper shipping conditions. The optimum conditions would be those maintained for storage of that species. Generally, this means cool temperatures and as dry as that species will tolerate. It is usually not feasible to ship under refrigerated conditions, especially for small volumes of seeds. Proper packaging can help prevent exposure to damaging environmental conditions. Moisture content of dry seeds can be maintained by sealing in plastic or foil pouches or in containers such as vials, plastic bottles, or tins. Short-lived seeds with high moisture requirements can be mixed with damp sphagnum moss, peat moss, or sawdust before placing in the container. Those species tolerant of environmental extremes can be shipped in boxes or bags without loss of viability. All seed containers should be completely filled to reduce shifting during shipment. For large shipments, the order should be divided into several containers that conform to carrier requirements and can be easily handled. Placing the seed container into a sturdy, outer container will prevent leakage. All containers should be clearly labeled on both outer and inner container and seed testing information and post-shipping care instructions can be placed inside (Stein et al. 1974).

## Woody Species

### Bare-root Seedlings

Bare-root seedlings and bare-root plants are shipped in the dormant state. They are cleaned, bundled, graded, and shipped in large boxes, crates, or bags. The roots must be kept moist using a material such as damp sphagnum moss, sawdust or shredded newspaper. Another option is to coat the roots with a commercial hydrophilic polymer gel. A plastic box liner can be used to increase moisture retention and prevent leakage. Excessive moisture should be avoided to prevent plant damage and disease development. Shipping temperatures should be 2 to 5°C to maintain dormancy; however, temperatures down to -1 and up to 21°C are acceptable for shipments of short duration (Davidson and Mecklenburg 1981).

### Containerized and Balled and Burlapped

These plants can be shipped year-round. The plants should be removed from the field and placed in a cool, humid area to remove field heat. Before shipping, the growing medium should be thoroughly watered and allowed to drain. When shipping under conditions of high temperatures and low relative humidity, misting of the foliage, or use of a foliar antitranspirant will reduce moisture loss. Small-size containers can be boxed for ease of handling. Larger size containers and balled and burlapped plants can be tipped and laid over one another to accommodate the size of the truck. A closed, ventilated truck is preferable. If an open truck is used, the plants should be covered with a Saran tarpaulin (90% shade cloth) that will protect against sun and wind damage and allow trapped heat to escape. Shipping temperatures between 4 and 16°C will reduce moisture loss (Davidson and Mecklenburg 1981).

## Vegetative Propagules

### Unrooted Cuttings

Dormant hardwood cuttings can be shipped under cool moist conditions. Cuttings should be bundled and the top of the cuttings clearly indicated. Cuttings can be kept moist using damp sphagnum moss or sawdust, or coating with wax or a hydrophilic polymer gel. Excess moisture should be avoided to prevent deterioration of the cuttings. A plastic liner can be used in the shipping box to prevent leakage. Temperatures should be 2 to 5°C during shipment to maintain dormancy.

## Herbaceous Species

### Seedlings

Seedlings should be cleaned, bundled, and the shoots and roots and rhizomes trimmed for ease of packing. Optimum shipping conditions are for the roots and rhizomes to be kept cool and moist to maintain viability and the shoots cool and dry to prevent water loss and deterioration. This can be accomplished by placing a plastic bag with a damp medium around the roots, taking care not to enclose the vegetative top. Many tolerant species are shipped for short distances and duration without protection around the root portion of the plant with adequate survival. Temperatures should be kept above freezing but as low as possible to prevent excessive water loss. Time in transit should be as short as possible; recommended shipping modes include express or hand delivery. Plantlets or sprigs can be shipped throughout the year. Unrooted herbaceous cuttings will not survive shipping.

### Containerized Seedlings

There are many styles of containers that are used to grow wetland plants. Herbaceous plants in small containers should be placed in boxes for ease of handling. The boxes should have air holes for ventilation. Stacking devices or sleeves can protect the plant shoot from damage within the box. The plants should be thoroughly watered and allowed to drain before packing. Antitranspirants can be used to prevent water loss; however, these should be tested on the species to be shipped before widespread use. Temperatures should be kept above freezing but as low as possible to prevent water loss.

### Rhizomes, Tubers, Corms and Bulbs

These propagules are shipped during the dormant season. Rhizome and tuber sections need to be kept moist using a material such as damp sphagnum moss or sawdust. A plastic liner can be used in the shipping box to retain moisture. Corms and bulbs can generally be shipped dry in ventilated boxes or bags. Care should be taken to prevent damage to the growing points of these propagules. All propagules should be free of field soil. Temperatures should be maintained at 2 to 15°C during shipping. Temperatures should not be allowed to drop below freezing or plant damage will occur.

# 6-6 Factors in Vegetation Costs[1]

## Introduction

Project costs related to the combination of all phases of vegetation establishment are dependent on several factors. A partial listing of items to be considered follows. In estimating costs for any project, the most important thing to remember is that all sites are different, and each site must be evaluated on an individual basis.

## Generalizations Pertaining to Vegetation Establishment Costs

There are many variables in calculating the total costs associated with the vegetation establishment phase of a project. Considerable information can be found in the literature relating to actual dollars spent on various project components, but much of it is dated and difficult to translate into current dollar values. Also, a fair amount of information can be found expressed as total dollars per acre. The unit costs are difficult to assess, however, because there is a great deal of variation in figures for any particular year depending on geographical region, wetland type, size of project, and whether completed by a for-profit or non-profit organization. Where available, costs expressed in man-hours are considered more valuable for use in project planning. The following generalizations, however, can be made:

*a.* Large projects have lower costs per acre than small ones. Materials costs are typically discounted, and mobilization costs make up a smaller percentage of the total cost (Garbisch 1986).

*b.* Projects having multiple goals (e.g., flood storage, erosion control, wildlife habitat, and threatened and endangered species) are generally more costly than those with a single goal (Allen and Klimas 1986).

*c.* Sites that are difficult to access are more expensive than those that are easily accessed. The costs of access and transport of materials to a site by boat, aircraft, or some other unconventional means adds to the expense (Allen and Klimas 1986).

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*d.* Projects requiring high levels of community diversity and/or species diversity are more expensive than those requiring low levels of diversity, often due to increased site preparation activities (site configuration, contours, and grading related to diversity in water depth) and costs of hard-to-find plant materials.

*e.* Costs of actual plant materials are highly variable

(1) seeds are much less expensive than transplants.

(2) containerized/balled-and-burlapped stock is more expensive than bare-root stock.

(3) topsoil seedbank materials are less costly than transplants (Clewell 1984).

(4) species that are difficult to propagate, in short supply, in short demand, or require specialized handling techniques are often very expensive.

(5) transplants grown by contract or acquired from commercial nurseries are often much more expensive than those acquired from the wild (Allen and Klimas 1986).

(6) bare-root plants transplanted from the wild are much more economical than nursery grown plants (Kane 1993).

(7) in general, large-sized or mature planting stock is more expensive than small-sized or young planting stock.

*f.* The cost of mechanized planting is typically much less than planting by hand particularly on large sites.

*g.* Planting under water is much more expensive than on non-flooded sites.

## Factors in Calculating Total Vegetation Establishment Costs

A checklist of factors to be included in the calculation of project costs related to vegetation establishment is variable but can be extensive. In general, the larger and more complex a project is, the greater the number of factors to be considered in determining project costs. Factors to consider include the following:

*a.* planning

(1) site selection

(2) site characterization

(3) engineering and planting design

(4) coordination

*b.* construction

(1) dike construction and maintenance

(2) post-construction grading and elevation changes

(3) other site preparation measures

*c.* planting

(1) labor

(2) seed

(3) contract-grown materials

(4) nursery materials

(5) bulldozer

(6) tractor/disc

(7) rental of other machinery

(8) fertilizer and other soil amendments

*d.* monitoring

*e.* maintenance

(1) fertilizer and other soil amendments

(2) irrigation

(3) replacement or supplemental plantings

(4) control of competing vegetation

(5) animal control

*f.* other cost factors

(1) costs associated with retirement of the land (equivalent to land rent) from a previous use (e.g., pasture or row crop production)

Garbisch (1986) suggested additional factors that can add to the cost of site restoration, including the following:

*a.* overhead (including bonding and insurance) *b.* per diem

*c.* guarantee (in addition to the period of maintenance)

*d.* labor plus benefits

*e.* profits

## Relationship of Planting Densities to Costs

The total number of plants needed in a wetland restoration project is dependent on both the size of the site being restored and the density of plantings. A major variable in determining planting cost is desired density. A planting established on 1-m centers, for example, requires 10,000 plants/ha. A 0.5-m spacing would require 40,000 plants/ha and 2-m spacing would require 2,500 plants/ha. It is important to factor in a contingency cost for more propagules than needed due to a high probability of loss of some propagules, death of some plantings, or the site being constructed at a different elevation than planned (Environmental Laboratory 1978).

Denton (1991) found that costs could be reduced on a cypress-dominated mitigation site by planting smaller trees at densities characteristic of natural cypress wetlands.

## Availability of Particular Species

The relationship between supply and demand is a major controlling factor in determining both availability and costs of planting stock, where it must be acquired from a commercial nursery. Plant materials that are in either short supply or small demand may be very expensive, if available at all.

For projects where there is sufficient lead time, plants propagated and grown under contract by a professional grower represent a good way to ensure that project needs are met. Particularly where project requirements dictate the availability of high species diversity or planting of unavailable materials, contract-grown materials may represent the only way to achieve project goals. Also, in the presence of a contractual relationship, contract-grown plant materials are often priced very competitively.

## Costs of Plant Materials

Costs of plant materials can be dramatically different according to type and size of propagule. Costs for seed in 1991 were as high as $90 to $140 per kg ($200 to $400 per pound) of pure live seed and ranged from $40 to $250 per pound in bulk. Grass seed prices typically are much lower, however, and in 1991 averaged about $5 per kg ($11 per pound) of pure live seed (Thompson 1992). In calculating project seed costs, however, it might be good to consider the fact that the number of seeds per pound varies widely according to the species under consideration. Some large-seeded species, for example, have a relatively small number of seeds per pound in comparison with small-seeded species. For this reason, some prefer to supplement the standard price of seeds per pound information with data on the Number of Live Seeds per Acre (NLSA) instead of or in addition to the more usually available percentage of Pure Live Seeds (PLS).

Garbisch (1986) reported 1981 costs for various vegetative propagules as follows:

*a.* sprigs - $0.15 per propagule

*b.* tubers, rhizomes, bulbs - $0.25 per propagule

*c.* plugs - $0.55 per plug

Denton (1991) documented containerized tree costs at $5 per 1-gallon size, $7 for 3-gallon size, and $22 for 7-gallon size. An Alabama supplier in 1994 distributed a price list for one gallon containers of bald cypress (*Taxodium distichum*), swamp maple (*Acer rubrum*), and sweet bay magnolia (*Magnolia virginiana*) priced at $1.85 each. Bare-root plants of herbaceous wetland species (i.e., *Pontederia cordata*, *Sagittaria lancifolia*, *Scirpus* spp., *Juncus effusus*, etc.) were priced at $0.35 to $0.50 each.

## Holding/Handling Costs

Some plant materials require special holding and handling procedures. Some materials, for example, may require refrigeration, and others may require storage in water. Some of these costs will be related to equipment and others to labor.

## Planting Costs

### General information

Most of the costs associated with actual planting are for labor, with additional costs related to planting equipment, site preparation, and soil amendments. Environmental Laboratory (1978) presented a summary of dollar figures and estimated times for planting. It was determined that costs varied widely due to regional differences, plant species selected, collection and planting techniques, skill of personnel, and other factors. The actual dollar figures are outdated, but the man-hour levels probably are still valid. Comparisons of planting costs are often difficult to make, because some authors have provided data only for man-hour requirements based on labor, while others include allowances for machinery.

To reduce vegetation establishment costs, some contractors have used mechanical devices, such as a trencher for cutting furrows. Plant materials are placed in the furrow by hand and the soil is firmed around the plant by foot. Various pieces of farm equipment, including various types of planters, have been modified for use in restoration projects. Most of these planters make a trench into which the plant is positioned and covered with soil. Mechanized planters allow for significant reductions in planting times and costs where local conditions are conducive to their use. Also, excavation of a furrow often results in improved soil moisture conditions for plant materials (Hammer 1992).

Labor costs for planting will be dependent on the type of worker utilized. Volunteer labor will be the least expensive of any labor group. Costs will vary depending on whether union or non-union labor is used.

# Costs Associated with Seeding

### Standard Seeding Techniques

The costs for broadcast seeding per square meter can vary considerably according to some literature sources. Reported costs in man-hours per square meter varied from 0.004 (Kay 1978) to 0.07 (Schiechtl 1980), depending on the degree of slope and the type of seeds used.

Seeding and planting costs in 1991 for Iowa prairie wetland restoration projects averaged close to $1200/ha ($500/acre) but were extremely variable dependent upon seed costs, with some projects costing up to $1550/ha ($625/acre) (Thompson 1992).

Where establishment of overstory species in forested wetlands is attempted, direct seeding is much less expensive than transplanting. Any potential savings associated with the planting method, however, may be offset by the higher success rate associated with establishing overstory tree species from transplants instead of seeds (Thompson 1992).

Garbisch (1986) provided estimates for seeding costs in 1981 (in man-hours plus materials). The estimated cost for broadcast seed followed by cultivation was 4 man-hours per acre, plus $2500/ha ($1,000/acre) for seed costs. Seed costs are defined to include collecting, threshing, cleaning, and cold storing approximately 1,200,000 seeds per hectare.

## Hydroseeding

Depending on the material used and the distance to adequate water, 4,000 to 20,000 $m^2$ can be hydroseeded by one hydroseeder machine per day (Schiechtl 1980). A hydroseeder normally uses a two-man crew. Fowler and Hammer (1976) reported the cost for using a modified hydroseeder on TVA reservoirs; production cost (seed, fertilizer, labor, vehicle operation) for applying 56 kg/ha of Italian ryegrass seeds and 6-12-12 fertilizer (220 kg/ha) was about $45/ha.

## Aerial Seeding

Costs for large-scale aerial seeding (helicopter, labor, and seed) amounted to $14/ha for over 400 hectares on a TVA reservoir (Fowler and Hammer 1976).

### Hydromulching

Mulch is often applied over seeds by a hydromulcher similar to a hydroseeding machine. For hydromulching or mechanical mulching without seeds, about 0.12 to 0.50 man-hour per square meter is estimated (Schiechtl 1980). Mulching after seeding increases the cost per square meter considerably. Hydromulching with a slurry of wood fiber, seed, and fertilizer can result in a cost of only 0.008 man-hour per square meter, according to calculations from Kay (1978).

## Costs Associated with Vegetative Propagules

### Sprigs, Plugs, Rhizomes, and Tubers

Total costs for plant materials that have been dug from their native habitat and transplanted will vary depending on the harvesting system used, spacing, and the site. Costs for using sprigs may be about one-third the cost of using plugs (Allen and Klimas 1986).

Costs for hand planting of transplants in prairie wetland restoration projects approached $1700/ha in 1991, with an additional cost of $2 to $3 per plant for stock (Thompson 1992).

### Bare-Root Tree or Shrub Seedlings

On good sites with deep soils and gentle slopes, plants can be planted at the rate of 100 to 125 plants per man-hour. On less than optimal sites, rates of only 200 to 400 plants per day per person can be achieved (Allen and Klimas 1986).

### Balled-and-burlapped Plants

Estimates of 10 to 25 plants per man-hour have been given in the literature for planting balled-and-burlapped plants (Allen and Klimas 1986).

## Costs of Planting Marsh Vegetation

Collecting and transplanting smooth cordgrass by hand on 1-meter centers required 134 man-hours/ha in coastal marshes in North Carolina. Marsh establishment on the Texas coast required a range from 11.3 to 29.3 man-hours/1000 plants (113 to 293 man-hours/ha) to hand dig, separate, and transplant various propagule types of 11 marsh species (Dodd and Webb 1975). Similar work done in marshes on the Oregon coast required a low of 87 man-hours/ha for digging and planting hairgrass (Ternyik 1978). The lower manpower requirements at the latter site may reflect the professional nursery work force, highly skilled in transplanting techniques, which accomplished the work (Environmental Laboratory 1978).

Environmental Laboratory (1978) estimated the following man-hour requirements for labor in marsh revegetation:

*a.* 100 to 200 man-hours/ha for transplants and sprigs;

*b.* 100 to 150 man-hours/ha for rhizomes, tubers, and rootstocks; and

*c.* 10 to 40 man-hours/ha for seeds.

## Costs Associated with Reservoir Shoreline Revegetation Projects

Allen and Klimas (1986) summarized costs of standard vegetation establishment techniques related specifically to reservoir shoreline revegetation projects. Clewell (1984) has reported the following:

*a.* Use of wetland topsoil/wetland mulch is less costly than the hand planting of transplants for marsh restoration.

*b.* The planting of tree seedlings is inexpensive as long as a mechanical tree planter can be used. On some wetter sites where a mechanical planter cannot be operated and where seedlings must be planted by hand, planting costs are considerably higher.

## Costs of Planting Bottomland Hardwoods Vegetation

Estimated man-hours and costs per acre for bottomland hardwoods restoration in the South (Johnson and Krinard 1987) are as follows:

*a.* Machine planting with a crew of nine people (i.e., three tractor drivers, five seeders, and one coordinator) allows sowing of approximately 360 to 400 ha in an 8-hour day at an estimated cost of $37.00/ha for labor and equipment.

*b.* Machine planting with a crew of three people (i.e., a tractor driver and two people on the planter) could sow approximately 16 ha in 6 hours at an estimated cost of $15 to $20/ha.

*c.* Hand sowing/planting with a crew of several people could sow 2,000 to 2,400 acorns/ha for a total cost of $110.00/ha for cost of seed, sowing (labor), equipment, and supervision.

The costs of acorn propagules, the labor to sow them, and site preparation are the major cost variables in the oak forest restoration projects in the South. For commercial sowings, a fairly reliable planning figure for percent seedling establishment from direct seeding is approximately 35 percent. A total of approximately 600 to 850 one-year-old trees would be expected from a sowing of 1,700 to 2,500 acorns per hectare. Total costs to establish 600 to 850 one-year-old tree seedlings at a restoration site (i.e., sow 1,700 to 2,500 acorns per hectare) may range from $30 to $125/ha depending on the variables associated with the project (Johnson and Krinard 1987).

### Machinery Costs

Machinery cost consideration could include a bulldozer for transplant bed preparation, tractor and disk for seedbed preparation, and planting equipment. If conventional equipment cannot be used on the site, costs for use of nonconventional machinery will need to be added to the overall project costs.

## Site Preparation Costs

Site preparation activities that may be directly related to planting include removal of litter and debris from the planting site.

Costs for site preparation on prairie wetland restoration projects in the Midwest of greater than 5 acres were on the order of $310/ha in 1991. Site preparation costs on simple prairie pothole restoration projects where earth moving and installation of tile plugs was necessary ranged from $370 to $620/ha in 1991. Projects requiring installation of sophisticated water level control structures may incur costs in thousands of dollars/hectare. The average cost for site preparation in forested restoration projects in the Midwest was close to $185/ha in 1991 (Thompson 1992).

## Soil Amendment Costs

Items to consider include fertilizer, lime, and organic amendments. Garbisch (1986) provided information on 1981 costs, as follows:

Fertilizer applied as a side dressing or surface applied at time of planting -

- 40 man-hours/hectare (60-cm grid for each transplant)

Fertilizer applied by surface broadcasting after planting -

- 5 man-hours/hectare; and

Fertilizer costs in 1981 were

- $ 1.90/kg for controlled release fertilizer
- $0.50/kg for 10-10-10 conventional fertilizer

## Bioengineering Techniques Costs

No definitive information on the costs of bioengineering techniques has been identified.

# Vegetation Maintenance Costs

Any maintenance technique chosen that is labor-intensive will be more costly to implement. An example is the comparison of mechanical weed removal versus chemical weed removal with herbicides. Mechanical removal of weeds by scraping the top 8 cm of soil with a hoe or other implement is more costly than the use of chemical herbicides. Techniques chosen for vegetation maintenance will be dependent on the nature of the problem that needs correction, the size of the site, the accessibility of the site, and the time frame or schedule required for the maintenance.

Denton (1991) estimated maintenance costs in a cypress planting at $6,200/ha for the first 2 years, $4,500/ha for the third year, and about $3,000/ha annually thereafter. Maintenance costs associated with prairie wetland projects are often low, averaging about $74 to $110/ha for a 3-year burning rotation following the establishment period (Thompson 1992).

Vegetation maintenance costs, primarily related to weed control, associated with Midwest forest restoration projects approached $270/ha/year during the first 3 to 5 years. Following the establishment of the overstory species, however, minimal maintenance requirements would be expected (Thompson 1992).

# Combined Cost Estimates per Wetland Type

## Bottomland hardwoods

In 1991, total costs for site preparation, establishment, and maintenance of bottomland hardwoods in Iowa were just over $500/ha, assuming the use of low-cost seedlings. Additional costs of $86 to $320/ha should be allowed for the costs of withdrawing the land from other uses (Thompson 1992).

# Section 6
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# Wetlands Engineering Handbook

## Section 7

## Site Construction and Management

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# 7-1 Construction Planning[1]

With a site selected and vegetation planning complete, the actual construction plan and site preparation can commence. This section outlines the major topics in planning and performing project construction. Monitoring during and after construction are permanent features of most sites. Construction monitoring is discussed briefly in this section; Section 8 discusses the purposes and goals of post-construction monitoring programs.

This chapter discusses issues in wetlands construction. The information is general in nature due to the volume of information that an exhaustive treatment would require. The chapter focuses on the most significant issues that must be addressed during the construction phase of the project. The chapter does not attempt to provide a specific activity sequence for the construction operation.

## Relating Functional Values to Construction

Before construction planning can commence, the objectives for the final product need to be defined. These aims can be categorized as functions and values. Functions are defined as any quantifiable property of the ecosystem. Values are subjective determinations as to the worth of those functions (Hammer 1992). The planning of a wetlands project requires flexibility on the part of the design team. Unlike other construction projects, the appearance and functions of a wetlands can only be anticipated in general terms and will display seasonal variation. Wetland values and functions can be defined broadly over time, but are not necessarily meaningful at a single point in time.

Aspects of the construction should be in harmony with achieving success, and success is best defined in reference to the stated objectives of the project. In summary, functional values include: life support, hydrologic modification, water quality improvement, erosion protection, open space and aesthetics, and geochemical storage (Hammer 1992). There is no accepted standard set of functional values, but the above list is suggested as a simple and useful description of target values for a project.

The values must be studied holistically to determine their compatibility. Modifications to a biological system will have repercussions throughout the ecosystem. Success in one aspect can be to the detriment of another valuable aspect of the ecosystem. Biological subsystems tend to

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be extremely opportunistic and eventually fill every available niche. Thus, construction planning should reflect the local ecology if it is to succeed (Hammer 1992).

Whereas most construction projects are relatively easy to pigeon-hole into their various sub-disciplines, wetland projects defy this type of compartmentalization. Although contractors and engineers are not biologists and vice versa, the need to understand each others' work and professional approach is much greater than in other projects. Seemingly innocuous actions taken by one party may have unforeseen consequences beyond that individual's professional scope. The design and specifications should represent the integration of all disciplines into a constructable wetland system. Corrections or modifications during the construction phase can be undertaken if necessary but can increase costs dramatically.

Plant selection is tailored to the intended values and must be compatible with the soil preparation and planting techniques available to the constructors. The selection of species is best left to a botanical or biological specialist. In planning construction coordination with planting, considerations include: the suitability of the topography, water elevations, water quality, site access, and erosion potential. Vegetation selection must be conducted early in the planning since planting requirements will determine numerous other planning aspects. Aspects of site preparation for vegetation are discussed in Section 6.

All project goals must carry a timetable for completion. Schedules can be determined to at least approximate terms and are essential to any planning process. Achieving goals on a rigid time frame within the constraints of the biological systems is not always possible. A particular source of uncertainty will be in the planting schedule. This schedule will be subject to changes due to weather and other factors and is perhaps the schedule that all other activity will have to work around.

Surveys and mapping will be required in construction planning. A topographic map drawn at one-foot intervals is recommended (Hammer 1992). Site surveys, and review of the location of vegetation to be preserved, will aid in access planning. Locations of cut and fill areas need to be established. A base map should be drawn to show: the extent of the site, contours, soil types, water clarity, and existing plant species (Payne 1992). The latter two items may vary seasonally. This information coupled with the design specifications forms the basis for the construction drawings and plans. Construction plans should include:

*a.* Boundaries of construction activities, including clearing and grubbing limits

*b.* Access for construction equipment and transportation corridors

*c.* Locations of cautionary or hazardous areas

*d.* Utility rights-of-way and contacts

*e.* Quantities, location, and dimensions of borrow areas

*f.* Areas of vegetation that should not be disturbed *g.* Erosion control measures to be taken during construction and revegetation methods during final stages

*h.* Locations, dimensions, and materials specifications for structures

*i.* Locations, length, top and base widths, elevation, upstream and downstream slopes, permeability and coring for dikes or berms and spillways

*j.* Type, size, location, materials, and elevations of water control structures

*k.* Pond bottom and side permeability specifications and methods to attain required permeabilities including liners and liner installation if needed

*l.* Elevations, slopes, and contours of pond bottoms and permissible tolerances

*m.* Elevations, dimensions, composition, grades/thickness, manufacturer, and/or model for piping and valves or other water control structures

*n.* Type and method of placement of sand, gravel, rock or rock riprap

*o.* Species, sources of supply, planting spacings, planting dates, and expected survival of wetlands vegetation

*p.* Seeding, fertilizing, mulching and liming, or sodding of dikes, berms, spillways, and any other disturbed areas

*q.* Provisions for onsite construction supervision

*r.* Methods for determining permeabilities and other contract specifications

*s.* Types, sizes, and numbers of construction equipment

Establishing success criteria is treated later in this section but requires some mention here due to its interdependence with functional values. Given that the goal of a wetland project is the attainment of certain functional values, the values must be quantifiable and qualifiable in terms of success criteria in order to determine success. The system will tend towards a predictable end, but achievement of precise goals will be elusive. In harmony with this concept, the stated goals of a project should be conservative and, if possible, flexible. If the public good is served, or if the specifications of a client are met by unforeseen means, then some success is achieved. Failure to remain flexible as to functions of the completed project may result in excessive maintenance costs and potential legal liability. Attempts to over-engineer a site into performing functions that do not naturally occur in the region or that are unsuited to topography or other characteristics are doomed to mediocrity or complete failure (Mitsch and Gosselink 1993). Caution must be exercised proactively in stating contractually the final qualities of the project.

## Construction Activity Sequence

Proper hydrology is integral to success, and construction planning will hinge on the availability and control of the water supply (Mitsch and Gosselink 1993). Water control, whether for hydrology or irrigation, will feature into every stage of construction planning. Although to a large degree, the available water will be determined in the site selection process, analysis of the water budget and precipitation will factor into planning. Planners should ask themselves whether temporary dewatering, water diversion, or water retention will be required during the construction process. Pertinent questions include: Will portions of the site need to be drained to permit or reduce the impact of construction operations? Will sedimentation or irrigation ponds be necessary? Will temporary alterations to existing hydrology have a detrimental effect on water quality? Most hydrologic information will be gathered prior to the construction planning process, but should be re-evaluated in terms of its effects on construction.

Frequently, sites require some flow diversion or dewatering either prior to or during construction. Dewatering can be accomplished by a variety of means. On seasonally wet sites or sites with excavation below the water table, the simplest option is to build during the dry season. On predominantly wet sites inflow diversion, ditch cutting, pumping, and drawdowns can be employed. Existing drainage and control structures may either be incorporated or removed in construction. Tile drains will require removal or plugging to restore final hydrology. Temporary channels and spillways can be constructed to prevent premature flooding of the site and permit vehicle access (SCS 1992b). Where water inflow is in excess of design flow it may be necessary to install an emergency spillway during construction for flood protection (Hammer 1992). Where dewatering is not required, some flow diversion will likely be necessary in the vicinity of control structure sites for construction access.

Construction will extensively disturb the original site which may present pollution problems. Chapter 13 of the SCS Engineering Field Handbook (SCS 1992b) recommends the following measures for controlling pollution during construction:

*a.* Stage clearing and grubbing operations to limit the size of the disturbed area.

*b.* Install terraces or diversions to divert water away from work areas or to collect runoff from the work area upstream of:

(1) borrow areas

(2) emergency spillway area

(3) storage areas

*c.* Use waterways for the safe conveyance of runoff from fields, diversions, and other structures.

*d.* Control pollution from access and haul roads or construction staging area by the following means:

(1) contour roads

(2) dust control

(3) erosion control- turnouts, pipe culverts

(4) vegetation of disturbed areas

(5) minimize tree, shrub, and other vegetation removal

*e.* Schedule the excavation and transport of soil materials to continuously maintain the minimum area unprotected from erosion.

*f.* Use culverts or bridges where equipment must cross streams.

*g.* Use sediment basins and vegetation to settle and filter out sediment from eroding areas.

*h.* Use straw bale filters or silt fences to trap sediment from areas of limited runoff.

*i.* Complete the work in a timely sequence.

*j.* Provide for winter or seasonal shutdowns as necessary.

*k.* Provide clean and sanitary conditions at the work site at all times.

*l.* Seed and mulch, temporarily and permanently, in a timely manner.

*m.* Provide for onsite storage and future disposal of hazardous chemicals generated as a result of the construction (e.g. drained lubricating or transmission oils, grease, soaps, and asphalt ).

*n.* Sanitary facilities such as pit toilets, chemical toilets, or septic tanks shall not be placed adjacent to live streams, wells, or springs. They should be located at a distance sufficient to prevent contamination of any water sources. At the completion of construction work, facilities shall be disposed of without causing pollution.

*o.* Fire prevention measures shall be taken to prevent the start or the spreading of fires which result from project work. Fire breaks or guards should be constructed as needed.

The layout of surface features should reflect some random variation, as is common in natural systems. This is not merely for aesthetics. Subtle alterations in hydrology and elevations will create unique niches which promote greater diversity (Payne 1992). For projects with surface water, the optimal proportion of surface water to vegetation cover will be a benchmark for the gross composition of the layout. Within this constraint, the relationship between water depth, topography, substrate, and their suitability to desired species will further define land usage.

If public access is intended, early consideration of trails, elevated walkways, and lookouts will simplify their inclusion into the design. Care should be taken in the design so that habitat is not divided by their inclusion, nor should any potentially hazardous materials be used in construction (Hammer 1992). Wood provides suitable strength and aesthetics for pilings and structural elements.

## Excavation and Geotechnical Planning

Wetlands projects carry unique excavation requirements. Soils must be carefully handled and segregated, erosion is problematic for the entire project, and attaining design elevations is critical to success. The soils must be divided by usage, either as a structural or vegetative medium. Soil type and soil strata will determine their ultimate function and treatment in construction.

Traffic, other than that of animals, is not a natural feature of any wetland. As a general rule, any unnatural intrusion in a biological system will alter that system, usually detrimentally. A judgment must be made early in the planning process as to what type, and to what extent, of damage is acceptable. The choice of vehicles and their usage will be an iterative decision process weighted upon: availability of vehicles, economics, mitigation of soil damage, planting techniques, and site topography and areal extent. Further discussion of vehicle types and their ground pressure characteristics is found in Chapter 7-6.

Compaction by vehicles can dramatically undermine the achievement of the intended functional values. As an example, where root penetration is affected, certain desirable plant species will not thrive. This will limit vegetative diversity, which is arguably the essence of a successful project. Improvements to water quality will be limited by a lack of biological complexity as will the site's aesthetic value. Animal diversity will follow that of the vegetation (Hammer 1992; Payne 1992). The site's planned relationship to groundwater will be altered where compaction decreases the permeability of the soil. Other improper construction techniques can have a similarly detrimental cascading effect on various aspects of the project.

High contact-pressure vehicles can be operated along planned lines of dikes and other structural features and in areas where tire depressions will not exceed planned excavation depths. This will limit vegetation impacts to secondary effects (Marble 1992). Since repeated load application will result in alterations to the soil structure, the geotechnical engineer should be consulted in regard to placement of access roads. Where possible, roadways used during construction should follow the routes of planned permanent access roads after construction. Joint use of these road paths will reduce damage by construction traffic to other areas of the site.

Structural damage to some soils is, for all practical purposes, irrevocable. For example, in riparian areas, strata of fine low-permeable silts and clays may be deposited in thin layers, often over highly permeable material. Extreme seepage may occur if the impermeable strata are fractured in construction, causing alterations to planned hydrology (Hammer 1992).

Planning of access to the site will be a consideration at every stage of development. During the initial site investigation a minimum of vehicular traffic will reduce potential damage to the subgrade and to vegetation. Where land clearing is required, the entire site will be traversed by surface traffic. Minimizing vehicle traffic will generally be beneficial and a carefully coordinated access plan will reduce unnecessary damage.

Preliminary planning of cut and fill work can be conducted simultaneously with access planning. Borrow areas will differ in shape and location from those of typical projects. Many designs will not require the creation of deep waterbodies, so borrow material will need to be gathered in thin lifts over large areas (Hammer 1992). Alterations to the site topography will affect the existing runoff patterns. These alterations must be considered in terms of their relationship to planned hydrology and water quality. Cut and fill locations must be determined in advance of excavation and orchestrated with other site planning aspects. Since excavated soils may serve as both a structural and vegetative medium, separation of soils during excavation can be useful.

The erosion potential on the site will be greatest during the excavation phase when large areas of bare and newly planted soils are present. Erosion will affect the viability of plantings, soil loss from the site, sedimentation, and downstream water quality. The erosion potential will hinge on the prevalent meteorological conditions and hydrology, and will have local variations dependent upon the progress of construction and planting. It is prudent to plan for the occurrence of a 5- to 10-year design storm during the construction period and the period of vegetation establishment in order to estimate the maximum erosive potential.

Weather is a significant component of erosion potential. Meteorologic data gathered for the hydrologic survey should be reevaluated as it relates to erosion. Protecting a site from erosion will first require the establishment of an acceptable level of risk. A statistical analysis of the likelihood and magnitude of a potentially destructive meteorological event should be assessed for the construction period. The purpose here is not to assure that the site will be free from erosion, but rather to increase the likelihood that erosion can be maintained at acceptable levels. Based on this analysis, erosion protection methods (sediment ponds, ground cover, grading practices, etc.) should be implemented to match the established level of risk. Meteorology will be less significant in certain coastal wetlands where tidal action dominates. Currents and wave action may make an otherwise suitable planting location a poor choice. Damage from scouring may be likely only in an extreme storm or other hydrologic event. Hence, the potential damage from a probabilistic event should be estimated and weighed versus a pre-determined level of risk.

New vegetation is highly susceptible to erosion; siltation and dislodging are highly destructive to new growth. The construction process must consider the potential erodibility of upland, onsite, and stockpiled soils. In any instance erosion may hamper planting efforts. If erodible soils are present in the watershed, sedimentation ponds and other erosion protection may be necessary (Hammer 1992). Planting problems associated with erosion are discussed further in Section 6.

Damage from erosion may be particularly acute where planting or seeding is concurrent with excavation, as may be the case in a large site. Temporary features during construction may be highly susceptible, especially bare soils and steep grades. Climatic conditions will subject the site to largely unpredictable and uncontrollable factors. Precipitation and wind can scour and deposit unprotected soils. Use of ground vehicles may contribute to airborne dust. Ideally, planting should commence from the upstream direction and from the direction of any prevailing winds to protect plants form water- and wind-borne sediment.

# Construction Planning for Wildlife

Regardless of whether establishment of wildlife habitat is a goal, various animal species will colonize and visit wetlands and will be a factor in their functions. Although the emphasis in establishing a site is on vegetation, animal species perform important maintenance functions that affect long-term status and viability. Hence, their presence or absence cannot be ignored in the planning process.

Wildlife is particularly sensitive to the physical layout. Knowledge of animal behavior will in large measure guide the planning phase where wildlife habitat is desired. Conversely, creating a physically inhospitable setting can avert the introduction of undesired species. If establishment of wildlife habitat, or merely attracting wildlife for its value in site maintenance, is intended, then prudent use in design and selection of appropriate vegetation will favor introduction. Animals will prospect for a suitable habitat in much the same way as a person. As with people, self-preservation is paramount. There are projects where wildlife should be discouraged from habituating a site. These include projects where wildlife may be damaged or where wildlife may injure the site or its surroundings. Sources of injury include man-made obstructions and chemical pollutants, with bioaccumulants of particular concern (SCS 1992b). In those instances where wildlife usage is discouraged, the methods and site characteristics used to attract wildlife should be considered and avoided.

The behaviors of animals are sensitive to surface features, particularly obstructions to line of sight. For example, some waterfowl avoid narrow valleys since visibility of predators may be reduced. Survival of prey depends on early threat recognition, thus reducing the stealth of the predator (Payne 1992). Small rodents typically require ground cover to hide in, or to shield an escape route. Birds may require high roosts to avoid threats or seek prey. Some bird species avoid spatially restricting sites because they lack sufficient unobstructed takeoff distances.

If establishment of specific wildlife species is a goal, then the known behaviors of that species must be considered in planning and construction. Colonization can be enhanced by connecting the site via corridors to other wildlife areas. Corridors promote colonization by creating safe passageways connecting wildlife areas. Water depths must be appropriate to the species. Muskrats prefer to lodge in areas one meter deep whereas certain ducks and shorebirds cannot feed in water deeper than 30 cm. The layout of islands should not be haphazard since many species are sensitive to fetch and visibility. Islands provide nesting, roosting, and loafing areas (SCS 1992b).

Diversity and complexity are sometimes, erroneously, used synonymously. Diversity is an enumeration of the number of species present. Complexity is the level of sophistication of interrelations between species. High complexity can be equated with the presence of many different orders and levels in an ecosystems food chain (Hammer 1992). Producers are those species that produce food through photosynthesis; primary consumers feed on these species; secondary consumers feed on the first order consumers and possibly the producers and so on. Although for most wetlands the initial emphasis is on vegetation development, long-term success will include the complex interrelationships of plants and animals. Even where habitat development is not a stated goal, increasing complexity is a feature of a maturing wetland and in general should be accepted as a positive trend.

## Anticipating Future Developments

The maturation of an ecosystem will be accompanied by changes in shape and areal extent which may affect neighboring landowners and local residents. Plans should not be developed without consideration of the project's relationship to offsite variables (Mitsch and Gosselink 1993).

Effects of a project on its watershed must be considered on a case-by-case basis to avert potential damage. Alterations to the existing hydrology may affect downstream water usage and channel characteristics; property damage may result. Property can be legally lost or gained as a result of the shifts in the stream channel. Poorly designed dikes may cause diversion of flood waters, or even the entire outflow, onto lowlands (Hammer 1992).

Waterfowl are prone to damage crops and vegetation; neighboring grain farms and residential areas may be impacted (SCS 1992b). Regardless of the quality of the design it may not be compatible with the regional plans mandated by regulatory agencies. Governmental environmental policy and opinions from local business and private citizens should be solicited in the information gathering stage. A holistic approach in planning encompassing the ecological, economic, legal, and societal impacts of a project will bolster the project's public acceptance and limit future liability. Failure to involve all concerned parties may result in delays and litigation.

Any significant change to the existing features will produce a corresponding alteration to the microclimate. Effects may include alteration to humidity, precipitation and wind patterns, shading, tidal flows, and lowland freezing. These alterations will affect plantings. Ultimately, alterations to microclimate will be reflected in variations in evapotranspiration, growing season, and succession. The alterations to topography and ground cover may produce undesirable effects from wind. Loss of windbreaks may produce blowouts or desiccation. The consequences of site alterations will be both direct and indirect. The loss of a species lost due to environmental modification creates a new niche for a competing species, but also may remove a natural control affecting seemingly unrelated biota.

## Costing and Financial Evaluation

The costing of the construction can be performed using established engineering industry techniques. Forecasting the costs associated with monitoring and maintenance, and establishing a value for the completed project will be more difficult. The value of wetlands to society has been well demonstrated, as is reflected in the renewed interest in their preservation. Placing financial value on many of the benefits is practically impossible. What value can be placed on aesthetics or on recreation? If a wetland is built for flood amelioration, what dollar value of protection does it afford?

Determination of the financial worth on wetlands' functions has been attempted, but is a vague process. The economic worth can be evaluated by a variety of means; no single method is entirely satisfactory. The valuation is subjective in that it is highly dependent upon the evaluation method used, and on the interests of the party performing the economic analysis (Mitsch and

Gosselink 1993). A relatively simple form of financial evaluation can be performed where a cash crop (e.g., timber or pelts) is harvested or where the wetland is a replacement for a mechanized process of determinate value (e.g., wastewater treatment) (Hammer 1992). The standards for estimating excavation, construction, and planting are common and straightforward. Hammer (1992) recommended that construction cost estimates include:

*a.* contour mapping surveys and construction staking

*b.* preparations of construction drawings and specifications

*c.* preparation and distribution of bid invitations and advertisements

*d.* site preparation: clearing, grubbing, and dewatering if needed

*e.* categorized construction activities for major units (i.e., dikes, water controls, roadways, spillways, visitor facilities, etc.)

(1) materials

(2) equipment

(3) labor

(4) supervision

(5) overhead percentages

*f.* planting wetlands vegetation

*g.* revegetating disturbed areas

Mitsch and Gosselink (1993) provide a sampling of construction costs for a variety of wetland projects. The presented costs range from $25,000/ha to $2,000,000/ha for wetland areas from 0.1 ha to 87 ha. The cost data show a trend of large unit costs for very small acreages (less than 0.2 ha).

## Selecting a Contractor

Once design is complete and construction specifications have been prepared, actual construction is usually left up to an independent contractor. Detailed construction planning will rest with the contractor. However, the unique requirements and fragile nature of the project involved should be emphasized in the invitation to bid. Some have recommended that the site be staked and the contractors be invited to a pre-bid site investigation and conference to help ensure that contractors understand the nature of the project and that bids will be realistic (Hammer 1992).

The invitation to bid should emphasize that the construction will involve specialized planting techniques and entail accurate and discriminating use of equipment and methods. Final grading of planting beds and control structures will require precise elevation checks. Optimum water depths for aquatic vegetation are typically determined to within 1 cm precision; significant deviations may undermine a project's success (Hammer 1992). Where fixed-height control structures are employed, attainment of proper grades and elevations of grade is of little use if the control structure creates an inappropriate depth of inundation. Plant sensitivity to depth of inundation will be most pronounced in the first growing season (Hammer 1992). In similar fashion, attainment of design grades may have a profound effect on flow velocities and sedimentation rates (Marble 1992). The seeming haphazard appearance of a wetlands may deceive a potential contractor into the belief that construction methods are simple and relatively crude. Although some aspects of the site preparation are coarse in nature, other construction methods require high precision.

Federal, State and most local government projects will require contractor selection through sealed public bids. Government procurement regulations usually require the lowest qualified bidder be selected as the contractor. Additional considerations can be included in the contractor evaluation, but they must be quantifiable attributes that can be fairly compared between bidders and carefully explained in the bid package. These additional considerations complicate the selection process and, thus, are usually discouraged by government procurement officers.

# 7-2 Site Preparation and Maintenance[1]

## Introduction

In this chapter, activities associated with preparation of a site for planting (site preparation) and activities required to maintain a site in its optimum condition (site maintenance) are treated separately.

## Site Preparation

A primary objective of the site preparation phase of project development is to prepare a site for planting. The following sequence may be useful in determining secondary objectives:

- Install erosion control measures, as soon as practicable.
- Achieve temporary control of site hydrology to facilitate required onsite activities.
- Remove part or all of existing vegetation from the site.
- For creation projects, (a) select soil materials and determine soil handling/spreading procedures, and (b) execute slope contours and grading.
- For restoration/enhancement projects, there may be less involvement with soils import, sloping, and grading activities.
- In both creation and restoration/enhancement projects, conduct soil improvement and final surface and seedbed/planting bed preparation activities.
- Complete and adjust erosion control measures after final surface preparation/seedbed preparation.

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## Initial Site Evaluation

An initial site evaluation should be conducted early in site planning as described in Section 2. This initial evaluation is to identify (1) any existing conditions and environmental factors that might affect vegetation establishment and (2) ways to minimize project costs without a reduction in quality. Evaluation of some factors through a review of published and unpublished file materials is usually possible; however, an onsite reconnaissance will be necessary to evaluate many factors. Table 7-1 provides a list of potential factors included in the initial site evaluation.

## Importance of Reference Wetlands to Success

Projects often are successful to a large degree because their planning has involved the utilization of information gained from the study of reference wetland sites. Reference wetlands help to identify hydrology requirements and candidate species for planting. Effective site preparation procedures should be determined following selection of the species to be planted. The chances for success are increased where site preparation activities are coordinated closely with plant species acquisition to:

- allow planting/seeding to occur as early as possible within the specified/planting windows, in order to minimize propagule storage time
- reduce the influence of potentially detrimental environmental conditions on an unplanted site
- stabilize site substrate features with vegetation cover
- minimize competition from undesirable vegetation

## Activities Included in Site Preparation

Previous authors have included the following activities within site preparation: development of a generalized project layout/landscape plan according to project and restoration objectives prior to onsite work, establishing slopes, shaping banks, and protecting the site from adverse hydrologic impacts (Allen and Klimas 1986). Because of the comprehensive nature of this handbook, these activities are discussed as part of planning and construction. The vegetation design portions of the handbook deal strictly with those activities directly related to species selection, planting schemes, and the success of vegetation establishment at a site.

**Table 7-1**
**Main Factors for Site Appraisal (modified after Coppin and Richards 1990).**

Vegetation Factors
- Description of structure and composition of existing vegetation

Climatic Factors
- Rainfall - Quantity, maximum intensity, duration, seasonality, and yearly variation
- Temperature - Daily averages, seasonal maximum and minimum, dates of first and last frost
- Potential evapotranspiration - Monthly averages, yearly variation, soil moisture deficits
- Exposure - Relative elevation and aspect; windiness
- Aspect - Local modification of all these factors

Soil and Physical Factors
- Particle grading - Soil texture class, especially content of clay, coarse material, and stones
- Soil profile - Detailed characterization of topsoil and subsoil components of profile
- Density - In situ dry density, potential compaction under load
- Hydrologic regime - Available water for plants; mainly derived from other measured parameters

Soil and Chemical Factors
- pH
- Conductivity - Potential toxicity from soluble salts
- Pyrite - Potential toxicity from acid production
- Soil reaction, lime requirement
- Exchange capacity - Potential to resist leaching of nutrients
- Nutrients/Organic Matter - Soil fertility and plant growth potential

Erosion Risk/Rain Erosivity/Soil Erodability/Overland Flow/Channel Discharge
- Each of these four factors is mainly derived from other measured parameters, but each can be measured directly.

Wave and Wind Erosivity
- Frequency of wind direction and strength
- Fetch
- Currents

Landscape Features
- Herbivores/grazers
- Public access
- Distance to plant or topsoil donor wetland (if necessary)

The following list represents activities that are generally accomplished in site preparation and which are discussed in detail in sections to follow:

- temporary control of hydrology (to facilitate equipment access, vegetation removal, and promote later vegetation establishment)
- vegetation removal
- exotic/undesirable plant species control
- establishing final grades and contours
- selection of soil materials and soil handling techniques
- seedbed preparation
- irrigation installation
- fertilizer application
- damage from wildlife and waterfowl

Planning for necessary site preparation measures on wetland restoration projects should be initiated as early as possible, and the following major factors should be considered:

- Previous vegetation conditions on the site
- Site accessibility to equipment
- Site ability to support heavy equipment
- Individual species planting requirements
- Costs (materials and manpower)

Careful planning and site preparation will help to increase the potential for successful vegetation growth and to ameliorate many problems associated with vegetation establishment. Normal engineering operations will accomplish much of what is required, but special equipment is sometimes required. Site preparation activities often involve major labor requirements; Thompson (1992) reported that site preparation is usually the most labor-intensive phase in prairie wetland restoration.

Table 7-2 (after Coppin and Bradshaw 1982) identifies common adverse site conditions and provides recommendations for their improvement. A soil having a texture that is too fine, for example, can be ripped or scarified and treated with inorganic or organic soil amendments. Table 7-2 also indicates that fine-textured soils are easily damaged by compaction. On the other hand, a coarse soil can be used to improve compacted soils in combination with other soil additives.

**Table 7-2**
**Common Adverse Site Conditions (after Coppin and Bradshaw 1982)**

| Ameliorants | Texture | | Water Retention | | Excessive temperatures | Unstable surface | Compaction | Acidity | Alkalinity | Salinity | Toxicity |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Too fine | Too coarse | Too high | Too low | | | | | | | |
| Natural weathering, time | | (+) | | | | | _ | (+) | - | - | (+) |
| Reducing slope | | | | (+) | + | + | | | | | |
| Compaction | - | + | - | (+) | | + | | | | | |
| Ripping / scarification | + | | | + | | (+/-) | + | | | | |
| Liming ($CaCO_3$ $Ca(OH_2)$) | | | | | | (-) | | + | (-) | | + |
| Inorganic chemical fertilizers | | | | | | | | | | (-) | (-) |
| Bulk additions | | | | | | | | | | | |
| inorganic e.g., soil, inert waste | + | + | (+) | + | + | (+/-) | + | + | + | (-) | (-) |
| organic e.g. peat, manures | + | + | | + | | | + | | + | + | + |
| Drainage | | | + | | | + | | | | | |
| Irrigation | | | | + | | | | | | + | (-) |

(-deleterious effect, + improvement, () depends on site and material)

# Temporary Control of Hydrology to Effect Vegetation Establishment

Successful vegetation establishment often requires temporary control over site hydrology. The target wetland type will determine what types of species are to be planted and, to a great extent, the protocol to be followed in their planting. True aquatics (e.g. wild celery, *Vallisneria* spp., and coon-tail, *Ceratophyllum* spp.) require planting under water and a prolonged period of flooding for their establishment. Seedlings of bottomland hardwood tree species (e.g., red maple, *Acer rubrum*, and pin oak, *Quercus palustris*), however, are normally planted when the soils are not at saturation and after planting their shoots must not be overtopped by floodwaters for more than a very few days during the growing season. The following techniques have been used successfully in duplicating hydrologic conditions found at reference wetland sites, as an integral part of site preparation:

- excavating or plugging existing drainage tiles to achieve desired hydrology (effective in prairie pothole and riparian wetlands restoration)

- installing unperforated standpipe directly on the tile line within a basin and then utilizing existing runoff patterns within the basin to pond water

- constructing earthen dams across drainage ditches to raise water levels

- removing levees, dikes, or other river impoundment structures to restore hydrology to riparian systems (Thompson 1992)

Additional information on achieving desirable hydrologic conditions for plant growth is provided in Section 5.

# Vegetation Removal

## Objectives of vegetation removal

The presence of vegetation cover, here defined to include both desirable and exotic/undesirable species, has the potential to adversely affect both site preparation and vegetation establishment. For this reason, existing vegetative cover may have to be removed. Areas to be planted must be inspected carefully to identify any vegetation having the potential to limit planting equipment accessibility and maneuverability; restrict planting crew access and efficiency; hamper future maintenance operations; or compete with new plantings for light, nutrients, water, or growing space. Also, any excessive surface debris and stumps originating from prior timber harvest or flood-deposited materials may require removal to facilitate equipment maneuverability. In some cases, however, there will be no need to remove vegetation or surface debris.

## Methods used to facilitate vegetation removal

Selection of the method to be used in vegetation removal largely depends upon (1) vegetation type present on site; (2) site conditions (e.g., the presence of a thick regenerated vegetation cover following timber harvest); (3) ecological requirements of species to be planted; and (4) cost.

Typical activities associated with vegetation removal may include: cutting or shearing of all trees greater than 5 cm dbh (Johnson and Krinard 1985), burning, flooding, raking, bushhogging, discing, and herbicide application. The type of vegetation present will play a major role in determining what vegetation removal activities are required. A forested site may require more activities than an unforested site, but individual project requirements will control those decisions.

On bottomland hardwood restoration sites in the South where timber harvest has occurred, it is common practice to make no attempt to remove tops, disturb the soil, or fill in the ruts left by harvesting equipment. This procedure allows for development or maintenance of microhabitats that contribute to increased species diversity within the bottomland hardwood community complex. Some equipment (e.g., many mechanical seeders), however, cannot be operated in forest openings having excessive amounts of surface debris and stumps remaining. To facilitate the use of a mechanical seeder, for example, all trees greater than 5 cm dbh should be cut off or sheared. Projects in forested slackwater areas of the South that have not been harvested typically require a site preparation program which involves a combination of tree clearing, raking, and discing prior to planting (Johnson and Krinard 1987).

Vegetation removal is often necessary to promote adequate regeneration of bottomland hardwoods on harvested sites in the South. Attainment of adequate regeneration is often difficult, and good advance silvicultural planning is necessary to optimize success. McKevlin (1992) identified site factors that influence, if not control, bottomland hardwood regeneration and provides detailed onsite procedures. Clear-cutting alone was found to be inadequate as an acceptable regeneration method for either species composition or community structure in a South Carolina river swamp study (Gresham 1985). Gresham recommended the following procedures to improve regeneration on previously logged river swamp sites:

- removal of all standing stems remaining from the clear-cut by within 6 months of harvest to ensure that reproduction begins as seedlings or sprouts at ground level

- use of prescribed fire to kill residual stems, prepare a seedbed, and dispose of logging slash; more project experience is needed to fully assess the value of fire in promoting regeneration in bottomland hardwoods

- use of natural seeding processes after clearing the site of residual stems and logging slash. Light-seeded species (e.g., sweetgum, ash, cottonwood, elm, and red maple) will probably invade sites cleared mechanically or with fire, but heavier seeds, such as oak acorns and hickory nuts, often wash into an area during spring floods where nearby seed sources are hydrologically connected (see Chapter 7-3)

- planting seeds or seedlings of desired species is often warranted

- additional treatments (e.g., bedding and control of competition by herbaceous species) as required

Wetland projects are often initiated in the South on old fields or sites recently taken out of cultivation. These sites typically are suitable for seeding either by hand or machine and require only minimal site preparation (Johnson and Krinard 1985; Johnson undated). Burning and/or discing of weeds, however, is sometimes necessary to accommodate machine planting (Fredrickson 1978). Cross discing, when combined with harrowing, smooths ruts left by machinery and reduces stubble, which facilitates easier planting with mechanized equipment (Johnson and Krinard 1987). This may or may not be desirable from the standpoint of microtopography. Discing also may help to reduce competing vegetation in the first growing season. Reduction of competition from competing vegetation in the first year is important, and discing is often supplemented with or replaced by herbicide application to achieve that goal.

## Exotic/Undesirable Plant Species Control

Exotic plant species are typically defined as nonnative, undesirable plants having an unusually high potential to out-compete native, more desirable species. These problem plant species are often perennials that are well adapted for rapid dispersal and competitive ability, and they often quickly take over an area.

In practice, methods used for the removal of undesirable species during the site preparation phase may be the same as those used for the removal of any other vegetation materials. Many exotic and other undesirable species, however, have especially persistent propagules that resist full eradication prior to site planting. For this reason, follow-up control measures may need to be implemented during the vegetation maintenance phase of a project (see Chapter 7-5, Vegetation Maintenance).

Numerous approaches directed to the removal of exotic or other undesirable vegetation components have been developed. These methods include various types of cultivation, fire, nurse and cover crops, selective herbicides, and manipulation of hydrology. Effective control methods are typically specific to the individual species involved, however, making it difficult to make generalizations. Contact the local Extension Service office to determine the most effective and preferred control methods.

The list of exotic species which are detrimental to wetland systems is extensive and includes purple loosestrife (*Lythrum salicaria*), saltcedar (*Tamarix* spp.), Japanese honeysuckle (*Lonicera japonica*), Australian pine (*Casuarina equisetifolia*), and common reed (*Phragmites australis*), to name some of the worst. Some native species behave much like exotic species, and the methods for their control are very similar to those for exotic species. These undesirable native species include most species of cattail (*Typha* spp.) and several species of hibiscus (*Hibiscus* spp.).

The control of undesirable plant species in wetland habitats can be a serious problem in most sections of the country. Many sites have undesirable species present prior to planting, and their removal may be an important part of site preparation. Topsoil seedbanks used in wetland creation projects, for example, often have a much higher potential for seeds of exotic or undesirable species than for native ones. In many instances it will be impossible to eliminate them through site preparation activities, and they will persist as asexual propagules and/or seeds following project development. This makes it difficult, if not impossible, to comply with agency regulations and mitigation requirements, and the control of these undesirable species will remain an important component of the vegetation maintenance phase in many projects (McGrain et al. 1992). Vines, both woody and herbaceous, represent a major problem for new vegetation on logged sites throughout much of the South. These rampant vines out-compete more desirable species for light, water, nutrients, and space and cause serious physical damage to young stems. A program for effective control of vine species through some combination of chemical, mechanical, and manual procedures will be required at many sites.

## Cultivation methods

The removal of existing undesirable herbaceous vegetation in bottomland hardwood sites through site preparation activities has been accomplished in Iowa by several methods of cultivation, including discing, harrowing, hoeing, and rototilling (Thompson 1992). Similar methods have been used in forested wetlands in the South.

## Fire

Prescribed fire is best described as the planned use of fire. The use of a prescribed burn is an economical way to control undesirable understory vegetation in both site preparation and vegetation maintenance, and it has been used in both forested wetlands and in depressional wetlands dominated by graminoids (e.g., prairie potholes). There are six common techniques used in the initiation of prescribed fire at a site: backing fires, strip-head fires, flanking fires, spot fires, ring fires, and slash pile/windrow fires (Figure 7-1).

A prescribed burn often can be used to eliminate top growth of competing vegetation and to remove organic surface debris in forested wetlands. In the South, this is normally accomplished during the summer unless the fuel load is insufficient to carry the fire or the site is too wet to burn (McKevlin 1992).

The timing of a burn will influence both the amount of vegetation and the species that will survive. Vegetation impacts from fire will be higher during the growing season than during the dormant period. When considering the use of prescribed fire during exceptionally dry periods in the growing season, the desire to achieve optimal site preparation may need to be weighed against excessive losses in desirable wetland vegetation and organic matter, biota, and nutrients from the soil.

Prescribed burns are especially effective control measures against undesirable weed and shrub cover in grassland wetlands (Environmental Laboratory 1986). On many forested wetland

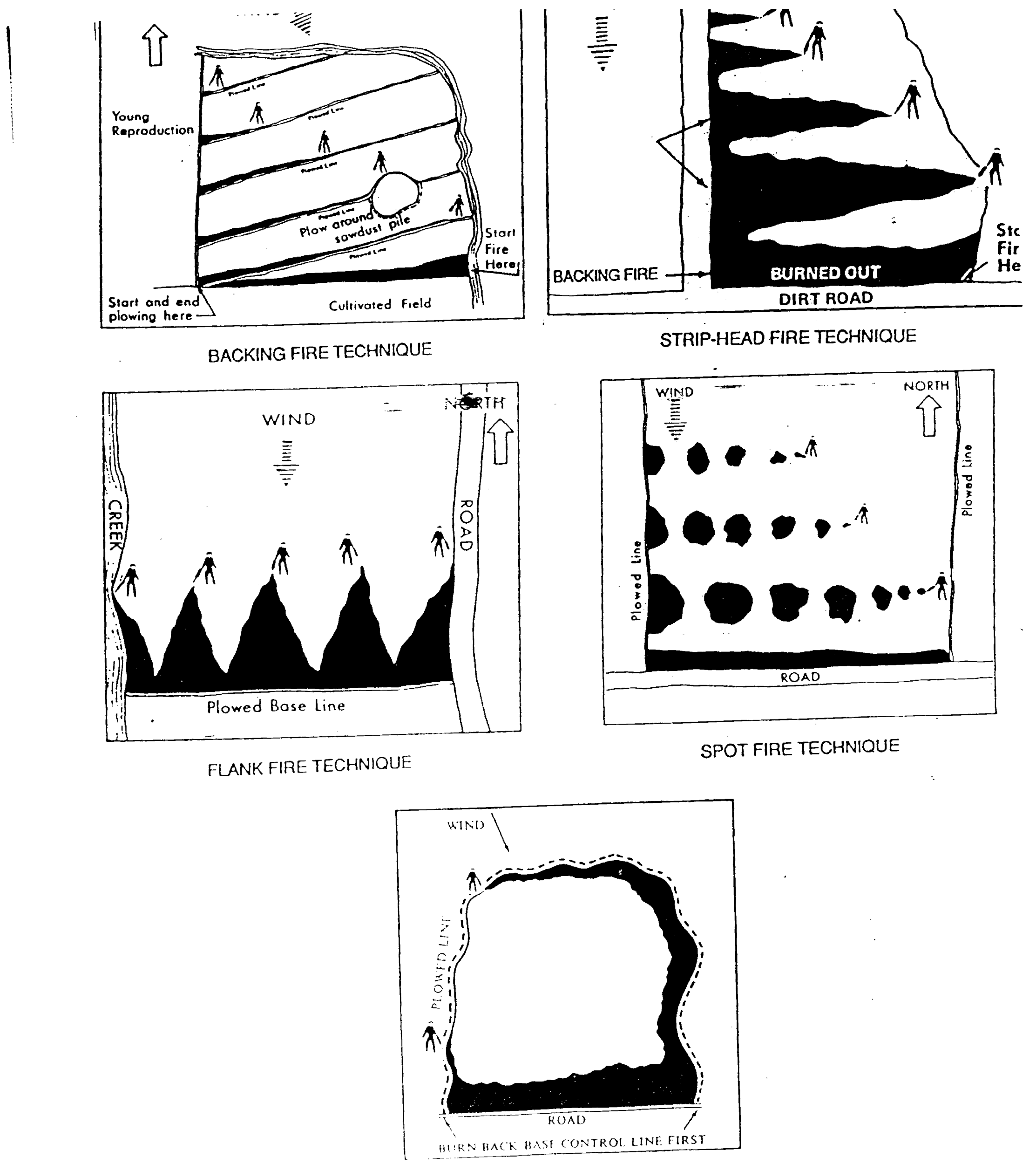


Figure 7-1. Examples of fire setting techniques (USDA Forest Service 1990).

restoration sites in Iowa, the establishment of tree seedlings is hampered by competition from weed species and sod. Initiation of a vegetation management program, including the possible use of prescribed fire, is recommended before planting (Thompson 1992).

Clewell (1984) has used fire successfully to remove turf of broomsedge (*Andropogon virginicus*) and the exotic bahia grass (*Paspalum notatum*) at a Florida swamp restoration project. Prescribed fire was the only site preparation activity used prior to planting seedlings on wet-mesic reclaimed phosphate mine lands.

The use of prescribed fire as a site preparation tool should be practiced only by individuals having adequate training and experience in its use. The use of prescribed burns as a vegetation management practice may require a permit or authorization from an appropriate state or local agency, e.g. natural resources agency, county conservation board, fire department, etc. (Thompson 1992).

## Nurse crops and cover crops

Nurse crops are species that are intentionally planted to promote the survival and growth of other species, and they have been used successfully at many bottomland hardwood restoration sites having adequate soil moisture levels (Clewell 1993). Nurse crops can be used to limit the establishment of undesirable species having the potential to compete with more desirable wetland species. A nurse crop increases the potential for tree seedlings to escape possible damage from desiccation by a reduction in exposure to wind and sunlight, to encourage mycorrhizal fungus development, and to increase populations of nitrogen-fixing bacteria resulting in increased levels of available soil nitrogen.

Examples of nurse crop species that have benefited the establishment and growth of bottomland hardwood tree species in the South include the following:

- wax myrtle (*Myrica cerifera*),
- cottonwood (*Populus deltoides*),
- Carolina willow (*Salix caroliniana*),
- slash pine (*Pinus elliottii* var. *densa*), and
- bushybeard (*Andropogon glomeratus*).

Nurse crop species have been effective in reducing competition from the exotic bahia grass (*Paspalum notatum*) in Florida and other parts of the South. Bahia grass is an invasive rhizomatous turf grass that escapes from improved pastures and threatens success at many bottomland hardwood restoration sites (Clewell 1993).

Some nurse crop species also function as cover crops. A cover crop is any species which is planted intentionally to provide rapid vegetation cover, reduce soil erosion, and seize space and resources that would otherwise be taken over by vines or other aggressively competitive weedy plants. For more information on specific nurse and cover crop species and their benefits, see Clewell (1993) and Rolfes (1993).

## Selective herbicides

Herbicides are widely used as agents of vegetation management. Table 7-3 provides a list of some of the more widely used herbicides. Some of the compounds formerly used to control vegetation (e.g., sodium arsenite) were very nonspecific in their action; they simply killed anything in their path. In more recent times, however, herbicides of a much more selective nature have been produced. Many of these selective herbicides represent synthetic auxins (man-made chemical variants of naturally occurring plant growth regulating substances). These auxin-like compounds are defined as herbicides in this general account of chemical compounds used to effect vegetation control in site preparation.

Undesirable plant species, including exotics, have been controlled with selective herbicide application at many sites in the Midwest (Thompson 1992) and elsewhere. McKevlin (1992) recommended the use of herbicides to control vines and undesirable woody growth in the South and manual cutting where herbicide use is unacceptable. A combination of herbicides and manual or mechanical methods has been used effectively in many parts of the country.

The use of herbicides to control undesirable or unwanted vegetation is regulated by both federal and state agencies. Any chemical applications made to the seedbed should be done by certified pesticide (i.e., herbicide and insecticide) applicators according to label specifications. Consult an appropriate agency (e.g., State Plant Board, Cooperative Extension Service, etc.) in each state for current recommendations on the use of herbicides in and around aquatic sites.

## Mechanical control methods

Specific mechanical vegetation removal practices have been advocated for several regions and vegetation types. Scheuler (1994), for example, recommends mechanical removal of problem vegetation, particularly exotic species such as Japanese honeysuckle (*Lonicera japonica*) and multiflora rose (*Rosa multiflora*), to improve the success rate in establishing riparian forest cover in the Northeast region.

**Table 7-3**
**Examples of Commonly Used Herbicide Products (with Chemical Classes Indicated) and Their Typical Applications**

| TRADE NAME | GROUP NAME | NOTES |
|---|---|---|
| Krenite[R] | Fosamine* | Used for non-cropland brush control; is applied as foliar spray; effects are delayed when applied in fall; spring bud development is prevented or limited. |
| Roundup[R]<br>Rodeo[R]<br>Accord[R] | Glyphosate | Used for control of weeds, grasses, and woody species; labeled for use as an aquatic herbicide; affects plants by interrupting photosynthetic processes. |
| Velpar[R] | Hexazinone* | Used to control weeds, grasses, and woody plants; applied as foliar spray, granular applications to soil, and cutsurface treatment; affects plants by inhibiting photosynthesis. |
| Arsenal[R] | Imazapyr* | Used to control weeds, grasses, and woody plants; applied as foliar spray, basal bark spraying, and cut-surface treatments; affects plants by inhibiting amino acid synthesis. |
| Tordon[R] | Picloram* | Used to control weeds and woody plants; applied as foliar spray and as cut-surface treatments; causes leaves to cup and curl. |
| Oust[R] | Sulfometuron* methyl | Used as broad spectrum, pre- and post-emergence herbicide to control herbaceous dicot weed species; applied as foliar spray; stops plant growth by arresting cell division in growing tips. |
| Many formulations | 2, 4-D | Used as broad spectrum, post-emergence herbicide. |
| Poast[R] | Sethoxydim | Applied post-emergent to actively growing grasses. |
| Garlon Pathfinder | Triclopyr | Used for post-emergent control of brush, annual and perennial broadleaf weeds. |

* restricted use in wetlands; not labeled for use as aquatic herbicides.

## Other control methods

Control of undesirable vegetation is often effected by relatively simple techniques. Bottomland hardwood sites in the South, however, are sometimes subjected to intensive site preparation by shearing residual trees and placing the debris to the exterior of the site. One must make sure, however, that the piles of debris do not alter site hydrology. Where its use is possible, this is an effective method to achieve a reduction in competition and to enhance the growth and survival of oak seedlings (Johnson and Krinard 1987).

Elimination of weed seeds from a site is an important but difficult site preparation consideration. On sites having former intensive cultivation, establishment of prairie wetland plants from seed is usually hampered by competition from weed species. Additional information on mechanical and chemical methods recommended by Thompson (1992) to eliminate weed seeds from the seedbed is provided in a later section on Seedbed Preparation.

Scheuler (1994) advocated vegetation removal by scraping the top 7 to 8 cm of soil and replacing it with topsoil. When using topsoil, however, care must be taken to prevent the introduction of exotic or problem species onto the project site. The use of a topsoil layer is expensive but considered attractive from an environmental viewpoint because it does not involve the use of chemical compounds. A downside consideration, however, is the potential for causing detrimental effects to the donor site. Removal of topsoil for project utilization is possibly best confined to sites that are already slated for destruction.

## Establishing Final Grades and Contours

The ultimate success of a restoration project is often determined by the final grade of a site and its interactions with hydrology and physiological adaptations of plants (Garbisch 1986). The establishment of specified final grades for a project would appear to be fairly routine but frequently has been a problem in restoration projects (FTN 1993).

Establishment of rough grades can often be accomplished in conjunction with soil excavation using large earth-moving equipment. Dynamite has been used successfully in establishing large deepwater areas in prairie pothole restoration projects (Thompson 1992; Waterways Experiment Station 1993).

Elevations should be monitored continually during final grading. For wetland systems having the high water level controlled by an adjustable weir, the final grade may not be so critical. Development of a final grading plan is most difficult for proposed wetland projects where the only water source is groundwater and/or surface runoff. In such areas, seasonal variations in rainfall provide uncertainties in designing and achieving desired water levels (Garbisch 1986).

In general, sites marked by variations in surface and shoreline topography have the potential to support vegetation having greater species and plant community diversity. This diversity usually relates directly to the hydrologic gradient.

Slopes require special attention during construction to ensure their ability to support vegetation. Any desired modifications to either the surface or soils on steep slopes where access will be impaired following construction must be made during slope construction. Landscape features that are difficult to vegetate (e.g., tops of slopes and areas having sharp changes in gradient) often have severe drought, exposure, and erosion problems. These problems usually can be reduced or eliminated by softening or rounding these topographic features (Coppin and Richards 1990).

## Selection of Soils Materials

Soils to be used as a planting substrate must be evaluated for their potential to promote good plant growth. The selection of soil materials for vegetation potential and suitable soil types for a range of uses is discussed in the following paragraphs; a more extensive discussion is provided in Section 4. Reference wetland sites can play an important role in providing insight into soil properties that are essential to establishment of the desired vegetation. Soil profile design is very important, particularly in creation projects, and should take into account the following:

- a careful selection of soil materials, with attention given to advantages/disadvantages of onsite soils vs. imported soils, and comparison of topsoils vs. other potential growing media

- methods for handling soil material, including management of soil density through loosening or compaction, protection of existing soil structure through avoidance of careless soil handling procedures, and integration of engineered profile layers through scarification techniques (Coppin and Richards 1990)

Coppin and Richards (1990) provided a useful overview to soils selection according to texture, nutrient content, and plant growth potential. Primarily on the basis of soil texture, these British authors characterized three major soil groups and addressed their suitability for (1) topsoil or subsoil uses and (2) vegetation growth potential. This system of three major soil groups is readily adaptable to American projects. See Coppin and Richards (1990) for additional details.

A category of high quality soils was characterized by Coppin and Richards (1990) as highly fertile, highly productive, requiring high maintenance, and promoting rapid successional changes. Rampant growth potential is seldom necessary in wetland systems, however, and these soils may be best suited for topsoil or as a final soil covering on intensively managed areas. This soil group includes sandy loams, sandy silt loams, and silt loams.

A category of intermediate quality soils was characterized by Coppin and Richards (1990) as having moderate fertility, and possibly requiring fertilizer applications to support high productivity. These intermediate soils are useful where growth potential is desirable but not critical. This soil group is suitable for use as subsoil layers beneath soils of the highest fertility and includes sandy clay loams, clay loams, and silty clay loams.

A category of low quality soils was characterized by Coppin and Richards (1990) as having minimal fertility and requiring fertilizer applications to promote good growth. These soils have the potential to support good growth when well managed, but they have certain soil handling problems, which may place limitations on plant growth. They are suitable for supporting low-maintenance vegetation and also are suitable for use as subsoil layers. This group of soils includes sandy clays and silty clays.

## Importance of selecting the right soil and using it correctly

In site preparation activities related to seedbed preparation, attention should be paid to existing soil horizons at a reference wetland. At many project sites, it will be necessary to remove and replace several soil horizons to achieve a duplication of soil conditions found at a reference wetland.

A soil considered for use within the potential root zone of restoration vegetation should be assessed for its potential as a medium for good plant growth. A soil that is suited for good plant growth will provide anchorage, water, mineral nutrients, and varying degrees of aeration for plant root systems.

A soil profile must have a functional relationship between the surface, root zone, and subsurface layers if good plant growth is to be supported. In constructed soil profiles, good growth and soil stability result from loosening the surface soils in the upper 0.5 to 1.0 m (20 to 39 inches) to ensure effective water movement through the profile (Coppin and Richards 1990).

The potential for loss of topsoil is increased when it is placed directly over a surface that has been heavily compacted through the use of heavy equipment. Any layer within the potential root zone which has received excessive compaction during construction must be loosened to improve its potential for supporting good plant growth (Coppin and Richards 1990).

Excessive seepage losses often occur in developed wetland sites, and these losses usually result from soils that are too permeable to retain sufficient water for a planned function. Losses may be reduced through a variety of sealing methods, including compaction of onsite soil materials, clay blankets, bentonite, chemical additives, and flexible membranes. The method to be used will depend primarily on the distribution of particle sizes found in the onsite soils (SCS 1992b).

## Topsoil and subsoil considerations

Soil profiles found at a suitable reference wetland should be examined and considered in site preparation activities. Under normal circumstances, when topsoil is available on a wetland site, it should be stockpiled for potential later use. When offsite topsoil is used, it should be compatible with its new location and purpose, because undesirable features of a topsoil may sometimes cause problems (e.g., when the pH level is extreme or markedly different from the subsoil or when high weed seed levels are present). In selecting soil materials for a project, it should be noted that topsoil is not necessary as the surface material in all projects. When topsoil is obtained from a cultivated field, for example, it may be too fertile for wetland project use because of its potential to promote vigorous weed populations. Also, many subsoils and mine spoils having low fertility make good soil substitutes and can support adequate vegetation growth for restoration purposes (Coppin and Richards 1990).

The use of an improper material for the subsoil layers of a constructed profile may result in poor root penetration, leading to inadequate root development and poor drought tolerance. For this reason, it is important to consider the entire soil profile and not just its upper portion.

Table 7-4 (after Coppin and Richards 1990) provides a comparison of the advantages and disadvantages of topsoil in restoration projects.

## Soil handling and spreading

A major soils problem in any project is balancing the requirement for adequate soil compaction to promote substrate stability against a favorable degree of looseness to induce good plant growth. Unfortunately, soil structure can be easily destroyed or impaired through poor soil handling and spreading techniques (e.g., worked when too wet or compacted by excessive tracking with heavy equipment). Also, a soil's microorganisms and other biota can be adversely affected by improper handling techniques (e.g., stockpiles that are too deep or too wet). The use of improper soil management techniques often leads to poor plant growth, and project soils issues must be evaluated on a case-by-case basis.

**Table 7-4**
**An Evaluation of Advantages and Disadvantages of Topsoil (Coppin and Richards 1990)**

**Advantages of Topsoil**

*a.* Has existing fertility and organic matter content
*b.* Vegetation should grow very well immediately
*c.* May be already available on site

**Disadvantages of Topsoil**

*a.* May be too fertile for the intended purpose
*b.* Can contain many weed seeds
*c.* May be expensive to import, especially from any distance
*d.* Can be of dubious quality unless source is well monitored
*e.* May be difficult to integrate with underlying soil layers
*f.* Fragile and difficult to handle without causing irreparable damage
*g.* May be difficult to match geotechnical requirements (e.g., compaction requirements) with plant growth requirements

The potential for damaging a soil through improper soil handling and spreading is directly related to the soil's clay and moisture levels. Clay soils are most at risk of damage among all the soil types, because clay soils lose strength rapidly when wet and are easily damaged with heavy equipment under that condition. Sandy soils are least at risk and generally can be worked and transported with little damage regardless of soil moisture content. Soil damage caused by excessive tracking with heavy equipment can never be fully eliminated by cultivation practices, however intensive, but the following practices are of value (Coppin and Richards 1990):

- Work and move soil with equipment of relatively small size and lacking oversized tires, where possible.
- Avoid the use of heavy earth-moving machinery over surfaces of existing or applied soils, where possible. Where use of heavy equipment is necessary, confine the damage by keeping vehicles to the same tracks as much as possible. Improve the tracks later by deep cultivation.
- Minimal traffic should be allowed over a soil that has been spread, to prevent the formation of a smooth, compact soil surface on which vegetation establishment will be difficult.
- Soil handling restrictions based on soil moisture conditions should be used, and double handling should be avoided or minimized.
- Stockpiles should be shallow, protected against compaction, and graded to shed rainfall.
- Long-term stockpiles should be seeded over to avoid erosion.

- Equipment should be allowed to track over a soil only when its strength is greater than the ground pressure of the machinery involved.

It is important to minimize soil disturbance. The existing relationship between soil structure and soil-binding root structure must be maintained wherever possible, which results in reduced erosion potential and takes advantage of existing soil nutrients and soil biota.

In general, a soil should consist of a minimum of 12 percent air pores by volume to promote good vegetation growth. Sometimes a greater degree of tightness is necessary, however, to prevent erosion. In general, a fast growing vegetation cover will compensate for any deficiencies in soil strength. Also, geotextiles or other measures may be used to prevent erosion (Coppin and Richards 1990).

## Use of ripping to alleviate compaction

The adverse problems associated with soil compaction can be reduced by ripping, which is essentially a technique for deep cultivation of a soil. Ripping achieves the following:

- increased water infiltration into the soil and reduced surface runoff

- reduced soil density and increased available water capacity and rooting potential

- effective drainage pathways when carried out along a gradient

- increased soil aeration and improved plant growth

Ripping as a soil modification treatment has been developed and much used by the forestry industry in the U.S.. Ripping is accomplished with a ripping tool (sometimes called a subsoiler or chisel plow), which typically is a large flat (and not winged) blade pulled through the soil at depths of 0.1 to 0.5 m (4 to 20 inches) and with spacing between rips of 0.08 to 0.3 m (3 to 12 inches). The ripped soil thickness ranges from 0.15 to 0.6 m (6 to 24 inches). Rippers typically are mounted on or pulled behind large farm tractors or bulldozers (USDA Forest Service 1990).

Ripping, also sometimes termed deep cultivation, may increase waterlogging on flat sites unless some drainage control is installed to regulate the water levels. The effectiveness of any deep cultivation program is directly related to soil moisture content. Where soils are too dry, the ripper tine does not effectively penetrate the soil. Ripping is usually an ineffective technique in heavy soils unless a soil moisture deficit of at least 51 mm (2 inches) is present (Coppin and Richards 1990).

# Seedbed Preparation

## Final surface preparation

The method of vegetation establishment to be used will largely determine surface preparation methods. In general, a smooth surface is required only where the vegetation will require close mowing. Various seeding methods are listed below with their appropriate surface type:

- Drilling - A reasonably level surface and a loose tilth are necessary for the seed drill machine, but specialized machines are available for use on rough terrain.

- Broadcast and harrowing - A reasonably fine tilth is needed to allow the harrow teeth to bury the seed to the correct depth.

- Broadcast without harrowing (includes hydroseeding) - A rough surface texture will result in the best seedling establishment.

## Seedbed/planting bed preparation

Preparation of a suitable seedbed/planting bed on a wetland site must be accomplished prior to planting seeds or vegetative propagules. The soil or the substrate must be prepared to provide a friable soil suitable for seed germination or for seedling/propagule establishment, allow root penetration of the developing seedlings or transplants, and reduce existing competition from undesirable vegetation (Environmental Laboratory 1986).

Where topsoil or other soil suitable for a seedbed bed is not present at a site, it should be brought in and spread to a depth of at least 15 cm (6 inches) for most species. Where an adequate topsoil or other desired substrate is present, it should be loosened to a depth of at least 15 cm (6 inches), particularly for most seeding operations. This practice will encourage root development and soil penetration.

Compacted soil layers that are present at depths of less than 20 cm (8 inches) should be broken up with a chisel plow. Plow pans may occur at depths of 20 to 30 cm (8 to 12 inches) in medium textured soils. To obtain the best growth from all species, plow pans should be fractured by subsoiling prior to planting (Johnson and Krinard 1985). Stones and other debris should comprise less than 30 percent of the rooting volume.

Table 7-5 lists equipment useful for seedbed/planting bed preparation under a wide range of field conditions. The size of the area to be planted, seedbed/planting bed requirements for the individual plant species, and site conditions will influence the selection of equipment appropriate for a site (Environmental Laboratory 1986).

Wetland restoration projects in the Midwest have included the following tasks in seedbed preparation: 1) light harrowing and removal of all large stones from the entire site, and

**Table 7-5**
**Equipment Used in Wetland Site Preparation**

| Site Preparation | Area Size (ha) | Equipment | Purpose | Comment |
|---|---|---|---|---|
| Woody Plant-dominated sites | < 40 ha | Bulldozer | Remove stumps and large trees | Not suited for rocky soils or larger areas |
| | < several | Tree remover | Remove and transplant in one operation | Good for individual trees; equipment may not be readily available |
| | > 40 | Grubbers | Remove stumps and sprouting species | Inappropriate for larger areas and dense stands |
| | No limit | Root plows | Control stump sprouting species; break up subsoil | Time consuming; may be expensive on a cost/area-basis |
| | No limit | Rotobeaters and shredders | Shred woody vegetation; good for surface-mulching | Not suited for rocky soils; good as surface treatment only |
| Herbaceous plant-dominated sites (low-use areas) | No limit | Std. oneway plow | Deep-plow all soil materials | Not suited for rocky or steep terrain |
| | No limit | Offset and tandom-disk plow | Deep and shallow plowing | Not suited for rocky steep terrain |
| | < 8-10 | Rototillers (tractor-mounted) | Shred vegetation and incorporate into soil | Not suited for rocky soils |
| | < 0.5-1-0 | Rototillers (hand-operated) | Shredding of vegetation and incorporation | Not suited for rocky soils |
| | No limit | Klodbusters | Good for steep slopes | Slopes greater than 20 percent |
| | No limit | Furrowers and trenchers | Create water catchments and control water in all climate regions | All work on the contour; furrowers used on slope less than 20%; trenchers on slopes less than 45% |
| | No limit | Land imprinters | Create small pits to collect moisture; useful in arid regions and rough rocky terrain, used on slopes up to 45% | Unsuitable for dense brush areas |
| | No limit | Spike harrows | Smooth rough-plowed soils | Unsuited for rough and rocky terrain |
| | No limit | Spring-tooth harrow | Smooth and incorporate soil amendments and broadcast seeds | Unsuitable for rough, brushy, rocky terrain |
| | No limit | Moldboard plow | Refer to Herbaceous plant dominated sites (high-use areas) | |

**Table 7-5**
**Equipment Used in Wetland Site Preparation (concluded)**

| Site Preparation | Area Size (ha) | Equipment | Purpose | Comment |
|---|---|---|---|---|
| Herbaceous plant-dominated sites (high-use areas) | <18-20 | Rototillers(tractor-mounted) | Shred vegetation and incorporate into soil; good for eliminating surface compaction | Not suited for removing rhizomatous vegetation |
| | <0.5-1.0 | Rototillers (hand-operated) | Eliminate shallow surface compaction; use on trails | Difficult with rocky soils |
| | 2 | Chisel plows | Relieve shallow compaction | Can be used on rocky soils |
| | All areas | Subsoilers/rippers | Alleviate deep soil compaction | Unsuited for rocky soils |
| | All areas | Harrows | Refer to herbaceous plant-dominated sites (low-use areas) | |
| | No limit | Moldboard plows (tractor-mounted) | Relieve shallow soil compaction; generally recommend as the first step in seedbed preparation | Unsuited for very rocky,brushy,steeply sloping terrain; all plowing recommended on the contour to lessen soil surface |
| | No limit | Soil slicers and renovators | Cut through sod, thatch, and soil; increase water and air exchange | Unsuited for rough, rocky terrain and dense grass areas |

2) cultipacking to produce a firm, smooth seedbed for good contact between the soil and seeds (Thompson 1992).

Restoration of forested wetlands often involves the elimination of weedy species or weed-infested sod prior to the planting of seedlings. On sloping sites where erosion is likely to occur, the control of brush, weeds, and erosion can be accomplished by killing undesirable vegetation with herbicides and leaving the standing dead material in place (Thompson 1992). This technique provides a number of benefits, including a reduction in raindrop/runoff impacts and flow rate of any waters that may cover the site, return of organic material and nutrients to the soil, protection of seedlings and young plants from wind and desiccation, and provision of wildlife cover and nesting sites during the period of vegetation establishment. This method involves both minimal site preparation and low cost factors, and when used in combination with a safe herbicide should be viewed as an environmentally preferred method.

Seedbed preparation techniques employed successfully in restoration of wet and wet-mesic prairie sites have included both mechanical and chemical (and combinations of these two) methods. Seedbed preparation should be initiated in the fall prior to sowing pretreated seed in the spring. Following is a brief discussion of the techniques and methods employed in seedbed preparation for restoration of prairie wetlands. Further information on site preparation techniques suitable for wet to wet-mesic prairie wetland restoration is provided by Thompson (1992). The methods described here assume level sites and spring sowing of seed.

## Mechanical methods of seedbed preparation

Mechanical methods of seedbed preparation include the following (Thompson 1992):

- Rototilling: Removal of weeds with periodic use of a rototiller for one full growing season prior to seeding has been successful in small-scale restoration projects.

- Discing: Shallow discing 2 or 3 times in the spring season, with the last discing just before seeding, is an appropriate method for large-scale restoration project sites supporting a row crop in the previous year.

- Mowing-plowing-discing: Late summer mowing to a height of 30 cm (12 inches), followed by fall plowing to a depth of at least 20 cm (8 inches) and shallow spring discing at 2- to 3-week intervals up to the time of planting. This method is appropriate for large scale restoration projects on sites representing former pastures or areas vegetated with annual and perennial weeds. On these sites it is important to completely eliminate any existing weeds or seeds in the sod before seeding prairie species.

- Discing-harrowing: Spring discing can be followed by harrowing (to level the area) and using a roller or cultipacker to firm the seedbed just prior to seeding.

## Disadvantages of mechanical methods

There are at least two major disadvantages to the above-listed mechanical methods of seedbed preparation, including:

- Exposed bare soil results from each of the methods and is subject to erosion from both wind and water. For this reason, it is imperative that a site be planted as soon as possible following preparation of the seedbed. Also, a light mulch application often assists in protecting the seedbed surface from adverse environmental factors (e.g., heavy rains).

- A potential exists to lose seed during heavy rains, especially on unlevel sites - Where there is essentially nothing to limit the impacts of raindrops and runoff on a newly planted seedbed, the inevitable result will be seed loss and poor germination/establishment rates. In general, there will be less seed loss on rough to very rough seedbed surfaces than on smooth ones. Also, there will be greater loss on sloping sites than level ones.

## Chemical methods of seedbed preparation

The following are generalized accounts of several different and commonly employed chemical methods for seedbed preparation; each method has the presence of erosion-prone bare soil for a long period following seeding, which is a major disadvantage (Thompson 1992).

Chemical methods:

- No-till chemical (herbicide) seedbed preparation - Apply Roundup$^{R}$ (glyphosate) at the rate of 7 liters/ha and 7 to 18 days before planting seed, to kill existing vegetation (both monocot and dicot species). This method has been used successfully for both small and large-scale prairie wetland restoration projects (Thompson 1992). It may be necessary to apply herbicides at more than one point in the growing season to effect weed control.

- Pre-emergence treatment - Prepare the site for planting, allow weeds to grow until they become established, apply a chemical herbicide, and then plant the desired species (Edmond et al. 1957).

Chemical methods combined with other control methods:

- Herbicide-mowing - Apply a suitable herbicide and later remove the dead vegetation by mowing. The mowing produces a light layer of organic mulch, which assists in prevention of erosion on long or steep slopes.

- Spray-disc-spray method - Apply a suitable herbicide, shallowly till the soil to produce a firm seedbed, allow weed seeds to germinate, and lastly again apply herbicide. This method can be adapted to either spring or fall sowings.

- Spray-disc method - This method is a variation on the spray-disc-spray method of seedbed preparation and has the potential for good success in early May in many areas.

It consists of an herbicide application followed by plowing and then discing every 10 to 12 days, followed by harrowing and planting seed approximately 3 weeks after the initial herbicide application.

- Disc-spray method - In this variation, the combination of plowing and discing is followed by a herbicide application shortly before planting.

Additional information on herbicide use is provided in the section on Exotic/Undesirable Plant Species Control.

## Soil amendments

Soils at most project sites will benefit from improvement through the use of soil amendments. Soil amendments generally fall into three classes:

- Bulk organic matter - Any type of bulk organic matter tends to improve the structure, fertility and water-holding capacity of a soil.

- Inorganic fertilizers, lime, and sulfate - These materials improve soil fertility and/or adjust pH.

- Soil conditioners - Soil conditioners offer the potential to improve soil structure and alter water-holding capacity.

An innovative technique was employed in Maine to distribute soil amendments consisting of a mixture of topsoil, composted municipal sewage sludge, and wood waste recycled from forestry operations. This soil amendment mixture was applied using an aero-spreader mounted on a six-wheel drive articulated forwarder. The aero-spreader broadcast the mixture, which minimized damage to existing vegetation, and allowed soil to be applied as a top dress conforming to the existing terrain. This method eliminated soil compaction and erosion problems through a reduced need for heavy equipment use on a site. When using an aero-spreader, substrate mixtures should be composed of particles of no greater than 5 cm (2 inches) in size, because larger sizes may clog the machine (Cowan 1993). See Chapter 7-3 for additional information on fertilizers.

## Organic soil amendments

Organic soil amendments should be used with caution, because those having a carbon to nitrogen ratio of greater than 25:1 (e.g., straw) will eliminate available nitrogen from the soil as the organic matter decomposes. Inorganic nitrogen fertilizer may need to be increased to compensate for this effect.

## Inorganic fertilizers, lime, and sulfate

Coppin and Richards (1990) recommend an evaluation of the following factors in determining the need for fertilizer and pH modifications:

- existing soil fertility levels
- demands of the intended vegetation and level of productivity required
- soil type and its ability to store/release soluble nutrients
- amount of rainfall available to leach out soluble nutrients
- nutrients contained in bulk organic soil amendments

Soil tests should be made to determine the presence of any onsite nutrient deficiencies. Nitrogen and phosphorus, for example, are usually limiting factors for plant growth on semi-arid and arid sites in the western United States (Doerr and Landin 1983) and elsewhere. Supplemental applications of these two nutrients significantly improve the growth of emerging plants in some situations (Kadlec and Wentz 1974).

Fertilizer application generally offers the potential for an increase in forage yields, vegetation canopy cover, and nutritive values of forages and can alleviate soil nutrient deficiencies (Doerr and Landin 1983). Also, Claassen and Zasoski (1993) reported an increase in mycorrhizal infection levels in roots following fertilizer application. Infection levels were greatest in response to applications of a moderate amount of fertilizer (equivalent to approximately 27 kg N $ha^{-1}$ and 39 kg P $ha^{-1}$) and less under both higher rates of fertilizer treatment and in unfertilized plots.

Inorganic chemicals are an inexpensive source of readily available plant nutrients. The more expensive slow-release fertilizers may be preferable for use on low maintenance areas, however, because the nutrient supply is released over a longer time period.

Lime can be used to reduce soil acidity (i.e., increase soil pH) in areas where the natural soil acidity levels may be detrimental to most wetland species. Ammonium sulfate can be used to lower soil pH.

## Soil conditioners

Certain soil conditioners are available, but their use should be approached with caution due to factors of cost and questionable benefits for many situations. Moreover, their use in drought-prone areas can be detrimental to plant survival. Materials of particular value include those which improve the structure of heavy soils and those which absorb water and help to retain it. Any soil additive to be used should be worked into the soil during site preparation activities. Some projects have indicated a benefit of deep rooting from deep placement of soil conditioners. Soil conditioners include the following groups:

- Alginates - Seaweed extracts which are used to provide nutrients, improve soil structure, and absorb water.
- Polymers - Synthetic compounds having the capacity to absorb large quantities of water and release it slowly.

- Polysaccharides - A group of both natural and synthetic products which are valuable in improving heavy soils.

## Damage from Wildlife and Waterfowl

Impacts on vegetation from wildlife and waterfowl can be of serious consequence to project success and should be considered at the time of site preparation activities. Control measures should be used at new planting sites where the potential for animal damage is high. Potential control methods include fencing the site to exclude animals, trapping and removing animals, locating the site at a sufficient distance from known populations of problem species, and planning the project to avoid a known pest problem.

Relatively small mammals (e.g., muskrats) and waterfowl (e.g., Canadian geese) sometimes consume great quantities of marsh and aquatic plants, and they can be serious problems for new plantings (Kadlec and Wentz 1974). Most small animals and waterfowl do not inflict permanent damage to established stands, although recent studies suggest that nutria on the Gulf Coast play a major role in causing a conversion of vegetated wetland areas to open water or mudflats (Johnson and Foote 1994). Nutria can have a significant effect on wetland vegetation because their feeding activity is concentrated in a localized area over time. Larger animals, such as beavers, also have devastating effects on both new and established vegetation. In addition, beavers have the potential to adversely affect project success through alteration of site hydrology.

Both wildlife and feral animals (e.g., hogs and horses) can destroy newly planted vegetation or alter normal successional patterns by excessive grazing, trampling, or uprooting. These various pressures vary among regions and wetland types. Consult the state wildlife agency for information on potential problem animal species, control methods, and regulations related to wildlife species.

## Site Maintenance

### Introduction

Site maintenance includes those activities necessary to maintain the physical character of the prepared seedbed or planting bed prior to and following planting.

### Objective of site maintenance

A major objective of site maintenance is to maintain the integrity of the project site in an optimal condition until it is planted. Often, planting will immediately follow the completion of the final surface and seedbed preparation. In many other instances, however, there may be a significant time period during which time the site could be subject to potential impacts from erosion, wildlife and other animals, undesirable vegetation, etc. In general, increased time between site preparation and site planting will result in increased site maintenance requirements.

### Site maintenance activities

Once the final grades at a site have been achieved and a surface soil covering has been applied (if necessary), maintenance of a site in optimal condition for planting is critical. A number of activities may be necessary to maintain and protect a site prior to planting. The list of potential issues that may have to be addressed includes the following:

- erosion control
- water level management
- control of damage from wildlife and other animals
- off road vehicle control
- control of exotic or other problem plant species

## Erosion Control

### Introduction

The need for soil surface protection prior to planting cannot be overemphasized. Erosion control measures are appropriate at all phases: during the site preparation phase (i.e., grading, filling, etc.), after site preparation is completed (and before planting), and after the site is planted. Erosion at a site can be caused by both water and wind, and erosion control measures will vary with topography, soil erodability, rainfall intensity, ground cover, and other factors (Environmental Laboratory 1986). Sandy soils are the most susceptible to wind erosion, while most soil types have the potential for erosion by water. Arrest and control of erosion is highly site specific and may require varied control techniques.

Table 7-6 presents a number of erosion control measures for forested, freshwater, and fringe wetlands in the South. Also, the control measures presented for shoreline erosion by Allen and Klimas (1986) are useful to this discussion.

### Mulches

Permanent plant cover is the most effective measure for erosion control, but mulches and binding agents can be used for temporary erosion control while vegetation is becoming established (Blaser 1978). Where a site is not planted immediately, mulches can be temporarily placed on the substrate to provide initial erosion control and weed suppression prior to planting. Clean, weed-free straw mulch is most commonly used (i.e., wheat or barley straw) and is applied at rates of 1100 to 1700 kg/ha (1000 to 1500 lb/acre) for initial erosion control (Scheuler 1994).

**Table 7-6**
**Measures to Arrest and Control Erosion Through Surface Management Techniques (after Environmental Laboratory 1986)**

| | PROCEDURES |
|---|---|
| **Humid regions:** | |
| **Larger areas with slopes >** | **Grading**: Slopes should be 1:1 or less; steps should be vertical, but not more than 1 m in soft (sandy) materials and ≤1 m in rocky materials (Wright, Perry, and Blaser 1978) |
| | **Grooves**: Used on hard, smooth compacted surface; grooves should be 7 to 15 cm deep (Wright, Perry and Blaser 1978) |
| | **Seeding method**: Hydraulic seeding |
| | **Slope protection**: Hay, hydromulches, nets and binders |
| | **Seed and plants**: Seed mixes, shrubs and trees |
| | **Soil fertility**: Test soil for pH and nutrients |
| **Slope less than 2:1*** | **Grading**: Crawlers should grade up and down slopes so that track cleats overlap; track cleats will trap surface runoff and act as miniature diversions; if graded across the slopes, tilt blade to form miniature diversions |
| | **Seeding method**: Drill or broadcast; drill seeding preferred |
| | **Slope protection**: Use hay mulch embedded with a cutaway disk; use hydromulching, tackifiers, or nets |
| | **Seed and plants**: Seed mixes, trees and shrubs |
| | **Soil fertility**: Test soil for pH, nutrients |
| **Small areas with slopes < 2:1** | Renovate for soil compaction; use hay mulch embedded with cutaway disk, if accessible; otherwise, hay mulch by hand or use wood chips or bark; mulch 1.5 cm deep with hay, and strive for 70 percent of the surface area to be covered if using wood chips; rills and gullies may need to be shaped to slopes less than 2:1; steep terrace paths or trails should have steps to flatten grades |
| | **Soil fertility**: Test soil for pH and nutrients |
| | **Seeding method**: Use knapsack broadcast seeder |
| | **Seeds and plants**: Seed mixes, trees and shrubs |
| | **Mulching**: Use straw, hay or wood chips for mulch; apply hay or straw at 4.5 metric tons/ha; spread wood chips to cover 70 percent of the area. |
| **Arid and semiarid regions** | |
| **Roadways and banks** | On all slopes, use grading and shaping techniques for maximum water retention; some general techniques are contour terracing, contour furrowing, contour trenching, construction of small basins, and pitting; these techniques are designed to control the velocity of surface runoff and windblown sediment and to trap and retain water |
| | **Soil fertility**: Test soil for pH and nutrients |
| | **Seeding methods**: Use knapsack broadcast seeder |
| | **Seeds and plants**: Seed mixes, trees and shrubs (see seeding, transplanting, and implementation sections) |
| | **Comment**: Because of the seriousness of wind erosion in arid and semiarid lands, lack of vegetation increases the vulnerability of soils, especially sands, to wind erosion.<br>Supplemental measures are suggested: wind breaks, shelterbelts, contour strips, mulching, soil binders, and contour tillage (Doerr and Landin 1983); and freshly exposed areas should be seeded and mulched with either hay, tackifiers, or straw, and land imprinted or crimped |
| **Camping & picnic areas, paths, trails** | All slopes and areas subject to high-use intensity should be ripped to at least 30 cm to loosen soil; in trampled areas, seed and mulch immediately; refer to arid and semiarid regions above and Doerr and Landin (1983) for seeding and soil fertility |
| | **Mulching**: All freshly exposed areas should be mulched with hay, straw, or tackifiers |
| | **Irrigation:** Watering or irrigation may be needed to assist with new seedings or plant establishment |

*Consult with engineers for proper ditching and culvert size and placement)

Mulches can also be used as one of the last steps in establishing permanent vegetation on a newly seeded site (Environmental Laboratory 1986). When applied to a newly seeded site, a mulch usually improves seed germination and seedling establishment in the following important ways:

- reduces soil surface temperatures
- improves soil moisture content through a reduction in water evaporation
- prevents soil erosion caused by impacts of rainfall and runoff
- increases water infiltration into soil

Erosion control blankets, dry mulchseeding, or mulches in combination with hydroseeding are often used on steep slopes and edges. Drawbacks to these methods, however, include possible delays or impairments in seed germination rates (Murn 1993) and seedling survival when these actions are conducted outside the optimal seeding periods. The negative effects on seed germination and seedling development attributed to these methods possibly relate to such factors as a light requirement for seed germination in many species, a general reduction in rates of all biological activity under reduced soil temperatures, an imbalance in the seedling's respiratory/photosynthetic relationships during the time period required to penetrate the mulch layer, a general tendency for smaller seeded species to be smothered under thick mulch applications, and a lack of adequate contact between seeds and soil (in dry mulchseeding).

There is no single best formula for accomplishing erosion control in all situations with mulches, binders, and stabilizers. Selection of a mulch/binder/stabilizer combination is usually based on intended use, cost, availability, site conditions, season of seeding, and field test results. Also, the type of hydrology present on a site to be mulched often must be considered (e.g., mulches are often lost through flotation during flood events). A mulch may be tracked with a bulldozer to increase the permanence of the mulch application.

Numerous soil stabilizers and binders are commercially available. Table 7-7 lists some of the common mulches and binders available for erosion control. See Chapter 7-3 for additional information on mulches.

## Cover crops

The use of a cover crop to stabilize the soil and prevent erosion is a temporary measure and has merit if the crop does not persist on the site. A cover crop is sometimes difficult to control, but one effective control method is to eliminate it chemically prior to seeding (Rolfes 1993). Cover crops are discussed in greater detail in the section on Site Preparation.

**Table 7-7**
**Mulches and Binders for Controlling Erosion**
**(modified after Environmental Laboratory 1986)**

| Site Use | Mulch | Application Rate | Method of Application |
|---|---|---|---|
| Small areas of less than 1 ha | Hay or straw (baled or loose) | Spread for about 2.5-cm depth (use on less than 1:1 slopes) | Manual or blown onto site; can be labor intensive |
| | Peanut hulls, corn cobs, cotton gin and sugar mill wastes | Spread to about 1- to 3-cm depth | Manual or blown onto site; can be labor intensive |
| | Hay or straw and asphalt tackifier | Spread to about 1- to 3-cm depth | Blower |
| | Wood fiber | Variable, depending on site; use on 1:1 slopes | Hydromulcher |
| | Wood chips, sawdust, and bark | Spread for about 60- to 70-percent area coverage | Blower, hydromulcher |
| | Soil binders or stabilizers | Variable depending on product | Hydromulcher |
| | Nets, wood excelsior mats, jute and burlap fabrics | Variable depending on product and use | Manual |
| Extensive areas of more than 0.8 ha | | | |
| All areas | Rock and soil mulches | Variable, but have at least 2- to 3-cm depth | Manual or heavy construction equipment |
| Windblown sands or sand dune stabilization | Soil stabilizers such as sand fencing and planting rooted stock such as beach grasses, trees, and shrubs | As needed | Hand labor |

## Other aids to vegetation establishment and erosion control

The time between final preparation of the planting surface and establishment of a vegetation cover is a critical period when risk factors for erosion, surface movement, and surface drought are at their greatest. Possible measures to reduce these risks include installation of plastic or degradable geoweb or other geotextiles on erosion-prone areas at the time of soil spreading and followed closely by planting. This will help to hold the soil in place until adequate root development has occurred, although the geoweb material may float on flooded sites. Wind erosion also can be an important factor, particularly in arid areas having little surrounding vegetation cover, and an application of some type of soil binder may be necessary (Coppin and Richards 1990).

Onsite rill and gully formation can be discouraged by shallow grading, rototilling rows along contours of the slope (horizontal to the slope contour), and installation of trees and shrubs in linear beds rototilled along the contours of the slope (Cowan 1993). This approach directs water flowing down slope into depressions that dissipate the water's energy and allows percolation of the water into the soil.

## Water level management

Water level management may be used as a site maintenance activity prior to planting. A manipulation of water levels may be important to facilitate effective site access by machinery and/or hand labor (i.e., mechanized planting is often difficult or impossible in saturated soils) and to provide optimal seed germination requirements (i.e., many seeds will not germinate under saturated soil conditions).

## Off road vehicle protection

Off road vehicles (ORVs) are general recreational vehicles designed and used to traverse areas inaccessible to conventional vehicles. Both ORVs and conventional vehicles can cause adverse environmental impacts to a wetland site that has been graded and made ready for planting (or after planting). ORVs generally impact a site's vegetation and soils by creation of deep ruts, formation of trails that are devoid of vegetation and subject to increased erosion, and compaction of soils.

ORV impacts are a special problem throughout the arid lands region of the West and Southwest where dry soils are extremely vulnerable to erosion by both wind and water. ORVs are also a problem in more humid regions, but their deleterious effects often may appear to be less severe in these regions due to the higher vegetation cover values associated with higher precipitation rates. Regardless of their appearance, however, ORV-impacted wetlands in moister sections of the country are highly subject to increased erosion, changes in species composition, destruction of vegetation cover, and altered hydrology on sites fed by surface water.

Where ORV use has widespread public acceptance, their control can be a very difficult task. An effective control program may have various components, including designation of specific areas where ORV use is prohibited or regulated by permit, law enforcement, erection of barriers, and education (i.e., signs, pamphlets, etc.). The use of barriers (i.e., placement of logs in a criss-cross pattern across sensitive areas, fences, etc.) has been effective in some areas to restrict ORV access (Cowan 1993).

## Control of exotic and other problem plant species

Unless there is a significant time lag between site preparation and planting, the control of exotic and other undesirable plant species is probably a greater problem in vegetation maintenance than in site maintenance. Thus, control of exotic and other problem plant species is discussed in the chapter on vegetation maintenance.

# 7-3 Planting Methods[1]

## Introduction

Typically, a site is ready for planting after landscape plans have been completed, soils evaluated, plant propagules located, site preparation completed, exclosures constructed (if necessary), and any other tasks to ensure the best conditions for plant establishment and site stability have been completed. At that point, the species to be planted and type(s) of propagules being planted will largely dictate planting methods and associated plant establishment requirements (e.g., fertilization, irrigation, etc.).

Some types of propagules have a wider range of planting method choices than others. Seeds, for example, can be sown in a number of different ways (e.g., broadcast, planted in furrows, etc.), and container-grown species can be planted in an equally diverse fashion (e.g., on raised hummocks, with a watering rim, etc.). Similarly, planting techniques for wetland sites are variable depending on the site and project constraints. For example, if the planting site is subject to high physical stresses such as erosion, siltation, or current and wave action, seeding will probably not be as successful as transplanting (Woodhouse et al. 1974). On the other hand, if the site is stable and sheltered, and the substrate is favorable and the site hydrology (e.g., water levels, volume, velocity) easily manipulated or controlled, seeds or a combination of seeds and transplants may be desirable and more economical (Kadlec and Wentz 1974).

This chapter focuses on planting techniques available for wetland restoration projects. The planting methods presented in this chapter are primarily organized by propagule type (e.g., seed, container plants, cuttings). Where possible, each propagule type section describes the range of planting techniques (if applicable) that can be used to establish wetland vegetation for the propagule type, advantages and disadvantages of the techniques, planting procedures, and wetland types or site conditions in which these techniques will and will not be most successful.

Many of the techniques described in this chapter are vegetation establishment techniques commonly used in upland habitats. They apply equally well to wetland habitats because many wetland sites are planted when the site is drained. Innovative techniques for establishing vegetation at wetland restoration sites are also presented in this chapter, but these techniques are proportionally fewer in number because they are difficult to find in the published literature.

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[1] By Lisa C. Gandy and Gary E. Tucker

## Seeding

If seeding has been chosen as the method of wetland vegetation establishment, the next step is to determine the seeding technique(s) to use at the site. This section describes the various seeding options. Also included in this section is background information on seeds and seeding that is needed to increase the successful establishment of wetland plants at a site from seed (e.g., seedling development, dormancy, etc.).

## Introduction to Seedling Production

Planting seeds is one of the most economic and widely used methods for establishing wetland vegetation at restoration sites, but at the same time it is one of the least reliable of all vegetation establishment techniques. The low reliability of this method is due to the high number of variables influencing the seed germination process and the extended time period to produce a mature plant from seed. Some of the variables influencing seed germination include substrate concentration of salts and gases, ambient temperature regimes, depth of burial, predominant hydrology and soil moisture, light, seed viability, and mechanical, physiological, and chemical germination inhibitors.

The seed germination process involves an accelerated growth rate in the seed embryo. After sufficient water has been imbibed by the seed coat, the embryo, and the endosperm and after the embryo has begun to elongate and grow, the root and the shoot break through the seed coat. This process is largely controlled by the availability of a continuous supply of water; however, water uptake alone is not enough to define germination. Oxygen availability, for example, is important to seed germination. Plant physiologists divide seed germination into four stages (Mandel and Koch 1992):

- Imbibition, where water penetrates into the embryo and serves to activate proteins and other colloids
- Formation or activation of enzymes which, in turn, activate metabolic activity used in driving the germination process
- Elongation of the immature primary root, leading to the emergence of the root from the seed coat
- Seedling growth in both the root and shoot regions

The seeds of most agricultural and horticultural plants usually germinate promptly if given access to moisture and air, if provided with a suitable range of temperatures, and in some instances if exposed to the proper sequence of light and dark. There are, however, many plant species whose seeds do not readily germinate even though they are placed under favorable moisture, air, temperature and light conditions. Germination will be delayed for days, or weeks or even months (Noggle and Fritz 1976). The seeds of such plants are viable but may be in a dormant condition. A dormant seed is a viable seed but the growth of the embryo is inhibited or blocked even under environmental conditions that are sufficient to promote germination.

The mechanisms of seed dormancy are complex. They involve interactions between internal factors (e.g., embryo condition, seed coat, and chemical inhibitors in seed tissues) and external environmental factors (e.g., light and site hydrology). The following sections briefly discuss mechanisms of seed dormancy. Much of this information has been derived from information on horticultural and agricultural species but applies equally well to wetland species. For more specific information on mechanisms of seed dormancy and methods to break dormancy refer to Reilly (1978), Hartman et al. (1975), and USDA Forest Service (1974).

## Internal Dormancy Factors

This section discusses the most common types of internal dormancy that influence seed germination and that decrease timely seed germination at a restoration site. Also included in this section are suggested treatments for overcoming internal dormancy and for increasing dependable seed germination at a site and contributing to successful vegetation establishment at a restoration site from seed at the appropriate time of the growing season.

### Internal Dormancy - Embryo Dormancy

There are two kinds of embryo dormancy:

- Dormancy of an underdeveloped embryo that needs a period of time to continue development before germination can occur
- Dormancy of a fully developed embryo that requires after-ripening to either accumulate or formulate growth promoting substances or to degrade or decrease levels of growth inhibiting substances (Noggle and Fritz 1976)

The latter dormancy phenomenon is noticed especially in seeds of the Rosaceae (rose) family and in conifers. These seeds can often be induced to germinate if they are stored moist but well aerated under low temperature (0ºC to 5ºC or 32ºF to 50ºF) conditions. This treatment is called stratification.

Many seeds of aquatic and wetland plants require either natural stratification or a stratification treatment prior to germination (Sharp 1939, Chapman 1947, Arber 1920, Kadlec and Wentz 1974). This is particularly true for aquatic or wetland plant species from cooler temperate regions that require an after-ripening period during the cold months before germination can occur. This natural stratification allows chemical inhibitors in the seed coat to be broken down during this period.

Seeds of many species in warmer or more southern temperate areas, however, typically do not have dormancy factors and germinate immediately following their separation from the parent plant. Seeds of many aquatic and wetland species that have been exposed to alternating temperatures, which approximate local natural conditions, often produce the highest rates of germination (Kadlec and Wentz 1974).

## Internal Dormancy - Seed Coat Dormancy

The seed coat has a strong influence on the resumption of the growth of the embryo and subsequent germination. Seed coats inhibit germination in the following ways:

- Decreasing water permeability,
- Decreasing gas permeability,
- Providing mechanical resistance to growing embryo, and
- Possessing chemical inhibitors to germination.

Each of these types of seed coat dormancy is discussed briefly in the next sections.

## Seed Coat Dormancy - Water Impermeability

Seed coats may serve as a physical barrier to seed germination by preventing the uptake of water by the seed. Seeds of some wetland plants, particularly those in the Fabaceae (legume) family and species having woody seeds, are virtually impermeable to water. Only after the seed coat becomes cracked or scarified (nicked) by either natural or man induced means, or after the seed coat is dissolved by naturally occurring soil bacteria and fungi or by chemical treatments, can the seed coat become permeable enough for water to penetrate to the embryo.

Under natural conditions, hard seed coats are softened in the soil by alternating temperatures, by drying and wetting, and by biological activity or decomposition by soil flora and fauna. For some species, this may take several weeks or months for their seed coats to become permeable (Noggle and Fritz 1976). For restoration projects under a schedule for establishment, or at sites where the rapid establishment of cover is important for stabilizing the soil, natural softening of seed coats may not be desirable and chemical or mechanical methods may be needed.

Chemical or mechanical methods that weaken, soften, or destroy the seed coat have been developed that improve water permeability of the seed coat and induce germination. Weakening of the seed coat by chemical decomposition (chemical scarification) may be similar to the processes of microbial activity or passage through an animal’s digestive tract (Mayer and Poljakoff-Mayber 1963). Seeds can be soaked in a number of chemical solutions including concentrated sulfuric acid and sodium hypochlorite (Choudhuri 1966, George 1963, Kadlec and Wentz 1974, O’Neill 1972) to soften or dissolve the seed coat.

Mechanical scarification (i.e., breaking, nicking, cutting, or altering the seed coat) is also an effective method of inducing germination. Mechanical scarification can be accomplished by a number of methods. Rubbing the seed coat with sandpaper, cutting the seed coat with a file, or cracking the seed covering with a hammer or vice are simple methods that can be used for relatively small amounts of large seeds. For large scale projects, mechanical scarifiers, such as a disc scarifier, or tumbling seeds in drums or concrete mixers lined with sandpaper or filled with coarse sand or gravel can be used. When using the latter method, the sand or gravel should be of a different size than the seed to facilitate separation prior to seeding (Hartman et al. 1975). Regardless of the method chosen, use of chemically or mechanically scarified seed will improve water uptake and enhance germination and early growth of seedlings in species whose seed coats are impermeable to water (e.g., legumes).

### Seed Coat Dormancy - Gas Impermeability

The seed coats of some species appear to be impermeable to dissolved oxygen and carbon dioxide while being permeable to water. If oxygen is being prevented from reaching the embryo or carbon dioxide is not released and accumulates in the vicinity of the embryo, the germination process can be inhibited. If the seed coats are broken or scarified, prompt germination normally occurs in these seeds (Noggle and Fritz 1976).

### Seed Coat Dormancy - Mechanical Resistance

Some plants have seed coats that are permeable to water and dissolved gases but have high mechanical strength and cannot be broken by the growing embryo. Mechanical resistance to germination may especially be a problem under conditions where the seed coat is moistened and softened and is then dried. Mechanical resistance to germination can be limited by keeping the germinating seeds continuously moist, by fracturing or by partially or completely removing the seed coat, or by applying the seed coat treatments described above under water impermeability.

### Seed Coat Dormancy - Chemical Inhibitors

Chemical inhibitors located inside, outside, or within the seed coat can interfere with any of the first three stages of germination. Growth inhibiting substances that are present within the seed must be leached out, diminished, or deactivated before germination can occur. Some of these inhibitory substances can be leached out by washing or soaking in water. This procedure, however, is often unnecessary because inhibitors are adsorbed to the soil under normal field conditions (Hartman et al. 1975). In some seeds, these inhibitory chemicals do not always act alone to block germination but often act in conjunction with one or more of the dormancy factors described above. The germination of some dormant seeds can be promoted by the application of plant growth substances such as gibberellins and cytokinins (Noggle and Fritz 1976).

### External Dormancy Factors

This section describes the most common external dormancy factors and their effects on seed germination.

## Light

Light quality and quantity exerts an important influence on breaking dormancy and on the germination of some seeds. Appropriate wavelengths of light are required to break dormancy of many wetland and upland plants and to initiate growth in seeds at or near the soil surface. Examples of aquatic macrophytes with light-stimulated germination are numerous and include species such as *Juncus tenuis*, *Alisma plantago-aquatica*, *Iris pseudoacorus*, and *Typha latifolia*.

## Water Levels and Soil Moisture

Hydrology and soil-water levels strongly influence the breaking of dormancy. For most emergent species, the best natural conditions for germination probably occur when the site water levels are lowered and the soil surface exposed (e.g., during drawdown conditions). The optimum time for germination appears to be immediately after the soil has been exposed and before soil crusting has occurred when soil moisture is high.

It appears that seeds of most wetland species do not germinate under water. A few aquatic or wetland species (e.g., *Zizania aquatica* and *Scirpus juncoides*) are reported to have much better germination rates when covered by water or exposed to reduced oxygen concentration (Kadlec and Wentz 1974). Presoaking of seeds of many marsh plant species in water has been shown to improve their germination (Harris and Marshall 1960, Kadlec and Wentz 1974, Miller and Arend 1960).

## Allelopathy

Chemical inhibitors can occur in portions of the plant other than the seed, such as in the leaf, stem, or root. When these inhibitory substances are leached out or released by the decay of litter, they also may serve to inhibit seed germination. The inhibitory actions of these types of compounds are termed allelopathy and may play a major role in vegetation establishment (Salisbury and Ross 1978), but few examples of allelopathic inhibition of germination have been noted in the wetlands literature.

## Seed Viability

There is great variability in the length of time a seed can remain viable. The seeds of many conifers and hardwoods, such as elm (*Ulmus* spp.), poplar (*Populus* spp.), and willow (*Salix* spp.), are viable for only a few weeks or months. Most legume seeds are among the most long lived, with life spans of 75 years or more common. Seeds of aquatic macrophytes tend to remain viable longer than do plant seeds from other vegetation types (Pederson and Smith 1988, Kadlec and Wentz 1974).

## Seed vs. Transplants

When choosing seeding or planting transplants at the wetland restoration site, many factors such as the location and size of the site, site hydrology, soil conditions, energy, and topography influence the decision to seed, to use transplants, or to use a combination of both methods. For example, at high energy sites, such as those where erosion, fluctuating water levels, or wave action are present, seeding is probably not the preferred planting method. Under these high energy conditions, most seeds will be washed away before germination and seedling establishment can occur. At high energy sites, seeding is best when used only to augment transplanting (Allen and Klimas 1986).

For large restoration projects (i.e., > 2 ha.), seeding may be a more practical and economical method than transplanting. Costs for planting live materials on large-scale projects are often prohibitive. This has been true in wet meadow restoration projects in the Midwest where seeding of wet meadows larger than five acres is more practical from an economical standpoint than planting live plant materials (Murn 1993).

## Seeding vs. Transplants - Advantages and Disadvantages

If the decision has not been made to seed a site, the next step is to decide whether to seed or to use transplants or a combination of methods to vegetate the site. The information provided in this section is an overview of the number of factors to consider in choosing whether to seed a site or to use transplants or a combination of both. It provides information on the advantages and disadvantages of each method and the number of considerations involved in the selection of propagule type for the restoration project. Specific techniques and methods of seeding and examples of sites where these seeding techniques are or are not recommended are also provided.

One of the biggest advantages to seeding over using transplants is that seeding is the most economical method of vegetation establishment. Seeding also can be a relatively fast method of establishing wetland vegetation at a restoration site, particularly on sites whose substrates have been well prepared or intensively cultivated, especially for establishing wet prairie vegetation on sites that have been intensively cultivated. Seeding is the typical method of establishing species in prairie restoration projects (Thompson 1992).

The biggest disadvantage to seeding is that its success is the least predictable of the vegetation establishment methods (Garbisch 1986). This is primarily because of the complex suite of physiological and chemical conditions that control germination (as discussed in the dormancy section above), and of the physical condition of the seedling. Seedling leaves, shoots, and roots are composed of tender tissues that have little protective and support tissues. Seedlings, therefore, are vulnerable to external factors such as soil moisture, incident radiation, temperature, soil microflora and fauna, and external energy. For example, lack of soil moisture can cause rapid desiccation of tissues to a degree that recovery is not feasible. Excessive radiation can increase or can cause scalding and death of tissues, freezing temperatures can destroy and kill tender vegetation, soil microflora and microfauna can destroy or weaken tissues (i.e., herbivory or fungal diseases such as damping off), and high energy from waves or currents can break seedlings that lack schlerenchyma or woody supporting tissues. Many variables too numerous to discuss in this document can influence the successful establishment from seed to a healthy stand. However, it is well understood that if conditions are not within the species tolerance range, seedling mortality or poor seedling health usually occurs.

## Seeding Methods

### Introduction

Once the decision has been made to seed a site or to use seed in conjunction with transplants, the next step is to select the seeding method. This section provides an overview of some of the types of seeding methods that can be used to establish wetland vegetation at a site. Also provided are a number of factors that need to be considered for achieving successful vegetation establishment by seed, or the constraints that may limit successful vegetation establishment by seed at the site. A critical evaluation of these factors and constraints is needed to maximize the compatibility of the seeding method with the site conditions and with the species selected for the site.

Because continued moisture availability is critical for the successful germination of the seed and for penetration of the root to deeper sources of water, any seed lying exposed on the soil surface with minimal seed to soil contact is subject to potential damage. This damage can result from drought or cold at a critical time, extreme temperatures, and lack of soil moisture. Any of these and other variables reduce the chance of seedling establishment. The damage to seeds and seedlings can be reduced by the following:

- burying seeds, either by placement (drilling) or incorporation into the upper few inches of the soil (harrowing or rolling)

- increasing surface roughness with a disc, plow, or rake before or after seeding to (Kadlec and Wentz 1974, Martin and Uhler 1962) provide seeds with a better microclimate and decreased probability of stress

- mulching to cover the seed as an alternative to burying (Coppin and Richards 1990)

Applicable seeding method(s) to use at a wetland restoration site are determined by location, size, and topography of the project site; hydrology; seed size and seed mixture; and soil conditions. For example, accessibility of the site to mechanical planting or seeding equipment is affected by the site's location (i.e., remoteness) and topography (i.e., slope steepness). The size of the site will influence the seeding method by directly affecting the number of man-hours a particular method will take to seed the site.

To increase successful establishment of vegetation from seed, seeding should, whenever feasible, be completed when the site is dry (i.e., drained) or moist (i.e., not flooded or saturated). Shallow or standing water usually inhibits the successful seeding of most species because uniform distribution of seed is difficult to control, and the seeds may float to the surface once germinated (Garbisch 1993; 1986). Seeding in shallow water may be feasible for seeds having a greater density than that of water but seedling development may be poor especially in shallow water where siltation of foliage occurs. Successful seedling development in shallow water is influenced by a number of factors including temperature, turbidity, soil, and water salinity.

Seeding in areas exposed to wind, waves, wakes, or currents is typically not successful because seeds and seedlings may be washed away before they become established. When economically feasible, barriers or structures which reduce the impact of waves and currents should be constructed (Kadlec and Wentz 1974). For more information on site preparation to reduce wave and current impacts see Chapter 7-2 or other parts of this handbook.

The size of the seed is an important consideration when choosing a seeding method. For example, broadcasting of extremely small seeds (i.e., seeds ranging from several thousand to millions per ounce) is difficult to impossible to get proper distribution on the site. True rushes (*Juncus* spp.) are an example of wetland plants with such small seeds and which are not practical to seed by broadcasting (Murn 1993). Small seeded species, such as *Typha* spp., *Sagittarian* spp., *Eleocharis* spp., *Salicornia* spp., and *Spartina patens*, are not recommended for broadcast seeding unless the site substrate is muddy and the seeds can be surface sown and lightly pressed into the mud to prevent washing out. Alternatively, some large seeds, such as arrow arum and mangrove seeds, do not disperse well by broadcasting and require individual planting (Garbisch 1986). Because the size and weight of seeds varies so greatly, planning the planting for the desired seed mix is critical to accomplish the desired results. Because many native wetland grass and flowering species have specific niches where they will grow, consideration should be given as to whether mechanical broadcasting of a seed mix over a whole site or hand sowing of single species will increase the success of seedling establishment. This is particularly important because the cost of some native wetland seed can be high and broadcasting of incompatible seed mixes is not an economic method of seeding.

The following sections describe various seeding methods that are typically used in wetland restoration. Where the information is available, a discussion of the situations where the methods are best applied and not applied is presented, and the actual procedures of seeding are presented. There are four principal methods of seed application:

- broadcasting - dry-spreading seeds over the soil surface, the water surface, or its edge either by hand or by machine

- direct seeding - direct placement of seeds in the soil at a particular soil depth either by hand or by machine (usually used for large seeds, such as acorns)

- hydroseeding - spreading seeds in a water slurry

- mulchseeding - wet or dry constituents with a heavy mulch layer applied dry (Coppin and Richards 1990)

These techniques are the most widely used in wetland restoration. The choice of whether to broadcast, direct seed, or hydroseed depends largely on site conditions, such as the severity of the climate, risk of surface erosion, and ease of site access. Regardless of the method used, if seeds are pregerminated under some sort of controlled conditions, they must be rapidly sown or planted at the site or they will die (Miller and Arend 1960, O’Neill 1972). Also, it is important to keep a copy of labels and tags until stands are satisfactorily established. Poor stands could be a result of poor seed quality (Doerr and Landin 1983). More information on seed quality is provided elsewhere in this chapter.

## Broadcast Seeding

Broadcast seeding is the method in which dry seeds are spread or distributed over the soil surface, water surface, or its edge. Broadcast seeding can rapidly distribute seed over a large area and, if done correctly, can result in a relatively uniform distribution of seed over the target surface. Broadcast seeding is an inexpensive, easy, and convenient method of seeding on most sites, particularly on sites accessible to a tractor or other land vehicle. Broadcast seeding is a cost-effective seeding method for both large and small sites whose seedbed has been well prepared or intensively cultivated, and at sites protected from wind, water, and wave action. Broadcast seeding typically is not used in exposed areas with high energy such as high winds, currents, flooding, and wave action. It also is not recommended for seeding large fluffy seeds that may plug the equipment or blow away on windy days. Broadcast seeding has been used successfully to restore wetland vegetation in a number of wetland types including but not limited to prairie potholes, wet to wet-mesic prairies, mudflats, and bottomland hardwoods. If seed quantity and availability are limited and the site is large, broadcasting is not recommended as the sole method of vegetation establishment.

### Procedures for Broadcast Seeding

**Seed Preparation.** Before broadcast seeding is conducted, seed should be thoroughly mixed with fertilizer, sawdust, or sand. The sand or sawdust serves as an indicator of areas already seeded and promotes a more even distribution of seed. The seed can be mixed with sand or other coarse material. Some wetland grass seeds (e.g., prairie species) may have to be debearded (i.e., have the seed awn removed) for proper dispersal from broadcast seeders. Having the seed debearded may increase the cost of the seed (Thompson 1992).

**Seeding Procedures.** Seed should be uniformly broadcast over the substrate surface. In most instances broadcast seed should be followed by some sort of method to “set” the seed. Methods that can be used to set the seed include the following:

- mechanical cultipacking
- rolling
- harrowing to lightly cover the seeds with soil
- hand raking the seed or seed-fertilizer mixture to the desired surface depth

These methods will firm up the seedbed and give a better seed-to-soil contact for germination and increase the success of seed germination Light harrowing or rolling can be used to promote seed burial or setting although these methods of burial may not be necessary on rough-textured soils (Coppin and Richards 1990). Use of heavy equipment to set the seed should be minimized to avoid soil compaction (Allen and Klimas 1986, Doerr and Landin 1983), which will decrease infiltration of surface water into the soil, decrease moisture available to the seed, and potentially increase soil erosion and loss of seed from the site.

The seeded area should be mulched if the potential loss of the seed from wind, water, erosion, or granivory is high, or if soil and air temperatures are high, relative humidity is low enough to decrease soil and seed moisture content, and water availability is unpredictable. If water is readily available and reliable, the seeded area should be kept moist but not flooded until seeds germinate and seedlings are several centimeters tall. At this time the area should be fertilized, if necessary (Garbisch 1986). More information on mulching, irrigation, and fertilization is provided below and in later chapters of this section.

**Seeding Depths.** Generally, seed should be covered with 1 to 3 cm.of soil. The depth of covering, however, is governed largely by the size of the seed and the soil texture (Ware and McCollum 1975). The following rules of thumb for seeding depths generally should be followed:

- very small seed should be covered lightly, if at all
- on heavy soils the covering should be less than on light soils (Ware and McCollum 1975)
- seed should not be sown any deeper than 2 times its diameter

Certain types of seeds, such as acorns, can be successfully sown at any depth down to 6 inches. However, care should be taken as to how deep a seed is planted since depth is directly related to percent germination and early seedling size (Johnson and Krinard 1985, WES 1990). Species that are more desirable to rodents and granivores, e.g., acorns, may be planted deeper than 2 inches to discourage pilfering by rodents and granivores. However, prior to sowing at deeper depths, the benefits that would be gained from deep sowing should be worth or outweigh the extra cost and efforts of sowing at increased depths.

## Broadcasting Techniques

Once the decision has been made to broadcast seed at the project site, the next step is to determine the techniques by which seed will be broadcast. Techniques by which seed can be broadcast at a wetland restoration site include seeding with a vehicle-mounted seeder (e.g., tractor, all-terrain vehicle, fixed-wing aircraft, etc.) or by hand. Several techniques are presented below along with when they should and should not be applied.

**Broadcast Seeding - Tractor-Mounted Seeder.** The most common method of broadcasting is to disperse seed from a tractor-mounted broadcast seeder. The use of a low-ground-pressure tractor is recommended to reduce soil compaction since soil compaction eliminates pore space, decreases soil structure, decreases root or shoot penetration, and increases soil erosion. A large salt spreader device mounted on an all-terrain vehicle is one variation on the tractor-mounted broadcast seeder method used to broadcast seed efficiently over large areas (Thompson 1992). This method is particularly suitable for sites where the terrain is rough and accessibility with conventional farm equipment is not feasible.

**Broadcast Seeding - Aerial Seeder.** Aerial seeding is a method of broadcast seeding that is accomplished with a fixed wing aircraft or helicopter attached with a hopper-spreader unit (e.g., 7100 Maxi-merge planter was used to drop acorns for bottomland hardwood restoration). Hovercraft seeding and helicopter seeding can be used to seed large inaccessible areas and sites whose substrates are soft and moist and would not support people or light equipment. A disadvantage of aerial seeding is that if site conditions, particularly moisture, are variable over the site, seed germination across the site using aerial seeding may also be variable with best germination success in areas with more consistent soil moisture. Aerial seeding has been successful for seeding mudflats where even hand seeding would be difficult (Fowler and Hammer 1976, Whitlow and Harris 1979) and for seeding of acorns on bottomland forested sites (Haynes et. al. 1993). In southern bottomland hardwoods, aerial dropping of acorns was followed by discing to increase the seed to soil contact and to lower rodent depredation. The height and speed at which aerial seeding is conducted and the seeding rate is dependent on the density of seeds desired on the site. Generally, seed density and distribution is lowered as the flying altitude and aircraft speed are increased. More information on aerial seeding can be obtained from the US Fish and Wildlife Service, US Forest Service Research Centers, and Tennessee Valley Authority.

**Broadcast Seeding - Hand Seeder.** Broadcast seeding by hand is usually conducted with a hand-held or a knapsack seeder, but hand distribution of seed or spot seeding is also conducted. This technique is especially important for seeding small and hard to access areas. Hand broadcasting is good for hard to seed areas (e.g., sites with little site preparation, steep sloped areas) that would not be seeded by other broadcasting techniques. Hand broadcasting of wetland species that have selective niches or specific requirements can result in increased seed germination by increasing the compatibility of the species with the site niche. Disadvantages or limitations of hand broadcasting include: (1) the extent of seed coverage or distribution at a site is small compared to other broadcast seeding techniques, and (2) a greater amount of time and man-hours is required to seed a site using hand-broadcasting techniques than with other broadcasting techniques. The time and man-hours is increased because the seeding method requires that the site be walked, but the absence of mechanized equipment may result in reduced overall costs. Broadcast seeding by hand, therefore, usually is conducted on small areas (i.e., 1 hectare or less), or on inaccessible sites or steep slopes. Because hand broadcasting is labor intensive, it also is recommended for small sites where mechanical means are not practical or possible (Doerr and Landin 1983).

## Hydroseeding

The use of hydroseeding is an alternative where broadcast seeding has been identified as an appropriate method of vegetation establishment at the wetland restoration site but where site access is limited or the terrain is too steep or diverse to obtain uniform seed distribution and densities from hand, tractor mounted, or aerial seeding. This section provides an overview of hydroseeding techniques, advantages and disadvantages of this method, and site conditions and situations where this method is or is not recommended.

## Introduction

Hydroseeding is a method of seeding where a slurry of seed, fertilizer, water, and sometimes mulch is sprayed onto the substrate. Constituents of the slurry may include:

- seeds
- legume inoculum (*Rhizobium* bacteria)
- soluble fertilizer
- slow release fertilizer
- mulch to act as a carrier for other constituents, to protect seeds, reduce soil moisture loss and provide initial erosion protection; the inclusion of mulch in the tank at sowing time is optional, however, and many practitioners apply mulch with a blower following the hydroseeding
- stabilizer/binder to protect soil surface from erosion and tack down seeds and mulch (Coppin and Richards 1990)

## Hydroseeding - Advantages and Disadvantages

Hydroseeding is a commonly used seeding technique for wetlands restoration, and it has several advantages over direct seeding or broadcast seeding. Benefits of hydroseeding include minimal soil compaction and soil erosion as a result of heavy equipment passing over the site, and rapid application of seeds and fertilizers onto areas where access and site conditions prevent rapid and effective seeding. For example, sites with steep banks and uneven terrain lend themselves to hydroseeding. Hydroseeding is an especially attractive method for the seeding of large inaccessible areas (Fowler and Hammer 1976). Because of its ease in application, hydroseeding is often incorrectly chosen as the seeding method for many restoration sites. The primary problem with hydroseeding is poor seed-to-soil contact. This poor seed-to-soil contact results in the inability of the roots to penetrate into the soil, thereby decreasing water uptake by the emerging seedling, seedling survival, and seedling stability. Hydroseeding, therefore, is not a recommended seeding technique in areas that receive insignificant amounts of precipitation or are subject to flooding (Rolfes 1993). Hydroseeding should be used as the preferred seeding method when it is known that the seeds will germinate and the seedlings will become well established before the site becomes flooded. If a site is flooded after hydroseeding is completed but before seedling germination and establishment, the mulch, tack, and seeds will float and often will be blown or washed to one side of the site (Garbisch 1994; 1986).

Correct preparation of the seedbed is as important for hydroseeding as for any other method (Coppin and Richards 1990) to increase the seed-to-soil contact, regardless of how difficult it may be to achieve at the site. Hydroseeding should not be used as an alternative to top soiling or proper soil surface preparation, although this is sometimes done, usually with poor results.

### Hydroseeding Techniques

Hydroseeding is often conducted with a tractor or truck mounted hydroseeder. Alternative hydroseeding application methods include hydroseeding from boats, barges, and train cars (Sick and McGee 1993). Many of these alternatives have been employed in remote areas where site accessibility is limited. Examples of the types of hydroseeders available, applications for their use, and rates of seed application can be found in many technical and trade journals for erosion control and reclamation, and in highway and transportation engineering specification documents.

After the seedbed has been prepared and the site hydroseeded, applying a mulch over the seeds is often required to protect the surface soil from soil erosion. Mulching should be used only if water levels will remain low up until the plants are growing well (Allen and Klimas 1986). Mulches should be applied at a sufficient level if their values are to be achieved. Coppin and Richards (1990) indicate application rates of 1.4 to 2.7 kg/ha for hydroseeding and 4 to 5.5 kg/ha for mulchseeding in the United Kingdom, but application rates in the U.S. are typically much higher.

## Direct Seeding

If direct seeding has been chosen as the technique for establishing wetland vegetation at the site, the next step is to determine whether direct seeding will be conducted by hand or mechanically. The section presents the options available for direct seeding mechanically or by hand, advantages and disadvantage of each of these techniques, and site conditions of types where these direct seeding methods are or are not recommended.

### Direct Seeding - Advantages and Disadvantages

Direct seeding is the placement of seeds directly on the site at specified locations and in some cases at the desired depths. Direct seeding can be accomplished either mechanically or by hand. Direct seeding is a common method of seeding for larger seeds and is generally preferred over broadcast seeding. It usually is less expensive and is a more versatile method when compared to planting of seedlings. Direct seeding has been found to reduce vegetation establishment costs by 1/3 or 1/4 of the cost for planting seedlings at a site (Moore 1986).

Direct seeding is advantageous in that it extends the planting season or the planting window for large seeded species, particularly acorns and seeds having slow germination (Haynes et. al. 1993). Because seeds, particularly acorns, do not undergo the stress in sprouting that seedlings go through during replanting (Moore 1986, WES 1990), seeds generally can withstand wetter weather and standing water better and for a longer period of time than seedlings. Seeds, therefore, can be planted earlier or later than most seedlings. Disadvantages of direct seeding are that this method may in some cases be more labor intensive if direct seeding has to be done manually, and seedlings that have developed from direct seeding may lag behind planted seedlings in their early development (first few years). Survival rates of approximately 90 percent have been reported after the first few years (Johnson undated; WES 1990).

Direct seeding can be accomplished by several methods including hand seeding, drill seeding, or by other automated machine planted methods. Drill and machine seeding are well suited for large open areas without stumps and debris, but they are not an option when soil moisture is high. Under high soil moisture conditions, planting machines may get stuck at the site or damage the substrate of the restoration site.

## Direct Seeding - Drill Seeder

Drill seeding places seeds in the soil at the desired depth for germination. Generally, drill seeders used in wetland restoration are composed of a tractor-mounted drill that has several seed boxes designed to seed various seed sizes and mixtures (small and dense, light and fluffy, or medium-heavy seeds) with fertilizer at the time of seeding. Drills also have coulters that will lay open the surface soil for seed placement, leading to better seed-soil contact than with broadcasting.

Use of a seed drill is usually recommended for large scale wetland restoration efforts because if properly manned, drill seeders can reduce time and man-hours associated with seeding at a large site. Drill seeding is limited by the terrain, (i.e., generally only recommended for flat to gently sloping sites) and the amount of contact in the surface soil (Doerr and Landin 1983, 1985; Environmental Laboratory 1986). A disadvantage of drilled wetland restoration sites is that they initially exhibit an undesirable row effect. In most cases this appearance becomes less noticeable after 2 or 3 years (Thompson 1992). To avoid this row appearance, some have planted grass seeds by drill, followed by a broadcast of forb seeds over the site. An irregular path could also hide this row-like appearance but would increase the amount of time required to seed to ensure consistent coverage of the site. Areas that are drill seeded should be lightly rolled (cultipacked) to ensure proper seed/soil contact (Allen and Klimas 1986, Rolfes 1993, Environmental Laboratory 1986).

Seed drills often can be loaned or rented from conservation commission district biologists or local SCS personnel (Thompson 1992). The following are a few examples of the drill seeders that are available from these sources:

- seed drills - several seed drills are designed for use with light, fluffy seeds and have been used successfully in seeding of prairie species (Thompson 1992). Examples of seed drills include the Nesbit drill, Truax drill, Marliss drill, Rangeland drill, and Great Plains drill.

- no-till drill - no-till drill seeding has been used by the US Forest Service and the Soil Conservation Service in forested wetlands restoration. It has also been used in both wetland and non-wetland restoration projects in the Midwest where concern for soil erosion is high. This technique is desirable over traditional drill seeding techniques in areas where erosion potential is high (e.g., steep slopes and areas subject to flooding and high winds). A significant benefit of this technique is the reduction in soil erosion and loss of topsoil from the site. An example of a no-till drill that can be used in the seeding of native grasses is the Truax 2 m. no-till drill. For more information on no-till drill seeding see Sick and McGee (1993).

## Direct Seeding - Modified Planters

Other machines that can be used for direct seeding are modified soybean, corn, peanut, and cotton planters. These machines can be adapted by taking the planting plates and modifying them to fit the seeds to be planted (Moore 1986, WES 1990). Machines will vary in the number of rows that are planted with a single pass (i.e., one-row and two-row planting machines) and whether seeds are automatically fed or dropped into the machine or need to be manually fed. For example, some planters will drop seeds automatically at intervals of approximately 80 cm. If an automatic feeder is used, routine inspection of the planter is needed to insure that a hopper has not jammed and long stretches of the site left unseeded. To eliminate this problem, machines can be manned by one or two people who drop the seeds into the hopper (Johnson and Krinard 1985, 1987).

The biggest advantage of machine planting over direct seeding by hand is that it is rapid, efficient, and inexpensive because it is not labor intensive. For example, when using a planting machine to direct seed acorns into a bottomland hardwood site, approximately 5,000 acorn seeds per hectare can be planted which in turn could produce as many as 250 trees per hectare (Thompson 1992). Another benefit of direct seeding with a modified machine planter is that cracks in the soil are not as likely to develop because the planter's shovels drag/pull soil over the holes and the wheels pack it down (Moore 1986, WES 1990). In the South, a converted John Deere Maxi-merge 7100 has been used on sites that have not been prepared and that contain agricultural debris. Planting machines are commonly used in planting acorns in hardwood restoration projects on abandoned agricultural fields.

## Direct Seeding - Hand Seeding

Direct seeding by hand is the placement of seeds directly into the soil at the desired depth. Unlike broadcast seeding by hand, direct seeding increases the seeds' contact with the soil at the time of seeding and does not require follow-up techniques such as rolling, harrowing, disking, or cultipacking to increase the seed-to-soil contact. Similar to hand broadcasting, however, this method of direct seeding is best applied when the site to be seeded is small (< 2 ha.), where machine planting cannot be conducted due to limited maneuverability, on sites with steep slopes, on poorly consolidated soils, and on sites where the substrate is unsuitable to support machine planters. Direct seeding by hand seeding is also a useful technique for establishing specific species on a site amongst existing vegetation. At sites where competition from existing vegetation may be detrimental to successful establishment of new vegetation on a site, direct seeding by hand may be desirable because the proximity to existing vegetation can be controlled to minimize competition from existing vegetation.

Direct seeding by hand is more labor intensive, slower, and more expensive than direct seeding by machine planters, drills, or by broadcast seeding and typically is recommended for small sites. Direct seeding of acorns using hand planters, however, has been conducted on bottomland hardwood restoration sites as large as 8 ha. in size when the site has been inaccessible to seeding equipment (e.g., forest openings, Johnson and Krinard 1987) or the substrate is unsuitable for supporting equipment. In the Midwest, moderate success has been achieved with direct seeding only on relatively large areas (> 2 ha.) and on very open sites (Thompson 1992) because larger and open sites are subject to less seed depredation by rodents.

## Seed Quality

Using high quality, disease- and weed-free seed mixtures is important to increasing the successful establishment of wetland vegetation at a restoration site, and high quality seed should be used at all times. Using high quality seed is important to obtain the desired mixture and diversity of wetland plant species at the wetland restoration site. Whenever possible, certified seed should be used in vegetation restoration activities.

Seed quality is defined by minimum percent germination and minimum percent purity. Important to the determination of seed quality are seed class (certified, registered, or common class), percent contaminants, and inert ingredients.

Seed class is a measure of overall seed quality and genetic purity. Both certified and registered classes are recognized by official seed certification agencies. The concept of seed certification implies genetic improvement. Its aim, traditionally, has been to provide the user with high-quality seeds of superior crop-plant varieties grown and distributed to insure the genetic identity and genetic purity (USDA Forest Service 1974). To be certified or registered, seeds must meet minimum standards regarding genetic quality, germination purity, and weed seed content. The common class of seeds represents seeds that do not meet certification standards. Use of common class seeds may introduce noxious weeds into a seedbed and require supplemental herbicide treatments to control weeds. Certified or registered seeds should always be used in wetland restoration and enhancement efforts if available and if it is possible (Environmental Laboratory 1986). Because many wetland species, however, cannot be obtained as certified seed, the same concern for germination and purity percentages, source of seed, seed storage methods, etc. should be investigated prior to seed purchase.

Federal legislation requires detailed labeling of all commercial seeds entering into interstate commerce, but most enforcement is accomplished at the state level. Seed certification programs are within the Department of Agriculture in most states, and for any questions concerning seed certification the appropriate state agency should be contacted.

If obtaining certified seed, each bag of seeds should have an inspection tag providing certification information including the following:

- lot number
- percentages of species and varieties
- percentages of PLS by weight
- percent purity
- germination percentage

- seed impurities by weight
- origin
- date of germination test
- name and address of tester

If this information is not on the tag, seed should not be accepted or purchased.

PLS is a measure of two variables: (1) seed purity or the percentage of pure seed (i.e., the seed or species under consideration), other crop seed, weed seed, and inert matter present in the seed lot and (2) germination percentage, the relative number of normal seedlings produced by the pure seed. PLS can be expressed in the following equation:

PLS = % Purity (from tag) x % Germination (from tag)/100

The following examples illustrate the importance of obtaining seed with a high PLS percentage for reducing the amount of seed required to meet desired densities and seed costs.

Example 1: PLS = 98 x 90/100 = 88.2 kg viable seed/100 kg seeds

Example 2: PLS = 98 x 70/100= 68.6 kg viable seed/100 kg seeds

At the same price, Example 1 yields a higher value for the cost because approximately 20 percent more seeds of Example 2 would be required to achieve the equivalent seed density as Example 1.

If PLS is not known, as may be the case for many wetland species, seed testing can be conducted to determine the germination capacity and the purity of the seed on a small representative sample drawn from the seed lot. Procedures have been developed by numerous agencies and associations for agricultural, vegetable, tree, shrub, flower, and grass species and can be used as a guide for seed test procedures for wetland species. For more information on seed testing procedures see Anonymous (1963); Association of Official Seed Analysts (1970); International Seed Testing Association (1966); and Western Forestry and Conservation Association (1966).

**Pregerminated Seed.** Typically, dry, unsprouted, properly stored seeds should be purchased. One exception to this is with certain species of acorns. Both sprouted (pregerminated) and unsprouted acorns can be sown directly into a restoration site with similar success for seedling development. If presprouted acorns are purchased, care must be taken to prevent the emergent radicle from drying out prior to planting. Good success in the establishment of seedlings of *Scirpus* spp. has been observed by planting pregerminated seed in outdoor peat pots for later planting (Garbisch 1993).

Regardless of the method used, if seeds are pregerminated under some sort of controlled conditions, they must be rapidly sown or planted at the site or they will die (Miller and Arend

1960; O'Neill 1972). Additionally, for most wetland plant species, care should be taken not to damage the radicle (primary root) when sowing or planting pregerminated seeds. Some exceptions to this do exist. The use of presprouted acorns or acorns with damaged radicles has not been shown to adversely affect seedling production, growth, and overall survival and establishment (Bonner 1982).

The advantage to using pregerminated seed is that the growing season may be extended by more than a month for many plant species in the greenhouse. This is particularly valuable for slow growing, woody species which would take 2 years instead of one to achieve a usable size without this extension.

**Seed Mixes.** Premixing of desired forbs with similar growing needs is important to achieve successful germination and growth of seedlings. This premixing of desired forbs so that their specific growing needs are met has been successful in wetland restoration and in roadside enhancement projects in the Midwest. Plant species like cardinal flower (*Lobelia cardinalis*), Joe-pye weed (*Eupatorium* spp.), and queen-of-the-prairie (*Filapendula rubra*) that tolerate wetter conditions than other native forbs have been premixed and planted in drainage ditches and wetland edges in the Midwest. While premixing of wetland forbs and grasses involves a greater effort on the front end of a project, this premixing has been highly cost-effective in the long run (Rolfes 1993).

**Inoculated vs. Non-inoculated Seed.** Use of inoculated legume seeds with nitrogen-fixing bacteria will enhance germination and early growth of seedlings. For more information on inoculation of legume seeds see Thompson (1992).

## Wetland Topsoiling

### Advantages and Disadvantages

Another method of introducing seeds and other types of propagules (e.g., spores, vegetative propagules, and whole plants) to a wetland site is wetland topsoiling. Wetland topsoiling, also referred to by many practitioners as wetland mulching, is the procedure of removing the upper 2.5 to 15 cm (1 to 6 in.) of topsoil from a wetland site and transferring the topsoil to the proposed project site, or from one portion of the proposed project site to another part of the proposed project site. While most applications of wetland topsoiling have been on wetland creation projects, the use of wetland topsoil as a means of establishing vegetation at a wetland restoration site is an attractive alternative to seeding or planting of transplants. Wetland topsoiling is an attractive alternative because it allows the rapid colonization of a new site with local or native vegetation (Clewell 1984). Other advantages to using wetland topsoil for vegetation establishment at wetland restoration sites include the following:

- A desirable mix of plant species is transferred to a site.
- Locally adapted (local ecotypes) plant species can be transferred to the site.
- Higher plant species diversity and richness can be obtained at a site.

- Mycorrhizal fungi which enhance vegetative growth are transferred to the site (Claassen and Zasoski 1993).

- High vegetative cover values are often achieved early at a site.

- The establishment of late successional plant species in sufficient quantities to resist invasion by nuisance and aggressive plant species is accelerated (Clewell 1984; Dunn and Best 1983; Erwin et al. 1985; Erwin and Best 1985).

- Trends toward zonation and dominance patterns similar to natural wetlands can be observed in the early years after restoration (Clewell 1984).

- Soil microbiota that contribute to the functional capacity of the restored wetland are transferred to the site.

Disadvantages of using wetland topsoil as a source of vegetative propagules include the following:

- weedy species are introduced, co-transplanted, or spread to or throughout the site (Davis 1993; Gilbert 1993; Kane 1993), and

- a proper match of hydrologic requirements is needed for successful vegetation establishment (Davis 1993).

Some wetland restoration practitioners consider topsoiling with wetlands soil highly experimental and believe the use of this method should be pursued with caution (Garbisch 1994).

## Applications

Successful vegetation establishment has been achieved with wetland topsoil in Florida marshes and swamps. The use of wetland topsoil as a source of propagules and seeds has also been an effective method of vegetation establishment in the restoration, enhancement, or creation of vernal pools in California under optimum rainfall and hydrologic conditions (Ferren and Pritchett 1988).

Use of wetland topsoil in open swamp sites, however, appears to be ineffective. It is thought that a combination of transplanting of tree seedlings and wetland topsoiling might be successful in exposed swamp wetland restoration habitats (Clewell 1984) or that wetland top soiling in swamps may be more successful once the tree seedlings have grown into small trees that have begun to form a closed canopy. This planting sequence may inhibit the growth of weeds due to shading by the tree canopy and allow desirable species of plants present in the mulch to proliferate (Clewell 1984).

Wetland topsoil should be obtained from the surface, preferably the upper 2.5 to 15 cm (1 to 6 in.), of nearby donor wetland sites. Wetland topsoil should be deposited in strips or piles between trees in swamp restoration projects where a closed canopy of saplings has developed, or spread thinly across the surface (e.g., approximately 30 cm (1 ft) deep for marshes; 30 to 60 cm (1 to 2 ft) deep for swamps) (Clewell 1984). Wetland topsoil should be placed immediately on the restoration site or within a few hours after borrowing (i.e., at least during the same day). If mulch or topsoil cannot be placed immediately into the restoration site, the topsoil will need to be stockpiled at the donor or the restoration site.

## Stockpiling of Wetland Topsoil

Stockpiling of wetland topsoil and its associated materials has had varied success. Greenhouse experiments on the stockpiling of topsoil indicated that the storage of harvested topsoil for five months had minor effects on plant growth, soil fertility, mycorrhizal infection, and microbial biomass (Claassen and Zasoski 1993). However, under field conditions, the degree of success of vegetation establishment at a wetland restoration site is dependent on contractor expertise, unavoidable construction delays, and weather conditions. Wetland topsoil contains viable plant parts and seeds; heat, freezing, desiccation, anaerobiosis, decomposition, or salt buildup can deteriorate propagules during storage if care is not taken prior to stockpiling. Activities such as spraying the stockpile with water to prevent desiccation and protect from high external temperatures and covering the stockpile to decrease radiant heat on the pile can decrease plant material deterioration within the stockpile. Limiting the pile size or configuring the pile to increase aeration within the pile can limit anaerobiosis and decomposition of plant materials within the stockpile. To maximize successful restorations, stockpiled materials should be limited to durations of less than 4 weeks (Garbisch 1986). Care should be taken when implementing any activity to eliminate deterioration of the stockpile that the activity will not accelerate deterioration through another means. For example, spraying the stockpile with water may keep the soil moist and prevent desiccation of the vegetative propagules. However, if spraying the stockpile is conducted improperly, saturation of the stockpiled material may lead to anaerobic conditions and natural decomposition or to the leaching of salts from the upper layers of the stockpile and accumulation of salts in middle and lower layers of the stockpile.

Accomplishing the final grade using wetland topsoil materials also is difficult and in some cases may not be possible without injury to the propagules. Plants are likely to be destroyed during grading and resurface areas may be left with scattered peat hummocks (mounds) and pockets of impounded water. Such conditions may prevent successful restoration of wetlands (Garbisch 1986). Hand spreading of wetland mulch or topsoil has been used in restoration projects where the donor topsoil was limited in quantity and to prevent injury to propagules.

## Seed Bank Studies

Prior to using wetland topsoil, particularly wetland topsoil from an offsite donor wetland, as a source of wetland propagules for the wetland restoration site, it is advisable to conduct a soil seed bank study. A soil seed bank can be used to obtain information on the species composition of the seed bank as well as the abundance and distribution of species throughout the donor wetland site. For example, seed bank studies may identify one or more undesirable, invasive species, which, if established at the site, could jeopardize project goals and objectives (Garbisch 1994).

For more information on use of wetland topsoil as a source of wetland species in wetland restoration, as a source of mycorrhizae, managing seed banks for preferred species, establishing vegetation using donor seed banks (topsoil), and case study examples see Claassen and Zasoski 1993; Sleszynski 1991; Van der Valk 1987; Van der Valk and Pederson 1989; Wilson et al. 1993. For information on seed bank study methods see Appendix E.

## Transplanting

### Introduction

Once the decision has been made to either plant transplants at a wetland restoration site or to establish wetland vegetation at a site by a combination of transplanting and seeding, the next step is to identify the method of transplanting and the transplanting requirements and procedures. This decision will be based on the type of transplant that is available, evaluation of the applicability of the method to the site, and availability of standard transplanting procedures.

This section on transplanting provides background information on the types of transplants that are available, technical methods for planting these into the restoration site, and numerous factors that must be considered to have successful vegetation establishment from the transplanting method or transplant type relative to the site characteristics.

Transplants are defined as sexually produced or asexually produced vegetative propagules, other than seeds, that are placed in the soil (modified from Environmental Laboratory 1986). Transplanting involves placing planting stock such as bare-root seedlings, containerized plants, rooted cuttings, sprigs, unrooted cuttings, plugs, balled-and-burlapped plants, rhizomes, or tubers into the desired site.

The appropriate planting procedure is dependent on the type of propagule selected and local soil and climatic conditions. For example, soil conditions will influence the size of the planting hole that can be dug. The following are principles that generally apply to transplanting regardless of the propagule being transplanted:

- Transplanting is the most successful as well as the most expensive method of wetland vegetation establishment.

- Whenever feasible, planting of transplants should be conducted when the wetland restoration site is drained. The presence of either standing or moving water at a site typically decreases the plant’s ability to anchor into the substrate and the stability of the plant. Removal or diversion of water will allow for the proper installation of plants.

- Planting underwater often will lead to improper installation of plants and fertilizer (Garbisch 1993).

- Planting seedlings should follow standard seedling planting methods and seasons (Environmental Laboratory 1986).

- Proper substrate preparation and planting techniques will prevent settling of the transplant in the planting hole and possible drowning of the transplant (Environmental Laboratory 1986).

- After transplants are placed into the wetland restoration site, water levels at a site should be established high enough to ensure saturated soils but not so deep as to reduce oxygen levels to seedlings that are not marsh or aquatic species. Many wetland plants (i.e., trees, shrubs, vines, and herbaceous plants) have the ability to grow in much wetter environments than terrestrial species. However, the optimal growing conditions for most wetland species are moist to wet conditions and not necessarily flooded soil.

- Nursery grown propagules are often colonized by few mycorrhizal fungi, and inoculation may be appropriate for some projects.

As identified above, the major disadvantage of transplanting is that it is a labor-intensive means of establishing vegetation at a site resulting in high project costs. Therefore, transplanting generally is not recommended as a general purpose method for restoration of large restoration sites but is usually recommended for small-scale restoration projects or for adding very sensitive, high quality species that are difficult to establish in the earliest stages of restoration. The greatest advantage of transplanting is that if proper installation and site and vegetation management techniques are employed, the use of transplants can be highly successful for the long-term establishment of wetland vegetation at a site. Transplanting not only is beneficial for increasing successful vegetation establishment at a restoration site, but it also can be used for successfully establishing species at a degraded site (i.e., site enhancement).

## Bare-Root Seedlings

Bare-root seedlings are young plants with exposed root systems that are transplanted from nursery beds or from natural stands to the planting site. Bare-root wetland transplants collected from the wild can provide a low-cost solution for wetland plant demand (Kane 1993). However, the disadvantages of bare-root seedlings may outweigh the economic benefits of this propagule type if not adequately considered. Bare-root seedlings (also called liners) are inexpensive, but their fibrous roots may be largely removed if the plant is improperly lifted from the ground. New fibrous roots develop poorly, if at all, in anaerobic substrates. For this reason, high mortalities can result from planting bare-root trees and shrubs in saturated soils (Garbisch 1993). It is generally recommended that bare-root trees and shrubs not be planted at a project site if the soils are saturated for most of the growing season. The following paragraphs provide information on bare-root seedling planting techniques and site conditions where they are recommended.

## Hand versus Machine Planting

Bare-root seedlings can either be hand or machine planted. Hand planting of bare-root seedlings is more labor-intensive, therefore more expensive. Under normal circumstances, hand planting of bare-root seedlings may be more practical for small (< 1 ha or 2 to 3 acres) wetland restoration projects, sites that are inaccessible for large machinery, or for under planting shrubs and understory trees after establishment of overstory species. Hand planting may be used on large project sites, however, where an adequate budget is available. Alternatively, machine planting of bare-root seedlings is recommended for large-scale sites, such as hardwood or forested wetlands. Machine planting of seedlings is less expensive than hand planting. However, machine planting can be limited by site physical, soil, and hydrologic conditions. Machine planting is limited to times when soil is dry enough to support the planting equipment and to open sites lacking debris, roots, and tree stumps. For example, machine planting may be more practical than hand planting in old agricultural fields, while hand planting (or seeding) may be the preferred method in forest openings (Johnson and Krinard 1985; WES 1990).

Bare-root seedlings can be planted in any pattern, however, using hand planting techniques. Machine planting of bare-root seedlings is typically restricted to a linear pattern of planting to maximize efficiency of machine planting. This linear pattern of planting results in an undesirable row or plantation appearance to the restoration site. By mixing species within rows, creating irregular boundaries, planting at densities slightly higher than ultimately desired, and allowing natural mortality to thin the stand, it should be possible to simulate a more or less natural looking canopy of overstory trees. However, some of the efficiency that is gained by using a machine planter over hand planting of bare-root seedlings will be decreased when implementing these alternatives.

**Handling.** Bare-root seedlings should be planted as soon as possible after seedlings arrive regardless of the planting technique used. The seedling root system should not be exposed to wind or sunlight unless clay treated, and may require maintenance to maintain root moisture by submergence in buckets of water or a thin mud-water slurry or being covered with wet burlap. If planting stock is shipped in quantity for a large project, cold storage may be necessary until the time of planting or if storage is one week or more. Roots of all species can be pruned, but should not be unless it is necessary to allow for planting (Fredrickson 1978; WES 1990).

Planting depth is critical to survival of bare-root seedlings because dry periods often occur after spring planting is completed and just prior to the formation of new roots. Extra care in the proper placement of seedlings taken at the time of planting by restoration crews will enhance the survival and establishment of wetland plantings. This care should result in better root placement facilitating more plant stability and better root development after planting (Paterson 1993).

**Procedure for Hand Planting Bare-root Seedlings.** One-year-old or two-year-old bare-root seedlings can be hand planted using either a mattock or hoedad, planting bar (i.e., dibble or spud), an auger, a posthole digger, or with a shovel to make the holes. If hand planting, the planting hole should be large enough to provide adequate space for seedling roots in the planting hole. At least a 20-cm (8-in.) diameter bit is recommended if using an auger or posthole digger to allow the roots of the seedling to spread out and not be crowded, rolled, doubled under, or bent to get all the roots in the hole. To decrease the planting time of larger sites, four to eight persons can simultaneously drill holes and plant bare-root tree seedlings using a two-person hand-operated auger (Thompson 1992).

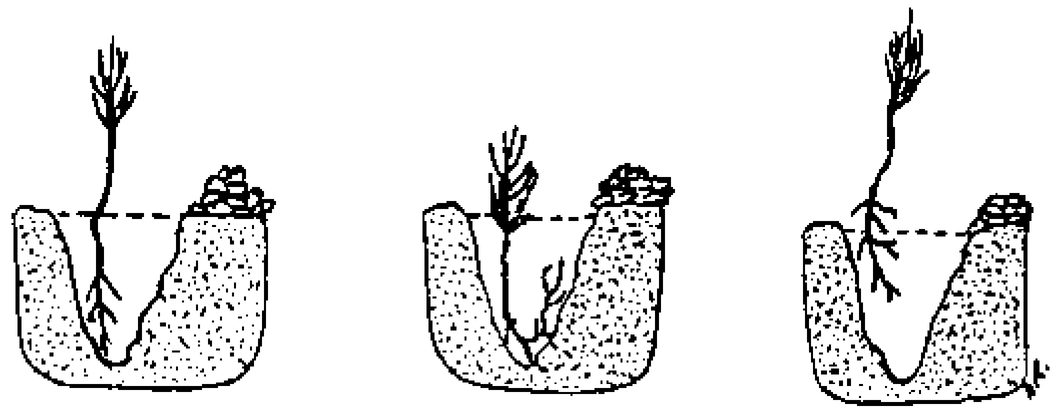


Figure 7-2. Illustration of proper planting depth for seedlings (from Environmental Laboratory 1986).

Seedlings should be planted about 1 cm (0.5 in.) deeper than the original soil line on the seedling (Figure 7-2). Do not place root collars above ground level. Holes should be filled immediately after they have been made to prevent the soil from drying out. With either the auger or the hand planting techniques, care should be taken to firmly tamp the soil around the seedling roots after it is placed in the planting hole (Allen and Klimas 1986; Environmental Laboratory 1986; Thompson 1992).

Once planted, young seedlings can be shaded by using a variety of materials including snow fencing, tree shelters, wooden laths, or commercially available shade cloth. Weeds should be removed on a frequent basis (Thompson 1992).

**Procedures for Machine Planting.** When machine planting bare-root seedlings, it is important that the planting machine selected is large enough to make a trench that will accommodate the seedling roots without forcing the seedling into the soil and bunching the root system. The trench should be deep enough that the seedling can be planted half an inch deeper than the original soil line on the seedling without crowding the roots. The machine's packing wheels should close and firm the trench around the seedling stem so that seedlings won't move upward when gently tugged. Having one person follow the planting machine on foot tamping the soil around the seedling will ensure that the trench is filled with soil.

Machine planting of bare-root seedlings can be accomplished with a tractor-pulled tree-planting machine or a tractor-mounted posthole digger. Machine planting is recommended for sites being considered for large-scale planting, such as hardwood or forested sites (Environmental Laboratory 1986). Machine planting, however, can only be done on sites accessible to tractors and when soils are not saturated. Machine planting is recommended for restoration of old fields.

Machine planting is not as easily and inexpensively accomplished in sites such as bottomland hardwoods where the soils are either too wet or too dry during the short planting season, or at sites such as forest openings where maneuverability of the machine may be a problem.

Planting machines are available for a nominal rental fee from state and federal agencies including natural resources agencies, state foresters, local county conservation boards, and Soil Conservation Service district offices (Thompson 1992). These planting machines can be used with a two- to four-person crew and can be an efficient way to plant up to 800 trees per hour.

For further information on procedures for handling and planting bare-root seedlings and transplants see Environmental Laboratory (1986).

## Containerized Plants

**Containerized vs. Bare Root.** Containerized plants, as defined here, include both small plants (i.e., seedlings or small rooted cuttings) that are grown in a rooting medium in small individual or multipack containers and larger plants in individual containers (e.g., 1-, 2-, or 5-gallon pots or containers). This stock may be in the same container in which it was originally propagated (in the case of small containers) or it may have been maintained over longer periods of time and replanted one or more times successively into larger containers. Containerized seedlings are transplanted to the planting site with the associated rooting medium contained in the container.

In contrast to the bare-root seedling or propagule, the costs of individual containerized seedlings are greater because of the labor, materials, and maintenance costs that have gone into the production of a container plant (Landin 1978). In some cases, however, the increased viability of the containerized plants far outweighs their higher initial costs. This increased viability is primarily a result of the decreased disturbance to the root system of the container plant during the transplanting. Because the containerized seedling is transplanted along with the associated rooting medium, its root system remains intact resulting in rapid recovery from transplanting, increased stability, and more rapid growth. Large container-grown plants will cover an area faster than smaller plants or bare-root stock (Environmental Laboratory 1986).

Yeiser and Pashke (1987) published a comparative study of regenerating wet sites with bare-root versus containerized loblolly pine seedlings. When bare-root seedlings were planted in the winter, spring inundation often caused high mortality. When bare-root seedlings were planted in May following removal of the flood waters, dry summers caused high mortality. Higher survival resulted from planting in soils having a perched water table after soil moisture levels declined than during periods of excessive wetness. Containerized seedlings, on the other hand, had nearly 20 percent greater survival than bare-root seedlings. A limitation may be that it is often difficult to find sufficient containerized seedlings to provide the desired spacing.

Meadows and Toliver (1987) had good success using containerized seedlings to regenerate pecan on streambottom sites. In the absence of containerized seedlings, however, good survival and growth can be attained with bare-root seedlings that are top-clipped to a 25-cm (10-in.) top or left unclipped.

After deciding to use transplants at a site, the trade-offs between initial costs, transplant viability, and the cost to replant a site need to be evaluated to determine the most cost-effective method of vegetation establishment and whether the selection of the propagule type will allow the project schedule to be met. For example, Thompson (1992) recommended transplanting one to two-year-old bare-root seedlings as the preferred method of vegetation establishment for tree species in forested wetlands in the Midwest at sites larger than 0.4 ha (1 acre).

An advantage of using containerized stock is that it has better survival rates than bare-root stock. Containerized stock, however, is more costly than using bare-root seedlings since typically more labor and materials have gone into producing the containerized stock.

**Procedures.** Holes should be of sufficient size and depth that root systems are neither crowded nor disturbed in planting. In general, planting holes should be deep enough to easily accommodate the root mass without planting too deep. If the soil is dry, irrigation prior to planting will make the holes easier to dig. If fertilization is necessary, fertilizer should be sprinkled into the hole and incorporated into the loose soil at the bottom of the hole (Horton and Cotton 1988).

When planting containerized plants, the container should be removed at planting time unless it is biodegradable (e.g., peat pots), in which case it is sometimes left on the planting stock. After the container is removed, examine the root system. If the roots are dense and encircling, four vertical cuts should be made in the root mass. These cuts will cause the roots to branch high and will eliminate root circling when placed in the hole. Root circling can weaken the plant stability and kill the plant. On sites that are wet on a periodic or seasonal basis, build a small mound around the outside perimeter of the hole to catch and store the water around the newly planted specimen. Plants should be watered thoroughly after planting. If the container is biodegradable, the rims of biodegradable containers should be trimmed so not to protrude above ground level, which could cause drying due to wicking. If roots have not penetrated the biodegradable container sufficiently to allow good contact with the soil, the container should be removed before planting (Environmental Laboratory 1986).

## Balled-and-Burlapped Plants

A balled-and-burlapped plant is one that has been grown in the field, carefully dug with a ball of soil adhering to its roots, and the root ball wrapped with a protective burlap covering. Balling and burlapping the roots is a method typically used with evergreen trees and shrubs but can be used on any large specimen of tree or shrub that is in full leaf or is very large in size (up to 3 m tall) (Environmental Laboratory 1986). Balled and burlapped plants are probably best used on sites having fairly good drainage properties, such as some riparian habitats. Because the leaves are always present on an evergreen shrub, they are transplanted with greater difficulty than with dormant deciduous trees and shrubs. To replace the loss of water in a relatively short time after transplanting, a large quantity of the absorbing roots and moist soil must be provided (Edmond et al. 1957). Balling and burlapping the roots provides the soil and moisture needed to sustain the trees under the moisture stress associated with transplanting.

When transplanting balled-and-burlapped specimens, it is important to prevent breakage of the ball of soil surrounding the root system. To plant a balled-and-burlapped tree or shrub, dig a large hole and loosen subsoil at the bottom of the hole. The proper depth of the hole is such that the top of the root ball is slightly lower (approximately 8 cm or 3 in. below) than the ground surface. Set the ball into the hole carefully. Fill the hole with soil to set the tree at the proper depth (top of the ball approximately 8 cm (3 in.) below the ground surface). Untie and remove the heavy cord that holds the burlap around the trunk. Move the burlap away from the top of the ball but do not attempt its complete removal. Leave the burlap around the rest of the ball, but trim the excess burlap away from the upper edges of the ball or fold the burlap back into the hole, and cut the burlap in several places. This procedure will prevent moisture loss from wicking that can eventually cause dryness and root binding (Environmental Laboratory 1986). The burlap around the lower ball will gradually disintegrate and does not need to be removed. Complete filling the hole with soil, firmly tamping the soil into the space surrounding the root ball. Construct a water basin, and water thoroughly.

Do not cover the top of the exposed root ball with a thick layer of clay soil that may prevent absorption of surface water into the upper portion of the root ball. Apply a thin soil layer to the surface (i.e., no more than half an inch in thickness, if it is clay; lighter soils can be applied at a thickness of up to an inch).

**Hydraulic Tree Spades.** For larger trees, commercially available hydraulic tree spades may be more cost-effective techniques for digging and transplanting directly into the project site. Use of a hydraulic tree spade often results in greater survival of large transplanted tree species (Environmental Laboratory 1986). With this technique, an operator of the tree spade can transplant approximately 200 saplings a week as long as the soils are firm enough to support the equipment. Tree spading was used in the restoration of swamps on reclaimed phosphate mines in Florida. Saplings up to approximately 8 cm in diameter were transferred from natural swamps to the proposed site. Success with this method was limited, but it was thought that the limited success was not due to the planting method but to the differences in site conditions between the natural swamp and the restoration site (Clewell 1984).

**Cuttings.** A cutting is a portion of a stem or root (stemand root cuttings, respectively) that is typically only a few inches in length. Cuttings may be unrooted or rooted, woody or herbaceous. For unrooted stem cuttings of some species, it may be advantageous to prepare the cutting for an application of a rooting hormone at time of planting to speed the development of adventitious roots on the stem. This can be accomplished by dipping the end of the cutting into hormone solution prepared at a dilution as specified on label directions. In general, however, the use of rooting hormones in wetland projects has been of questionable value.

Most cuttings can be pushed directly into soft soils, but in hard or rocky soils a hole will need to be made with a dibble or star drill. Holes should be no deeper than the length of the cutting. The length of the cutting should extend to the bottom of the hole to avoid an air pocket, which would allow the cutting to dry. When planted, cuttings should extend deep enough into the soil to be firm and relatively difficult to pull out. Only cuttings that are long enough to maintain contact with moist soil and still retain a few nodes above the ground level should be used. Only 3 to 6 cm of the cutting should remain above ground to prevent moisture loss due to wicking. Any excess should be removed (Allen and Klimas 1986). The soil around the cutting should be tamped firmly to eliminate any air pockets (Allen and Klimas 1986). Care should be taken when transplanting stem cuttings that have been cut at both ends that the basal end (in contrast to the apical end) of the stem cutting is inserted into the soil.

Because cuttings are live materials that have been severed from either a stem or from the root system, it is important that the cutting is exposed to the air and sun for as short a time as possible before being planted to prevent desiccation (Allen and Klimas 1986).

**Woody.** Certain woody wetland species, such as *Salix* spp. (willows), *Cephalanthus* spp. (buttonbush), and *Populus* spp. (cottonwoods) ,can be started from cuttings. Cuttings approximately 0.5 m long and less than 2 cm in diameter, with at least one vigorous bud, are collected just prior to the cessation of dormancy in spring. These cuttings may be stored overnight in moist sand and pushed into saturated soils the following day (Hammer 1992).

**Herbaceous Microcuttings.** A specialized type of cutting known as a microcutting may become more available to wetland restoration practitioners in the near future. Microcuttings of wetland species are derived from *in vitro* micropropagation (i.e., plant tissue culture) of species collected from the wild and propagated under sterile, controlled conditions. Procedures for the propagation of freshwater aquatic species, such as *Pontederia* sp. (pickerelweed), *Orontium* sp. (golden club), *Sagittarian* sp. (arrowhead), *Peltandra* sp. (arrow arum), and a coastal dune species, *Uniola paniculata* (sea oats), have been developed and proven to be successful for the propagation of wetland plant species and of specific adapted genotypes (i.e., ecotypes) (Kane 1993). These cuttings are handled much in the same way as other types of cuttings.

## Sprigs

The term sprig usually refers to small transplants that are obtained by breaking or cutting multistemmed plants into smaller clumps containing one to five stems. These sprigs are often obtained from an entire plant that is dug and removed from its natural habitat. Sprigs may be either bare-root or with soil remaining in an attempt to minimize root loss and disturbance. Transplants should have root clumps no larger than 10 to 15 cm in diameter, with top shoots of a compatible size. Much smaller clumps can be used successfully if adequate roots are associated. The sprig typically can be planted in a shallow hole made by hand and tamped in with either hand or foot. Large sprigs may require the aid of a trowel or other tool (Allen and Klimas 1986).

## Soil Plugs

The term soil plug usually refers to a root mass that has been extracted with some type of coring device, similar to those used in commercial nurseries. The technique has been used both for establishment of individual species and for establishment of mixed species populations (i.e., a mixture of various marsh species). When planted on stabilized soils, plugs are sometimes planted with the aid of a coring device of the same type used in their removal. The plug of the desired species is simply placed into a newly formed hole and tamped in well. In unstable soils, plugs can be planted with the hand or with the aid of a tool, covered over with soil, and tamped to ensure good contact between soil and plug. Advantages of using soil plugs are that the roots of the transplants are left intact. Disadvantages include the transfer of unwanted species and weeds into a site.

It should be noted that the nursery industry also uses the term plug (or tubeling) to refer to rooted cuttings or seedlings that are grown (up to 1 year) and marketed in a slender polyethylene tube. In this handbook, a plug of this type is considered synonymous to a bare-root seedling and should be planted accordingly.

### Rhizomes

Rhizomes refer to underground stems that often grow horizontally. Typically, rhizomes are broken into segments and planted horizontally, making sure each fragment has at least one viable growth point (node) on it to ensure new growth. Rhizomes of most species are planted shallow, covered over with soil, and tamped to ensure good contact between the rhizome and soil. In inundated areas or in areas where the substrate is saturated, rhizomes can be pushed in by hand. In denser substrates, tree planting bars, or dibbles, or trowels may be necessary (Warburton et al. 1985). Under certain circumstances, establishment may be enhanced through the use of nurse crops (see Chapter 7-2) or through the establishment of temporary cover (Warburton et al. 1985). Planting underwater or planting dormant underground plant propagules must be done manually (Garbisch 1986).

### Tubers

Large tubers (e.g., *Helianthus tuberosus*, Jerusalem artichoke) should be planted in a hole at a depth of about twice the size of the tuber and covered over with soil. Small tubers (e.g., *Cyperus esculentus*, chufa) may be broadcast on a site and raked into the soil (Environmental Laboratory 1978).

## Protection Measures for New Transplants

### Tree Shelters

Tree shelters have been used in riparian forest buffers to increase the growth rate and survival of tree seedlings. A tree shelter is a cone or tube about 1 m (3 to 4 ft) in diameter made out of plastic, fiberglass, or other hard material that is placed around the tree seedling (Figure 7-3). The tree shelter, also often called a collar, encloses the tree seedling and protects the seedlings from grazing, mowing, desiccation/water loss, and sun scorch. The use of tree shelters or collars has been shown to sharply increase the growth rate and survivorship of slow growing species, such as red oak and black walnut (Scheuler 1994) and to ensure that slow growing climax species remain established at the site once planted.

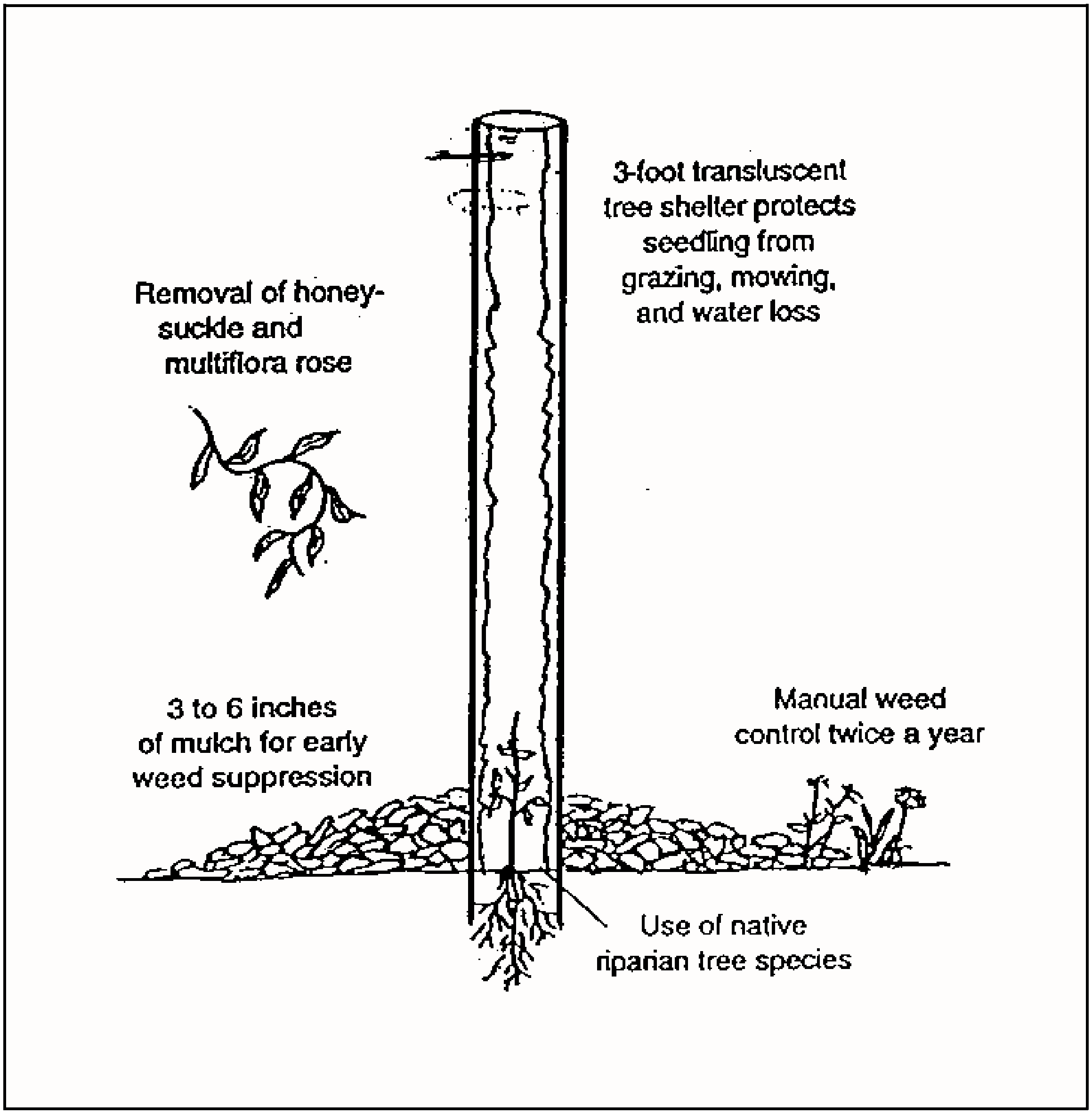


Figure 7-3. A typical tree shelter.

## Stem Wraps

Stem wraps consist of weather-resistant cloth that is wrapped around the base of a large tree or medium sized tree seedling to prevent stem blistering, cracking and subsequent disease or fungal infection of the newly transplanted seedling. Some stem wraps will also deter rodent damage. Large trees with 5-cm or larger diameter stems should be stem wrapped to prevent sun blisters (Landin 1978).

### Antitranspirants/Wax Emulsifiers

The use of emulsified waxes sprayed on trees and shrubs during transplanting has been used in normal landscaping transplanting practices to reduce the rate of transpiration and subsequent wilting and to facilitate the recovery of the trees and shrubs that are transplanted in full leaf. Little information is present on the use of waxes in wetland restoration. Emulsified waxes are soluble in water and relatively permeable and colorless, and can be applied to plants in the form of a spray. Frequency and timing of application is at the time of digging and again after the plant is set (Edmond et al. 1957).

### Mycorrhizal Fungi

Mycorrhizal fungi increase the surface area of the root system of plants, increasing the absorption of nutrients that may be in short supply or limiting at the site. Because the mycorrhizal relationship is essential to the healthy growth of trees, especially where soil nutrients are limiting or conditions are harsh, a thorough consideration of whether to inoculate trees at the nursery or soils at forested wetland restoration sites with mycorrhizae prior to or during planting is needed.

Inoculation of soils at both wetland and upland restoration or reclamation sites with single or multiple species of mycorrhizae has proved to be beneficial in the establishment and growth of numerous plant species at sites where soil fertility and productivity is generally low. Leaf growth of sweet gum (*Liquidambar styraciflua*) was significantly increased at sites where mycorrhizae were added to the soil over sites where mycorrhizal fungi were not added (Wallace et al. 1984).

When evaluating whether to inoculate the restoration substrate with mycorrhizae, consideration should be given to other site management and vegetation management techniques such as fertilizer application. Recent studies have indicated that there is a relationship between the level of fertilizer applied to the soil and the percentage of roots infected with mycorrhizae. When the levels of fertilizer increased, vegetation growth increased, but the percentage of mycorrhizal infections and microbial biomass decreased. On a total weight basis, however, infection was found to be greatest with a moderate level of fertilizer (Claassen and Zasoski 1993). For more information on the benefits and applications of and species of mycorrhizae used in wetland restoration see Claassen and Zasoski 1993; Richter and Bruhn 1993; Wallace et al. 1984; Wallace and Best 1983).

## Bioengineering Techniques

### Introduction

Sites characterized by eroding substrates, as on eroding banks around reservoirs, require specialized planting techniques. Certain techniques developed for use in erodible environments have been termed “bioengineering” or “biotechnical” techniques because they employ both plants and construction materials. Most of these techniques utilize woody plants that have the ability to sprout adventitious roots from the stem (Allen and Klimas 1986). A summary of the major types follows.

Consult Allen and Klimas (1986), Coppin and Richards (1990), Gray and Leiser (1982), and Schiecthl (1980) for additional details on bioengineering techniques.

## Willow/Fence Combination

This is a technique where live willow cuttings are laced through the spaces of a partially buried woven-wire fence. Important sequences in the process include the following:

a) Trenches about 60 cm deep, 40 cm wide, and 6 m long are dug perpendicular to the shoreline

b) Woven hog wire (10-cm mesh), 60 cm tall and 6 m long, is placed in an upright position in the trench and anchored with 120-cm-long steel posts woven through the wire in the center and at both ends

c) Posts are driven 60 cm into the sand at the bottom of the trench, and then the hog wire is tied to the posts with galvanized wire

d) Twenty willow cuttings (basal end down) are woven through the wire at 30-cm intervals, and the trench is filled with sand. About half of each cutting is buried (Allen and Klimas 1986)

## Wattling Bundles

Wattling bundles are cigar-shaped bundles of live cuttings (stems) of willow or other easy-sprouting woody species approximately 2 m (6 to 8 ft) long that are tied and placed in trenches, staked, and partially covered with soil. Wattling bundles are usually placed on contour, starting at the bottom of a slope and working up. Once placed in contact with the soil, the stems root and send up new shoots to create thickets that catch any overland flow and any eroded soil in the flow (Allen and Klimas 1986). The planting method requires that the reservoir or source of water be drawn down at the time of planting and that the wattling bundles receive adequate supply of water during the period of establishment. Typically after the first growing season, the plants will probably be able to obtain water from deep roots during summer drawdown. For more information on wattling bundles see Allen and Klimas (1986); and Whitlow and Harris (1979).

## Brush Layering

Brush layering is a technique in which cut, live woody branches of willow, poplar, etc., are successively laced in V-like trenches along contours on a slope. The bottom of the trench should be sloped slightly downward so as to catch and retain water. The cut material may vary in length depending on the depth of trench one can dig into the reservoir shoreline but generally will range in length from 0.5 to l.0 m. Branches should be long enough to reach moist soil back in the sloped bank. Cut branches should be laid in a crisscross pattern, and branch ends should not protrude excessively over the lip of the trench. Excessively protruding branches (>15 cm) could excessively dry and kill the live plant material (Allen and Klimas 1986).

## Brush Mattress or Matting

This procedure involves digging a slight depression on the bank and creating a mat or mattress from woven wire or single strands of wire and branches from sprouting trees or shrubs. The branches may be placed in the depression with or without woven wire. In either situation, live, freshly cut branches are tied down by a combination of stakes and woven wire or a network of wire or other material to hold them in place. Branches can vary in length but are normally cut 1.0 to 3.0 m long and l.0 to 2.5 cm in diameter. The branches are crisscrossed and turned alternately so that the butts protrude slightly out of opposite sides of the mattress. This crisscrossing and alternate facing of branches creates a more uniform mattress with few voids. The branches are laid down and covered, staked, and tied with wire; then, the structure is partially covered with soil and watered. Covering with soil and watering several times in succession will fill the air pockets with soil and facilitate sprouting. The structure is covered with only enough soil so that some branches are left partially exposed on the surface (Allen and Klimas 1986).

## Plant Rolls

Plant rolls are cylinders of plant clumps in soil that are wrapped by burlap, secured by hog rings or wire, and placed in a trench. Plant rolls can be pregrown in the greenhouse or lathhouse to develop root systems, installed in water with a jet pump or shovel, and treated with fertilizer without excessive leaching of the fertilizer.

Plant rolls are constructed onsite as follows:

- A length of burlap (about l m wide by 4 m long) is laid on the ground.
- Sand or soil is placed on the strip of burlap, and six to seven clumps of plants are spaced at 0.5-m intervals on the burlap.
- About 28 g of 18-6-12 slow-release fertilizer is applied to each plant clump by hand.
- The sides of the burlap are brought together around the plants and fastened with hog rings creating a 3-m-long roll of plants and soil.
- The plant rolls are positioned at the toe of the bank or upon any existing shallow benches lakeward of the toe and are oriented parallel to the bank.
- The rolls are buried in the reservoir substrate by a jet pump or by shovel.

Plant rolls are spaced about 1 to 2 m apart with the option of placing individual transplants between them. The rolls are more difficult to dislodge and to wash away than single transplants because the whole structure acts as one bed of plants and is much more massive (Allen and Klimas 1986).

# Fertilizer

Before a site is seeded or planted, a determination should be made as to whether fertilization is needed to augment vegetative growth and establishment at a wetlands restoration site. This section provides an introduction to fertilization, particularly background information on the goals of fertilization, advantages and disadvantages of fertilization, the specific terminology associated with fertilization, methods to determine fertilizer requirements, examples of fertilization techniques, and examples of when fertilization of wetland plant species at a site is or is not desirable.

## Soil Fertility and Testing

Before attempting to fertilize plants at a wetland site, a review of the soil fertility and species fertility requirements should be completed to determine whether fertilization is needed and will be beneficial to growth of the desired wetland plants. Most of this information should have been obtained during the planning phases of the project. If soil fertility information was not obtained during this phase, it should be collected prior to seeding or transplanting.

The use of fertilizers during seeding or planting of transplants into a site has been found to be beneficial in increasing productivity (standing biomass) in freshwater wetlands. Fertilizer application has enhanced the productivity of sandy and peaty substrates in freshwater tidal systems (Garbisch and Coleman 1987) and in wetlands developed on mineral soils (Warburton et al. 1985). The application of fertilizers during planting, however, is not always advantageous to wetland vegetation establishment. Because many wetland plants generally do not have high nutrient requirements, unwarranted fertilization of wetland plant species can be an unnecessary expense and can lead to the domination of a site by undesirable species. Because exotic species often have high fertility requirements (Thompson 1992), fertilization may enhance the rapid establishment and growth of these species over native wetland species. For example, in the establishment of wildflower meadows in New Jersey stormwater detention basins, fertilizers did not have a positive effect on the establishment of the species. In fact, fertilization may have benefited competing weed and grass species (Scheuler 1994). Similarly, in wetland prairie communities where wetland prairie species have low fertility requirements, fertilizer applications during planting may enhance the growth of aggressive, exotic species (Thompson 1992). In addition, unnecessary fertilization may result in the site being over-fertilized and a temporary buildup of salts to levels toxic to the wetland species. Consequently, a knowledge of the soil fertility and the fertility requirements of the species intended to be planted at a site is important.

## Soil Fertility and Testing - Soil Tests

Soil tests have been developed to determine the nutrient deficiencies of soil and to recommend fertilization requirements for good plant growth. The drawback of these soil tests and recommendations, however, is that the recommendations are based on nutritional requirements for agricultural species and not for wetland species for which there is limited information. Nevertheless, the soil tests can provide a quick chemical analysis of nutrient status of a small sample of the soil.

The soil sample is extracted with a weak acid or with the salt of a weak acid, and the extracted solution is treated with chemical reagents. The object of the soil test is to determine soil fertility. The Agricultural Extension Service in each state should be consulted regarding the availability of soil tests and for soil sampling techniques.

## Soil Fertility and Testing - Plant Parts Testing

Plant parts testing is an alternative option for determining nutritional status of the plant species at a site, particularly at a site where wetland vegetation or other vegetation already exists. In plant testing, plant parts are chemically analyzed by a laboratory for concentration of nutrients. The existing concentration shows how much the plant has obtained from the soil during its growth to the time of sampling and in relation to the available soil concentration. Care should be taken when conducting nutritional analyses with plant parts since many factors influence the nutrient-element concentration in plant parts including age, location, and season. This procedure is expensive and less often used to determine soil fertility than the standard analyses of soil samples.

Analysis of plant parts can be either tissue tests or plant analyses. Tissue tests are primarily conducted on herbaceous species and determine the free or soluble nutrients in the tissue. Tissue tests are a valuable tool for rapid diagnosis of nutritional status. Plant analyses are mostly used to determine the total amount of nutrient elements present. The leaf is generally used for plant analysis, therefore, this procedure is often known as leaf analysis. Leaf samples are typically collected midway along the growing season and from around the entire plant to obtain a representative sample (Furuta 1976).

## Fertilizer Applications

Prior to applying fertilizers at a site, it is important to have an understanding of the distinctive terminology associated with the application of fertilizers. Knowing the terminology is necessary so that the correct type of fertilizer and rates of application are used at a site and the fertilization efforts are cost-effective. Both under-fertilization and over-fertilization can reduce the cost-effectiveness of fertilization efforts. Under-fertilization will be of no added benefit to the restoration or enhancement efforts and may promote the growth of weedy species. Over-fertilization can result in mortality in desired wetland species.

The following sections discuss fertilizer analysis, fertilizer formula, fertilizer ratio, and rate of application. The first terms are used in connection with the preparation, purchase, and application of fertilizers, respectively (Edmond et al. 1957).

- Fertilizer Analysis - The fertilizer analysis is a statement of the percentage of nitrogen, phosphoric acid, and potash contained within the fertilizer mixture. Examples of fertilizer analyses are 5-10-5, 8-8-8, and 10-20-10. The first number indicates the percentage of total nitrogen (N), the second number is the percentage of available phosphoric acid ($P_2O_5$), and the third is the percentage of water-soluble potash ($K_2O$).

- Fertilizer Formula - The fertilizer formula is a statement of the kind of materials and the quantity of each used to make a ton of mixed fertilizer. The nitrogen, for example, could be derived from sodium nitrate, ammonium sulfate, or some other carrier of nitrogen. This information enables one to know whether the mixture will make the soil more or less acidic and the relative availability of the nitrogen in the fertilizer mixture.

- Fertilizer Ratio - The fertilizer ratio indicates the proportion of the three major ingredients in a commercial fertilizer. Fertilizers having a fertilizer analysis of 4-8-4, 5-10-5, and 15-30-15, for example, each represent a fertilizer ratio of 1-2-1. To supply 80 kg of nitrogen, 160 kg of phosphoric acid, and 80 kg of potash to the soil, one could apply 2000 kg of 4-8-4, 1600 kg of 5-10-5, or 533 kg of 15-30-15.

- Rate of Application - The rate of application refers to the amount of commercial fertilizer applied per unit area of land. Sometimes the rate of application is expressed on the basis of kg per hectare and at other times on the basis of 100 square meters. In general, the rate of application depends on the analysis or concentration of the mixture and the cash value of the species (traditionally of the crop species) or site on which it is to be applied. High analysis fertilizer mixtures contain more nutrients per kg than low analysis mixtures. Thus, if 80 kg of nitrogen, 160 kg of phosphoric acid, and 160 kg of potash per hectare is the desired rate of application, 1600 kg of 5-10-10 or 1000 kg of 8-16-16 may be applied to achieve this rate of application.

## Fertilization Methods

Several options exist for the method of fertilizer application. These options include the following:

- preplant incorporation - incorporation of fertilizers into the substrate prior to planting

- side dressing - placement of fertilizer in the furrows or the seedling hole at the time of seeding/transplanting

- topdressing - placement of fertilizer over the seeds or seeded area or surface of the new transplant and

- broadcast - spreading of fertilizer over the site/substrate either with the initial seeding or transplanting

## Organic versus Inorganic Fertilizers

Types of fertilizers include organic and inorganic. Most commercial fertilizers are inorganic fertilizers. In general, commercial fertilizers contain compounds which supply relatively large amounts of nitrogen, phosphorus, and potassium (the macronutrients), and compounds which supply small quantities of magnesium, manganese, boron, zinc, and copper (the micronutrients or so-called trace elements).

## Slow-Release Fertilizers

Other fertilizer options include the use of slow-release fertilizers that provide a continuous source of nutrients to the plants for an extended period of time (4 months or greater). Slow-release fertilizers (e.g., Osmocote,® Agriform tablets) are desirable because they provide nutrients to the plants for an extended period of time and require fewer repeat applications of fertilizer. Osmocote® is a controlled-release fertilizer that performs well under saturated soil conditions. For transplants, controlled-release fertilizers normally are applied at the time of planting and again only as plant conditions warrant (Garbisch 1986).

When a slow-release fertilizer is impracticable or when mechanical equipment is used which is not designed to simultaneously place plants and fertilizer in the substrate, a conventional 10-10-10 (or 20-10-10) fertilizer may be used. Seedlings should be fertilized with a standard 10-10-10 or 20-10-10 fertilizer at a rate of 670 kg/ha (600 lb/acre) or 335 kg/ha (300 lb/acre) respectively. This fertilizer may be applied to the base of the transplant after new growth appears. Applications should be made when no water will be covering the substrate for 4 hours or more (Garbisch 1986).

For underwater planting, burlap sacks containing the fertilizer can be placed beneath the transplant (Garbisch 1986).

## Dry or Liquid Applications

Fertilizer may be applied in either dry or liquid forms. Dry applications have the advantage of low investment costs for equipment and flexibility in the use of any fertilizer including low cost and slow-release fertilizers. Disadvantages of dry application are that it can be labor-intensive when the dose must be carefully controlled, and uniform distribution of the fertilizer is difficult to achieve. When using liquid fertilization, the fertilizer is mixed with water and then either applied to the soil for root absorption or to the leaves and shoots for foliar absorption. Liquid applications of fertilizers are easily distributed and automated, can be incorporated into irrigation, and are not labor-intensive. The disadvantages of liquid applications are the limited number of fertilizer materials that can be used and the initial high cost for mixing and application equipment (Furuta 1976).

### Frequency of Fertilization

When seeding has been the method of vegetation establishment at a site, at least one fertilization normally will be required. Garbisch (1986) indicates that this is best accomplished after the seeds have germinated and the seedlings are one month old or once the seedlings have grown to be several inches tall. Fertilization should be repeated at the suggested rate one month following the initial fertilization (Garbisch 1986) or twice again at one month intervals using the rate of 20 grams of 10-10-10 per transplant (or 10 grams for 20-10-10). Additional information on fertilization for maintenance of vegetation is provided in Chapter 7-5.

## Mulching

In many instances where seeding has occurred, mulching with a clean, weed-free material (e.g., wheat or barley straw, wood chips, etc.) is desirable to promote the germination of seeds, and the growth and survival of young seedlings. Mulches serve to maintain soil moisture, decrease soil temperatures by providing shade from the radiant sun, and reduce establishment of weed seeds from adjacent areas at a site by providing a physical barrier to contact with the soil. The addition of a mulch after or with hydroseeding is important in keeping the seed in place at the site and from not washing away during the first rainstorm before the seed has had an opportunity to germinate and the roots to take hold. Mulching is discussed further in Chapter 7-5.

## Irrigation

### Introduction

After the vegetation method(s) for the restoration site have been determined, an evaluation of the site characteristics and compatibility with the planting method should be conducted to determine if irrigation of the site or individual specimens planted into the site is needed to protect the planting investment. If irrigation is necessary, the next step is to determine what type of irrigation system will be most effective and how often irrigation will be needed. This section only describes irrigation methods and advantages and disadvantages of these methods. A determination of the frequency of irrigation is dependent on many variables including but not limited to the wetland type being restored, soil conditions (e.g., drainage, water-holding capacity, etc.), climatic conditions (e.g., precipitation, relative humidity, etc.), plant density (influences evapotranspiration and foliage interception), and species requirements and tolerances.

While care should be exercised in the acquisition, handling, and planting of transplants to minimize the loss of root hairs and damage to portions of the root system, the root system of a plant is almost always damaged during these phases of transplanting. Consequently, the amount of water uptake by the plant is reduced or stopped entirely while transpiration continues. As a result, the water supply within the plant is decreased and growth and survival are affected (Edmond et al. 1957).

Most transplants should be watered to withstand desiccation and water loss due to transplanting shock. Bare-root stock should be kept moist and containerized stock should be watered frequently until planted. Both transplant types can be watered during planting after the hole is two-thirds filled with soil (Landin 1978). In prairie restoration, transplants need to be watered regularly (Thompson 1992). Most herbaceous transplants should be transplanted with water. The application of water at transplanting is essential to rapid recovery and to securing good stands. The water settles the soil around the roots, eliminates air pockets, and is available for immediate absorption.

Irrigation or watering after planting may be necessary for the first growing season in particular regions of the country that typically experience a drought period during the growing season or in seasonally or temporarily inundated wetlands. Where drought conditions are often exceptionally severe, it may be most practical to install or use automatic irrigation systems (Garbisch 1994). When watering will be necessary, the following sources of irrigation water may be used:

- water periodically trucked into a site
- water pumped from adjacent sources such as streams, lakes, ponds, reservoirs, and municipal water supplies
- installation of shallow aquifer well

Irrigation systems can be controlled manually or can be automatically controlled by timers or precipitation. When using automated irrigation systems, use reliable equipment to reduce the probability of malfunctions. Also periodically check the irrigation system during the establishment period to ensure that malfunctions do not go unnoticed for more than 24 hours. If an automated system is used at the site, it is a good idea to have a backup water source or a backup plan for irrigation to prevent desiccation and loss of vegetation in the event of an equipment failure or in the event that the equipment cannot be back online within 24 hours.

Several techniques can be utilized to reduce the water supply losses from a newly transplanted plant and are discussed below. Methods to increase the water supply to the plant via irrigation are discussed in this section.

There are essentially three major methods of applying water to a site and to transplants (Edmond et al. 1957).

- Surface irrigation is the direct application of water over the surface of the land.
- Subirrigation is the application of water below the surface of the land. Soils adapted for subirrigation consist of those with an impervious lower layer to hold water against the force of gravity, an open, porous intermediate layer to act as a reservoir for water and a finely textured top layer to facilitate capillary action. Subirrigation is a method that has been employed in agricultural production in Florida, Michigan, and New York. In Florida, water is often obtained from artesian wells and is transported through lines of 8-cm (3-in.) drain tile placed 0.5 m (18 in.) deep and 7.3 m (24 ft) apart. Little information is available about the use of this type of irrigation at wetland restoration sites.

- Spray irrigation is the application of water on the surface of the land in the form of a spray similar to a gentle rain. This type of irrigation is adapted to all types of soils and to both level and rolling land. Spray irrigation generally requires less labor and less water than surface irrigation.

## Surface Irrigation

Techniques for surface irrigation include the following:

- Drip irrigation - Drip irrigation, also referred to as spaghetti irrigation, is the method of applying water at such a slow rate that it immediately enters the soil mass and is distributed in the soil. Drip irrigation permits the maintenance of a higher and more uniform soil moisture content than flood irrigation. Drip irrigation is particularly beneficial in hot, arid climates where evaporation rates are high and soil salinity builds up due to evaporation of water from the soil surface. Advantages of this system include:

  - reduces the buildup of soil salinity and accumulated salts in the soils

  - needs less water

  - less water is wasted

  - water is applied directly to the root zone of the plants where the water is required

## Irrigation Installation

At project sites in regions having an arid climate or subject to periods of undependable rainfall, irrigation may be needed on a regular basis until plants are established. Drip irrigation is an effective means to supplement the water supply in most parts of the country, especially in arid regions, and involves minimal physical preparation of a site (Doerr and Landin 1983; Environmental Laboratory 1986). Drip irrigation is a valuable irrigation technique because there is less hazard of runoff and erosion on steep slopes; excessive salts and phytotoxins can be leached from the root zones; it is adaptable to remote areas without pressurized water systems; it conserves water where water is costly or scarce; and it helps to promote deep root growth and better plant development (Bengson 1977).

- Trickle irrigation - Trickle irrigation is similar to drip irrigation but has a faster rate of application. Free water may flow on the surface of the soil before entering the plant.

- Border or basin irrigation - This method of irrigation may require a gentle sloping site and a deep compact soil and plentiful water. With this method, the land is level and borders are constructed along the contours in both directions approximately 15 to 20 cm (6 to 8 in.) high. Water is introduced into each basin.

- Furrow irrigation - The land is leveled or ridged and furrowed. The furrows vary from 10 to 25 cm (4 to 10 in.) in depth and follow the contours of the land. This method is commonly used to irrigate plants planted in rows and in arid and semiarid regions of the country.

## Spray Irrigation

Techniques for spray irrigation include:

- Overhead fixed spray heads - This system consists of nonportable parallel lines of galvanized iron pipes placed approximately 15 m (50 ft) apart and supported on low posts about 1 m (3 to 4 ft) high, or on high posts 2 to 3 m (6 to 10 ft) high, or on a cable supported by posts 3 to 6 m (12 to 20 ft) high. A line of pipe is equipped with nozzles and an oscillatory. The nozzles can be of two types: (1) those that deflect the spray and break the water into a fine mist, or (2) those that discharge the water in the form of a small stream. The main disadvantage of this system is the high initial cost; however, it is profitable in its use and application. The advantage of this type of system is that it generally covers a small area and has a high precipitation rate (Furuta 1976).

- Portable pipe system - This system is similar to the overhead fixed spray system. The advantage of this type of system is that it can be moved and assembled and disassembled easily.

- Rotating impact sprinklers - Impact sprinklers are sprinklers that rotate slowly. This method is particularly beneficial for irrigating large areas (Furuta 1976).

## Non-automated Irrigation

Techniques include:

- Hand irrigation - Watering can be done by hand at a restoration site; however, for hand watering to be cost-effective, it should be restricted to very small sites or to watering of individual specimens with high irrigation requirements for establishment at a site (e.g., large trees). Disadvantages of hand watering are that it is labor-intensive and time-consuming, especially if the water must be carried to the site.

- Tractor- or vehicle-mounted irrigation - Irrigation water can be sprayed onto a site from a tractor or other vehicle that is able to access and traverse the site.

Irrigation water may be local water or may be a starter solution containing readily available nutrients in high concentrations. Starter solutions have shown markedly increased rate of recovery of seedling plants. The solution promotes rapid recovery and early growth by providing the plants with an adequate supply of readily available nutrients and by stimulating the rate of root regeneration (Edmond et al. 1957).

# Planting Arrangements and Spacing

## Spacing

Rates or spacing of wetland plant species at a site is influenced by a number of factors including the size of the transplant, the method of reproduction, species vigor, whether fertilizer is used during transplanting, desired densities or cover, time to achieve desired cover, and many other variables. Propagules should be spaced to allow for lateral spread of rhizomes, tillers, and roots within each stand. For quicker coverage, plants can be planted at closer spacings (Doerr and Landin 1983; Environmental Laboratory 1986). If plants have vigorous growth habits and spread their roots rapidly, then closer plantings may not be necessary.

Depending on the species 0.3- to 1.5-m (1- to 5-ft) intervals are recommended or are typical (Warburton et al. 1985). The following are examples of spacings used or recommended for transplants at wetland restoration projects:

- In the restoration of freshwater marshes, the following are plant spacing intervals for these species:
  - *Pontederia cordata* - single seedling transplants were planted on 1.0- to 0.5-m centers to yield a $1 \times 10^3$ to $4 \times 10^3$ kg/ha standing crop, respectively (Garbisch and Coleman 1978).
  - *Scirpus americanus* (threesquare bulrush) - 1.5-m (5-ft) intervals are adequate for this rapidly spreading species.
  - *Scirpus acutus* (hardstem bulrush) - 0.3- to 0.9-m (1- to 3-ft) intervals are adequate for this less prolific species.
- In the restoration of riparian forested wetlands in the Northeast, success in establishing wetland vegetation was greatest with a mix of successional species and climax species planted on 3-m intervals. Scheuler (1994) suggested that a riparian forest can become established within 7 to 10 years using this spacing technique.
- In hardwood and bottomland forested wetlands, the following spacings have been used and are dependent on the method of planting and the site condition:
  - Mechanically seeded acorns were planted approximately 1 to 1.5 m (3 to 5 ft) apart within a single row. Rows were spaced 3 to 3.7 m (10 to 12 ft) apart.
  - Hand planted acorns were planted at approximately 1.2-m (4-ft) intervals and in rows approximately 3.4 m (11 ft) apart.
  - Acorns should not be sown closer than 1.5 m (5 ft) to stumps ranging in size from 4 to 12 inches or under piles of logging debris (Johnson and Krinard 1987).

- A spacing of approximately 1.5-m intervals for woody species (i.e., trees and shrubs) and the staggered placement of plants between adjacent rows can result in rapid achievement of cover on the site. Thinning will be required later when plants are established this close together.

- Typical spacing for woody species is 2 to 2.5 m apart but is dependent on the species.

- Shrubs typically are planted more closely than trees, usually between 0.5 and 1.5 m apart and again the spacing interval is dependant on the species (Coppin and Richards 1990).

The following are examples of wetland plant spacings used or recommended for herbaceous and underwater planting:

- When transplanting herbaceous species when the substrate is moist or drained, most herbaceous species can be transplanted on 0.6-m (2-ft) centers. At this spacing, uniform vegetative cover is likely within one full growing season.

- When completing underwater planting (i.e., planting of submergent species), the above spacing for herbaceous species might be increased from 0.6-m (2-ft) centers to 1- to 2-m (3- to 6-ft) centers (Garbisch 1986).

## Seeding Rates

Seeding rates are dependent on land use (e.g., nurse crop or permanent cover) and species variety. For further information on specific seeding rates see Vogel (1981). The following are examples of seeding rates. Some of the information presented in this section has been derived from wetland restoration projects and some from the agricultural literature.

- Mixtures of annual and perennial meadow species combined with a nurse crop were established at rates of approximately 10 to 12 lb/acre of the meadow species along with the 20 lb/acre of the nurse crop. Overseeding of annual species in the spring and perennial species in the fall was found to be essential to the maintenance of species diversity in the meadows over time. Scheuler (1994) also found, however, that the meadows became dominated by a few species in 3 or 4 years if they were not overseeded annually.

- Seeding rates for prairie restoration are typically calculated on a bulk seed basis or on a PLS basis if seed is obtained from a commercial source. A wide range of recommended seeding rates is found in the literature. The following are generalizations from Thompson (1992):

    - Heavier seeding rates are recommended for the following:

        * more rapid establishment,

  * higher quality sites,

  * sites with fine-textured soils,

  * if seed is broadcast and not drilled.

- Grass to forb seed ratios should range from 3:2 to 1:2.

- 80 PLS/$m^2$ to 500 PLS/$m^2$ are good seeding rates for small areas.

- 16 kg/ha (14 lb/acre) to 20 kg/ha (18 lb/acre) PLS are good seeding rates for large areas.

- 6 to 11 kg/ha (5 to 10 lb/acre) of mixed grass seed and 11 to 22 kg/ha (10 to 20 lb/acre) of mixed forb seed for bulk seed have been used in prairie restoration sites.

- Garbisch (1986) recommended seeding at a rate of 110 viable seeds per square meter (10 seeds/$ft^2$).

## Arrangements

Once transplants spacing or seeding rate has been determined, the next step is to determine planting arrangements or pattern of species placement at the site. Plants can be arranged in a number of ways depending on the function of the wetland and the desired appearance. Transplanting on a grid pattern is the easiest pattern for transporting the transplants to the site. This arrangement is desired because it produces a uniform vegetative cover. It may, however, limit the appearance of the site to a row-like plantation appearance if the grid spacing is wide. Clustered planting arrangements of perennials provide both species and spatial diversity within a given area. Clustered planting arrangements have also been found to result in good establishment of wetland plants under variable hydrologic conditions. For example, plantings placed along the perimeter aquatic bench of three created wetlands constructed for stormwater detention in Maryland had 82 percent survival/persistence rate when six to eight species of wetland plants were planted in single species clusters at an average density of 4 plants per square meter (Scheuler 1994).

Planting arrangements should reflect the principal function of the wetland and anticipated water flow patterns. For example, planting rows which traverse the narrow axis of the site rather than the long axis can slow water entering the wetland and limit plant colonization in the wetland. Orientation of the rows is especially important in wastewater treatment wetlands, where rows running the length of the wetland cell result in water flowing down each row, thereby avoiding the filtering action of the planted vegetation (Hammer 1992).

Planting in linear rows is a common arrangement that results when mechanical planters or seeders are employed as the planting method. This type of arrangement results in a nonnatural, plantation-like appearance to the restored wetland. Interplanting (i.e., planting between the rows) is one option for reducing this row-like appearance. Another option is to create sinuous or undulating rows; however, this option will increase the amount of planting time.

If more than one species of ground cover or shrub is to be planted, a checkerboard or diamond-shaped planting pattern is usually the best (Environmental Laboratory 1986). This type of pattern is beneficial because it increases the species diversity over short distances; however, this type of planting arrangement can only be implemented when the seeding or transplanting is conducted by hand.  Other patterns such as bull's-eye patterns or linear zones may be appropriate for wetland sites where there is a hydrologic, topographic, or elevation gradient across or within a wetland. Wetland types that may be suited to these types of patterns, for example, may be vernal pools, prairie pothole, and freshwater submergent/emergent wetlands along lake shorelines.

# 7-4 Planting Schedule[1]

## Introduction

Planting, as defined here, includes both seeding and planting of vegetative propagules. Numerous individual factors can affect a project planting schedule. The allowable planting period or window is very important regardless of the propagule used. Many other factors that affect planting schedules exhibit some degree of region-specific variability, although some tend to be operative without regard to geographic considerations.

A number of key factors relate to the formulation and execution of planting schedules. A discussion of these and other factors is provided in remaining sections of this chapter. Significant factors include the following:

- Adequate lead time is often necessary to obtain desired propagules in sufficient quantity to plant a site and the amount of time is sometimes difficult to predict accurately
- Propagules of some or all types are very difficult to obtain for many wetland species (e.g., most species of *Carex, Quercus*, etc.)
- Climatic variables affect planting schedules in a number of ways (inability to plant because of frozen ground, drought, etc.), and they are often very unpredictable
- Modify site preparation results or implement site maintenance activities to correct difficult site conditions (e.g., inadequate control of hydrology, unexpected erosion, etc.)

## Effects of Plant Materials Availability on Planting Schedules

A desired planting schedule will often dictate which species can be acquired in time to achieve project goals. Similarly, the availability of certain propagules may impact a planting schedule. Regardless of how carefully a project may be planned in advance, however, wetland restorationists should remain alert to the possibility that an unexpected last minute unavailability of desired plant materials may require changes in the content of a desired planting schedule.

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There are major differences in availability of wetland plant materials in the US on a geographic basis. Some areas of the country (e.g., California, Florida, Maryland, and many parts of New England) are blessed with numerous local growers of a diversity of wetland plant materials. Other sections of the country have almost no local sources for more than a few species. A publication by SCS (1992) provides an excellent current listing of sources for wetland plant materials in the US. This publication should be consulted on a local basis in locating suitable sources of planting materials.

For many projects requiring large amounts of plant material and for those projects requiring hard-to-find materials, contract-grown materials may be the answer. In many cases, the contractual arrangements to obtain materials in an adequate stage of development for planting will need to be in place as much as 2 to 3 years prior to the intended planting date. In warmer sections of the country and for those sites where well-rooted cuttings are adequate propagules, however, it may be possible to propagate and plant in the same year.

## Site Conditions

There may be a need to modify site preparation results or to implement site maintenance activities prior to planting. Depending on the severity of the problem, these activities have the potential to require planting schedule adjustments. A properly graded site having a well prepared seedbed, for example, may experience severe erosion from stormwater runoff prior to planting, requiring extensive repairs and causing modifications to the planting schedule.

Site conditions often play a major role in determining what species will be planted, propagule types to be used, and planting methods (e.g., tractor-mounted planting equipment cannot be used on some soils during the wet period).

The attainment of desired water levels often plays a major role in planting schedules. Manipulation of the local hydrology may be required to allow access to the site or to facilitate mechanized planting. In prairie pothole and wet to wet-mesic prairie restoration, for example, seeding or topsoiling to augment the native seed bank is mechanically easier to conduct during natural drawdown periods (Thompson 1992). In many instances, moreover, the water levels determine whether favorable ecological conditions for plant establishment are at hand. Attainment of desired site conditions may affect the schedule.

The potential for competing vegetation and its control is an important consideration in development of any planting schedule. Where vegetation removal has been achieved earlier in site preparation, a follow-up evaluation may be necessary to assess the need to implement additional vegetation control methods prior to planting. Unexpected events (e.g., delayed access to site for planting because of floodwaters) often result in unexpected competitive growth, which will require action before planting.

# Availability of Planting Crew

Ideally, a site is planted most efficiently and inexpensively by an experienced planting crew. In some areas of the country, experienced planting crews are composed almost entirely of volunteers. In other areas, however, the most experienced crews may be associated with commercial enterprises. Again, in some sections of the country, planting crews may be available on a year-round basis, while in others they may be available only on a seasonal basis. Plan ahead far enough to know about planting crew availability. If necessary, consult a local regulatory agency or conservation organization for information on planting crew availability (e.g., Corps, SCS, US Fish and Wildlife Service, State Forester, The Nature Conservancy, or state wildlife agency).

# Planting Considerations

## General considerations

Ideally, planting should be done under optimum environmental conditions. For a variety of reasons, however, this is often not possible. The timing of the permit process, for example, often plays an important role in development of a planting schedule for mitigation projects. Planting should be undertaken during periods of optimal soil moisture levels. Also, one should avoid planting propagules during freezing weather or in frozen ground.

Both seeding and planting of vegetative propagules, as a general rule, should be conducted at a time when favorable soil moisture and temperature conditions are going to occur (Allen and Klimas 1986). Use of vegetative propagules, in effect, extends the planting season by allowing more efficient use of labor and equipment and access to areas that cannot be seeded during wet seasons (Landin 1978). Sandy soils and south-facing slopes represent sites that may provide conditions that induce physiological stress on transplanted materials (Allen and Klimas 1986).

## Importance of local planting practices

Considering the country as a whole, there are many local variations in the preferred season for planting. In those parts of the country characterized by cold winter conditions and short growing seasons, early spring planting usually is preferred for herbaceous plants since it provides an entire growing season for plants to establish. Fall plantings in these colder sections of the country often risk severe freeze damage before the plants are fully established. In warmer parts of the South, however, fall is a preferred season for some species. Especially in areas where local hydrologic conditions make early spring planting difficult and where very hot conditions occur early in the growing season, fall planting is often effective. These southern areas allow for considerable root growth prior to the onset of generally mild winters in which freeze damage is normally minimal. In various parts of the arid West, the preferred planting time is just before or during the rainy season, and there are local variations as to when the rainy season occurs.

Consult a local authority (e.g., Soil Conservation Service, Cooperative Extension Service, or a local nursery) to determine whether the desired planting schedule is feasible under local conditions.

# Seeding

## General seasonal considerations

Seeds are often effectively precluded from use during particular times of the year, thereby affecting the planting schedule. Garbisch (1986) says that seeding for most species is best completed in early spring to realize the full growing season (Table 7-8). For some species, seeds that are planted before the last spring frost may result in seedling damage from freezing, while midsummer seeding may result in severe damage from heat and drought stress. Broadcast seeding generally cannot be used effectively during the driest season of the year, primarily because the seeds are either scavenged or blow away before germination. Conversely, drill seeding cannot be used during the wettest periods, when the soils cannot support a tractor-mounted drill. Mechanized planting of other propagule types also may be limited by site conditions related to soil moisture.

Spring is excellent for seeding over much of the country, particularly in the temperate or cool-humid climate zones, although fall seeding is often effective when nutrient amendments are applied (Environmental Laboratory 1986; Garbisch 1986; Warburton et al. 1985). In the arid

**Table 7-8**
**Recommended Planting Time for Propagule Types (after Garbish 1986)**

| Propagule | Season | | | |
|---|---|---|---|---|
| | Spring | Summer | Fall | Winter |
| Seed | X | | | X[a] |
| Dormant (sprig, bulb, rhizome, tuber) | X | | | X |
| Growing (sprig, bulb, rhizome, tuber) | X | X[b] | | |
| Plug or peat-potted nursery stock | X | X | X | X |

[a]Seeds may after-ripen in the ground at the site; however, bird consumption and erosion may lead to seed loss.
[b]Transplant mortality rates may be high. Clipping aboveground parts to 6-12 in. in length may reduce the shock of processing and planting and may increase survival.

Midwest, August is usually considered the best seeding time due to seasonal rainfall (Doerr and Landin 1983). Seedings made too late in the season (i.e., July through September) often risk severe damage from winter conditions in more northern latitudes, although winter kill is not normally a problem in more southern latitudes. Caution should be exercised with fall seedings, because there is a greater likelihood of adverse cold weather effects on young seedlings from frost or cold desiccating winds.

## Seeding Wetland Prairie Habitats

For wetland prairie species, seeding should be done to take advantage of the warm summer days when most prairie plants can out-compete weedy species. The greatest success in germinating and establishing wet and wet-mesic prairie species from seed has occurred when stratified seed was sown in late May to mid-June. Successful seeding of stratified materials has occurred as late as early July (Thompson 1992). Early spring and fall sowing will often be met with less success due to seed predation and greater competition from early germinating weed species. Legumes, in particular, are very sensitive to cold and may fail to establish with an autumn seeding. Native grasses, on the other hand, have been planted on Midwest sites from as soon as the soil warms sufficiently into July. Dormant seeding of native prairie grasses and forbs can be conducted from the latter part of October until the ground freezes (Rolfes 1993).

### Direct seeding of woody plants other than oaks

Direct seeding of hardwood tree species is not a recommended practice in the Midwest, especially in the fall season. This is because of the high potential for intense rodent damage and weed competition (Thompson 1992). It has been used with success, however, in the South.

### Direct seeding of oaks from acorns

Recent research indicates most acorns of most red/black oaks (*Quercus* spp.) can be planted successfully at any time of the year. This finding is particularly important in regenerating sites covered with water or otherwise unworkable during the dormant season. The previous season's viable seeds can be planted after the water recedes, which for some bottomland areas could be as late as June or July. Bonner (1982) found that generally there was no difference between the fall planting of ungerminated acorns and spring planting of stratified, sprouted acorns in test plots. Fall plantings of ungerminated acorns produced fewer but larger seedlings than spring sowing.

In the South, acorns sown in water overflow areas after the water has receded (i.e., April, May, or June) typically result in good germination and healthy seedlings (Johnson and Krinard 1987). Acorns of the following species can be sown during late spring or early summer with good results, depending on local site conditions: water oak (*Quercus nigra*), cherrybark oak (*Quercus pagodifolia*), and Shumard oak (*Quercus shumardii*). Nuttall oak (*Quercus nuttallii*) acorns can be sown at any time of the year, but winter-sown acorns seem to result in higher germination. For many sites in the South, however, the period of July through October is marked by soils that are hot and dry, resulting in poor success.

# Vegetative propagules

## Herbaceous species

Vegetative propagules of herbaceous plants are generally best planted when the daytime temperatures average less than 68°F. Along the climatically mild Gulf and South Atlantic coast regions, planting of herbaceous propagules is often accomplished in all but the summer months.

Sprigs and fleshy propagules (e.g., tubers, bulbs, and rhizomes) normally must be transplanted in early spring when surface soils are moist, when soil temperatures are at least 10°C, and before new growth commences (Environmental Laboratory 1986; Garbisch 1986; Kadlec and Wentz 1974). Planting these materials during their dormant period is best, because there is less shock to the transplanted materials when they are moved from a donor site or a holding nursery at that time. This practice limits the optimal planting times to late fall, winter, and spring months; often, however, these materials are planted on into midsummer.

A high rate of success with some of the more fleshy propagules typically requires careful control of water levels and water quality. If the water quality is poor (i.e., low dissolved oxygen or high organic loading), submerged plants may die from inadequate oxygen during the winter months. Also, shallow water levels or simply wet substrates may freeze hard enough to kill tubers and other fleshy propagules if winter temperatures are extreme. Nonfleshy rootstocks having 20 to 30 cm of top growth protruding above the water's surface allow higher water levels, even if the water is of low quality, because the top growth provides a pathway for oxygen from the atmosphere to the roots.

With good water quality conditions, tubers, bulbs, and rhizomes of the most common emergent wetland plants, except graminoids, are best planted after the onset of fall dormancy. Most grasses, sedges, and cattails seem to develop and spread faster if planted immediately after dormancy is broken in the spring. Cattails and bulrushes (*Scirpus* spp.) have been planted as late as September in the South, but these plantings are often not successful if inadequate time remains for new root growth before the arrival of freezing conditions (Hammer 1992). Peat-potted nursery stock may be transplanted at any time of the year, including dormant periods and during the growing season, but lower survival rates can be expected when planted outside the optimal window. Appropriately sized plugs from natural wetlands may be transplanted successfully at any time. Fall planting, although a horticulturally acceptable practice for many of the individual freshwater marsh species, is not recommended for restoration of an entire marsh habitat in many areas because of the potential for severe loss of propagules resulting from erosion of sediments away from the root systems before new growth is initiated in the following spring.

## Woody species

The planting window for transplants of woody species is considerably smaller than for herbaceous species. In general, deciduous trees and shrubs are transplanted most advantageously when dormant (Edmond et al. 1957), and for many parts of the country this is accomplished in either spring or fall. During this time, transpiration is at a minimum and the root system can establish well before new stem and leaf growth begins. The longer the time available for root development, the greater is the chance for survival until leaf development and plant growth occur. Some woody species will survive if planted in early summer, but the percentage lost to impacts from various stress factors is likely to be considerably higher (Hammer 1992).

In most regions of the US, balled-and-burlapped trees and shrubs are usually transplanted in the fall, winter, or early spring. In southern Florida, however, trees and shrubs are planted during the summer. Rainfall is higher there in summer than during winter, resulting in light intensity, higher relative humidity, and low rates of transpiration (Edmond et al. 1957). These factors all help to promote successful establishment.

Spring (i.e., 1 April to 15 May) is the best time to plant tree seedlings over most of Iowa, but fall planting may be done if bottomland sites are too wet for spring planting. For more information on planting schedules for bottomland hardwoods and riparian wetlands in Iowa, see Thompson (1992).

In the northern states, trees are generally planted in the spring when soil temperatures and light intensities increase at a slow rate. In the South, trees are generally planted in the fall. Fall soil temperatures there are sufficiently high for the development of a new root system during the winter, and good top growth is accomplished in spring because of the rapidly increasing air temperatures and light intensities.

The US Fish and Wildlife Service’s efforts on bottomland hardwood reestablishment efforts in the Southeast suggest that the optimum planting time for woody seedlings is in January during the dormant season (Haynes et al. 1993). Better survival was achieved in dormant season plantings, and the seedlings were easier to monitor.

## Acclimation of Planting Stock to Site Conditions

A propagule that is not in dormant condition often must be prepared for planting through some type of gradual acclimation procedure. This preparation is necessary because a newly planted plant typically does not achieve all of its fully functional physiological processes (e.g., its root system is not yet capable of absorbing water at the same rate it is evaporated from the shoot) until some time after planting. This period of adjustment in preparation of adjusting to site conditions may need to be considered in planning the planting schedule.

To lessen transplant shock, propagules held in storage inside a nursery or greenhouse should not be planted until temperatures at the field site are at least as warm as those in the storage area. Propagules held in shaded areas should be gradually acclimated to sunny conditions to prevent blistering and death of leaves.

Extremes in temperature, both hot and cold, have the potential to limit periods of effective planting. High temperature levels often contribute to excessive water losses through the evapotranspiration process, resulting in repeated wilt and planting failures. Extremely cold temperatures have the potential to cause freeze damage to aboveground plant portions and, where the ground freezes, may contribute to root damage and resulting planting failures. Death by winter killing or cold at any time, however, is usually related directly to desiccation. Potential damage from low temperatures can be reduced through implementation of the hardening process.

The term hardening is used in referring to a process of making plants less susceptible to injury from both cold temperatures and drought. Seedlings that have been grown in a greenhouse are highly susceptible to both drought and freeze damage. Many kinds of plants may be hardened by subjecting them to drought before the advent of freezing. Perennial plants, in general, are less likely to experience winter kill if they experience a period of moderate drought than if they are kept wet and green up to the time of severe freezing. If seedlings are placed in an enclosure for a few days at a temperature several degrees above freezing and watered sparingly before planting, they increase in hardiness to a point where many species will better withstand frost. Some species, in fact, may be frozen stiff without damage.

## Desirability of Matching Planting Stock to Geographic Region

Plant materials should represent local genetic stock when possible. Many species having broad geographic distributions in the US (e.g., black willow, *Salix nigra*, and soft rush, *Juncus effusus*) include populations representing numerous physiological variations. Within a species there may be significant variations in the ability of individual populations to withstand extremes in temperature, soil water availability, and light intensity. Frost resistance, for example, determines the northward range of many woody plants. Also, flowering and seed production in many species is controlled by photoperiodic (i.e., relative length of daylight versus night) responses. When planting stock is planted far outside the area and conditions under which its genetic material developed, the potential for failure is much higher than when those materials are planted close to their place of origin. This factor has been a major reason for project failure when planting materials were obtained by mail-order from a far distant state.

# 7-5 Vegetation Maintenance[1]

## Introduction

Vegetation maintenance, as defined in this document, refers to all measures implemented after initial planting and having the potential to further affect or alter the condition of vegetation existing at a project site. After planting vegetation on a site, decisions on whether or not to employ vegetation maintenance measures must be made as the site develops.

A lack of vegetation maintenance measures has the advantage of allowing natural vegetation succession processes to proceed without the involvement of additional expenditures. Nature's processes are often unpredictable, however, and potential disadvantages arising from a lack of maintenance include the following:

- Invasion by unwanted and undesirable plant species, resulting in a major alteration of the site and its intended purpose
- Insufficient vegetation cover to prevent erosion and loss of substrate
- Major changes in topography such as breaches of dikes, severe storm damage, and erosion gullies, which have the potential to produce undesirable alterations of vegetation components
- Colonization by exotic plant species, wildlife species, disease, insects, and other pest organisms that may impact or exclude plant species for which establishment measures were initiated
- Lengthened time to reach success criteria

## Reasons to Continue Site Monitoring and Maintenance

In most instances, maintenance of a site's vegetation should be continued through at least one full growing season (Garbisch 1986), or preferably longer. Reasons to continue site monitoring and maintenance include the following:

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- Determining the need for additional soil amendments (e.g., fertilizer application)
- Determining the need for replacement plantings or supplemental plantings
- Determining the need for control measures for exotic or undesirable plant species
- Controlling plant diseases and insect pests
- Removing accumulations of litter or debris that might smother the plantings
- Ensuring that site topography and hydrology are adequate for meeting success criteria
- Controlling depredation by problem animal organisms
- Controlling mosquito population levels
- Checking and maintaining fences
- Re-firming plants loosened by wind or frost damage
- Pruning or removal of dead or diseased plant parts
- Controlling vandalism
- Repairing fire damage

Success criteria should be used as a standard against which the site development process is measured. If the site is not developing at a satisfactory rate toward the success criteria, maintenance will be required. Site development may be hindered by any of the factors listed above.

An evaluation of project success with wetland vegetation establishment requires the establishment of measurable success criteria at the outset, and these success criteria should lend themselves to quantitative assessment, wherever possible. Mitigation projects initiated as a result of regulatory requirements related to the Corps' Section 404 permitting process usually have specified success criteria which must be met within a prescribed time frame. Success criteria in these projects tend to be simple, few in number, suitable for assessment over a relatively short time frame, and easy to evaluate (FTN Associates 1993). Other types of projects (e.g., nonregulatory projects related to stewardship or conservation activities), however, often have success criteria that are much more complex, more ecological in nature, and often requiring some degree of maturation before success can be achieved. Both types of projects always require monitoring to evaluate success.

Intensive or frequent maintenance activities (e.g., repetitive pruning or hand weeding) are both costly and inefficient and should be avoided (Schnick et al. 1982; Environmental Laboratory 1986). A good project plan should require little maintenance (e.g., seasonal mowing or periodic fertilization as opposed to monthly activities). Species requiring little or no vegetation maintenance should be selected for planting. Management or control measures for species having the potential for aggressive establishment to the detriment of others should be considered in project planning, and those species should not be planted unless effective control measures are guaranteed (Environmental Laboratory 1978). Realistic planning allows for mid-course corrections when necessary.

## Decision to Implement Vegetation Maintenance Activities

A realistic assessment of whether desired project outcomes (i.e., vegetation cover values and species assemblages) can be achieved without maintenance and within a desired time frame requires a thorough knowledge of local conditions and vegetation requirements.

The presence of undesirable species, predation, disease, or improper hydrology, etc. all play a role in making the maintenance decision.

A maintenance program should be developed in close association with a monitoring plan (see Section 8 on monitoring for parameters that can be routinely monitored).

## Types of Problems Associated with Typical Sites Needing Maintenance

Table 7-9 provides a checklist of individual items that can be evaluated to determine whether the condition of a site's vegetation warrants implementation of a maintenance program.

**Table 7-9**
**Considerations in Determining the Need for Vegetation Maintenance**

| | |
|---|---|
| bare soil areas | insect attacks |
| rills and gullies | evidence of wildlife damage |
| rocky areas | evidence of domesticated animal damage |
| accelerated erosion | fungus or other disease symptoms |
| exposed tree and shrub roots | plant nutrient deficiency symptoms |
| loss of trees | exotic or other undesirable species |
| loss of shrubs | incorrect hydrology, including storm water runoff |
| loss of herbaceous plants | surface debris |
| windthrow damage to plants | vandalism (particularly in populated areas) |
| ice damage to plants | excessive salts buildup in the soil |
| drought damage to plants | mosquito problem |

Numerous environmental factors have the potential to damage newly planted vegetation that is becoming established. Some of these specific risk factors, together with recommended protection measures, include (Coppin and Richards 1990):

- Wind damage - Encourage deeper rooting by lowering the water table until plants are established. Plant stands of trees in a dense pattern to provide mutual protection.

- Fire - Encourage superficial recurring burns, which will minimize vegetation damage and allow shoot regeneration.

- Grazing and browsing and other animal damage - If possible, plant a type of vegetation that is not preferred browse or which exhibits low grazing impacts (e.g., willow trees usually recover more easily than some other woody species). Use protective fencing that is regularly maintained, at least during early stages of development. Implement effective pest control measures.

- Natural causes (including decline related to old age, disease, and pests) - Encourage natural regeneration. Implement disease control measures (e.g., fungicides, insecticides) in response to specific problems. Establish diversity of species and age classes among plantings.

- Climatic extremes (wetness/drought) - Avoid planting sensitive species. Plant species having known high tolerance levels for specific conditions. Use adjacent structures to provide shelter. Utilize mulches to reduce damage.

- Wear and traffic (trampling by humans, animals, and vehicles) - Use fencing to reduce or exclude use. Increase soil fertility to promote vigorous growth and regeneration. Reinforce soil surfaces to increase soil strength and reduce erosion. Plant species that will tolerate trampling.

- Vandalism - Use secure fencing. Employ vigilance and regular maintenance.

- Pollution - Plant species known to be tolerant of pollution (e.g., numerous emergent species are known to tolerate high levels of heavy metals).

## Corrective Measures for Site Maintenance Problems

### Introduction

A number of corrective measures are available for potential use on problems related to site maintenance. The following paragraphs address these corrective measures.

### Soil Amendments

Two primary types of soil amendments are commonly utilized in restoration and creation projects to assist in vegetation establishment: fertilizers (including lime and ammonium sulfate) and mulches. Each can be applied either prior to or after planting. In this section, however, the discussion is restricted to post-planting applications. See Section 6 for additional details on soil amendments, both fertilizers and mulches.

## Fertilizer Application

In some instances, application(s) of organic or inorganic fertilizers may be warranted in areas where soil nutrition is poor, leaching of minerals is high, and where a vigorous stand of wetland cover is desired regardless of species composition. In other instances, low fertility wetlands may be the project goal. The fertilizer application(s) may be made at the time of planting or seeding, during the several months subsequent to planting or seed germination, or in later growing seasons. Follow-up applications of fertilizers will enhance growth and vigor of wetland vegetation in most cases. Rates and types of fertilizer applied will be dependent on many factors including soil type, plant condition, mycorrhizal associations, climate, etc.

Regional and soil type differences may affect the vegetation response to fertilizer application. Blackmon (1974), for example, reports that gains from fertilizer application in bottomland hardwood species sites in Mississippi appear to be greatest in stands older than 2 or 3 years. His work suggests that young trees do not respond to fertilizer application until a stand begins to utilize its site fully and trees are able to compete with each other for nutrients. Francis (1984) indicated that fertilizer applications on stands established in old fields have a high probability of producing positive response. Sites that have never been cultivated, however, are less likely to respond to fertilizer.

Baker and Blackmon (1976) studied tree growth on eroded silty upland soils of Arkansas, Louisiana, and Mississippi sites, where they found that a broadcast application of fertilizer followed by discing significantly improved height growth in yellow poplar (*Liriodendron tulipifera*) during the first and second years following treatment. There was no response to a broadcast fertilizer application during the third or fourth years. When fertilizer was combined in a vertical mulch with sawdust, however, significant growth occurred during the second, third, and fourth years following treatment but with no growth responses during the first and fifth years. A vertical mulch is a method of applying fertilizer to trees by means of deep holes in the ground. In the Baker and Blackmon study, two holes that were 17.5 cm (7 inches) wide and 50 cm (20 inches) deep were placed on opposite sides of each tree and filled with a column of partially decomposed sawdust. A horizontal layer of fertilizer (i.e., at the rate of 0.4 kg of 13-13-13 per tree) was applied at the midpoints of the sawdust columns.

Deep placement of fertilizer particles into rice paddy soils by machine in the Philippines has shown promise in increasing the efficiency of fertilizer use, but performance has not been consistent (Khan et al. 1984). Bautista and Schnier (1989) reported a new method for mechanical application of liquid urea solution into rice fields. This method may have potential for use in wetland restoration projects.

## Mulches

Surface mulches protect a soil from direct sunlight and, as a consequence, reduce the loss of water due to evaporation, reduce sediment loss by wind, increase water infiltration from rainfall, decrease water runoff, increase total available water in the soil profile, and lower surface soil temperature during the summer months (Edwards 1992). Also, as organic mulches decay, organic matter and nutrient content of the soil is increased. Edwards (1992) has reported on trial studies in Alabama in which a mixture of soil, ground newsprint, and chicken broiler litter, applied as a surface mulch at a ratio of 50:40:10, resulted in dramatic increases in cotton production. This method may have promise for wetland restoration projects. Newsprint and chicken litter are both readily available in many sections of the country and may represent a potential source of low-cost organic mulch, but more studies are needed to assess potential environmental concerns (i.e., the fate of heavy metal and viral constituents).

### Need for Replacement or Supplemental Plantings

The need for supplemental plantings can be determined by either a general visual assessment or from detailed vegetation sampling. The methods of assessing the success of vegetation establishment are not well defined, nor are uniform standards available by which that success can be achieved. Normally, however, the relative success of vegetation establishment is based on a comparison of the project site with a reference area. Site factors that are evaluated include percent survival, growth, reproduction, height, percent cover.

Comparisons between project and reference sites involve comparative studies requiring vegetation sampling. Complete standardization of techniques for sampling vegetation is not available, and probably is not desirable, because no single method can satisfy all objectives. Techniques include quadrant (e.g., 1-$m^2$ plots, 10-$m^2$ plots, etc.) and transect (e.g., belt transect, line intercept transects, etc.) methods. An excellent reference for a variety of techniques suitable for sampling vegetation, however, is Chambers and Brown (1983).

Replacement of plants at a restoration site may be needed as a result of many factors, including but not limited to: wildlife depredation, debris deposits, erosion, vandalism, washing out, or other causes (Garbisch 1986). Plant replacement methods include the following:

- Reseed areas on which seeding still appears to be a viable method
- Use propagules other than seeds to replace unsuccessfully seeded areas
- Replace all dead plants with new transplant materials

## Control of Undesirable Plant Species

### Overview of control measures for undesirable species

Several categories of plant species are sometimes considered undesirable, and measures directed toward their control may be warranted following planting (Fredrickson and Reid 1988). The following categories include most exotic (i.e. introduced) species but also include many native species:

*a.* plants that quickly shift diverse systems toward monodominant systems (e.g., cattails, *Typha* spp.)

*b.* plants having minimal value for wildlife species (e.g., common reed, *Phragmites australis*)

*c.* plants that outcompete other plants considered to have higher value (e.g., cattails and common reed)

Possible control measures for undesirable species include burning, mowing, hand pulling or other mechanical removal of plants by their roots, and herbicide application. In general, each region of the country has a specific list of plant species that are of particular concern as undesirables. In some cases, these species are exotics and tend to be undesirable at any site of occurrence. In others, however, the species may be particularly aggressive native species having a tendency to form monodominant stands. A few species (e.g., cattails, *Typha* spp., and common reed, *Phragmites australis*) are wide-ranging and of potential occurrence throughout most of the country. Most of these species are of little value to wildlife, although cattails are preferred food for muskrat. Because these plant species sometimes play a role in the prevention of shoreline erosion, conflicting values should be evaluated carefully before totally eradicating the species. Table 7-10 provides a regional list of problem species.

**Table 7-10**
**Common Wetland Nuisance Plants**

| Scientific Name | Common Name |
|---|---|
| *Eichornia crassipes* | Water hyacinth |
| *Hydrilla verticillata* | Hydrilla |
| *Lythrum salicaria* | Purple loosestrife |
| *Phalaris arundinacea* | Canary grass |
| *Phragmites australis* | Reed |
| *Sali spp.* | Willow |
| *Typha latifolia* | Cattail |
| *T. domingensis* | Cattail |
| *T. angustifia* | Cattail |
| *Elaeagnus angustifolia* | Russian Olive |
| *Sapium* | Chinese fallow |
| | Brazillian pepper |
| *Casurina* | Austrailian pine |
| *Tamerisk* | Salt cedar |
| *Alternanthera philoxeroides* | Alligator weed |
| *Spiraea douglasii* | Douglas spiraea |
| *Ranvnaulus repans* | Creeping buttercup |
| *Juncus effusus* | Soft rush |
| *Cytisus scoporius* | Scot's broom |
| *Lysinachia terrestris* | Yellow loosestrife |
| *Iris pseudoacorus* | Yellow iris |
| *Spartina alterniflora* | Saltmarsh cordgrass |
| *S. anglica* | |
| *S. patens* | |
| *S. townsendii* | |

The best method to remove common reed from a site is probably through the use of herbicides. Physical control methods, such as mowing, discing, and burning, have been found to facilitate its spread and propagation. It also can be controlled by cutting stems at ground level followed by long-term flooding.  For specific information on control of common reed, see Garbisch (1986).

Very few native species have the ability to adapt to the complex of stress factors resulting from a major encroachment of weedy species into a wetland system due to effluent-derived nutrients.  Such factors need to be considered when designing a wetland system or when incorporating effluent into an existing wetland (Mandel and Koch 1992).  In prairie pothole restoration, unmanaged wetlands may be invaded by species such as cattails and common reed, which often form monotypic stands that are of little value to a diversity of wildlife species. Methods used to manage prairie pothole vegetation include the use of artificial drawdowns, prescribed burns, limited mowing, or light grazing to regulate successional trends (Thompson 1992).

Finding an effective method to control competing vegetation, especially weedy grass species, is considered critical to the successful establishment of tree seedlings in restored riparian wetland projects in the Midwest.  Several potential methods for controlling weed populations in these wetland restoration projects, e.g. mechanical cultivation, mowing, mulching, and chemical control, are detailed in Thompson (1992).

## Importance of weed control

A weed is here defined as any plant that is not valued at the site where it is growing.  Weed control may be the most critical vegetation maintenance activity required on many sites.  A few trade-offs need to be considered when using any weed control method.  In general, weed control reduces percent cover values.  Selective weed control usually has little effect on seedling damage caused by rodents and rabbits.  The elimination of all competing vegetation cover at a site, however, may increase seedling damage caused by wind and water.  Weed control is considered necessary in Midwest forest restoration projects only when the seedlings' exposure to sunlight has been eliminated (Thompson 1992).  In some forest restoration projects in the South, however, the presence of weedy vegetation has been thought to be advantageous in the reduction of damage to seedling transplants of woody species by beaver.

In Iowa forest restoration projects, weed control is considered important during the first three to five years following planting or until such time as the woody seedlings have reached a sufficient height or density to eliminate competition.  Several methods, including mechanical cultivation, mowing, mulching, and chemical control, may be used to limit weed growth in restoration of forested wetlands (Thompson 1992).  Other vegetation maintenance activities besides weed control are sometimes used on forested wetland restoration sites, including pruning, thinning, replacement plantings, and pest control.

The best time to kill weeds is when they are young, and most weeds are easily controlled at that time.  A continuously moist soil will often require more frequent cultivation or treatment for weed control than a continuously dry soil (Edmond et al. 1957).

## Prescribed fire

Prescribed fire has been used to reduce the dominance by woody plant invaders, control exotic species, and increase plant species diversity (Van Horn et al. 1994). Prescribed fire has the potential to injure or kill vegetation of any kind, however, with the degree of impact controlled by plant characteristics, fire type and behavior, topography, wind speed, temperature, length of exposure, and season (USDA Forest Service, Southern Region 1989). Natural fires also are of significant value in some parts of the country.

The value of prescribed fire in managing vegetation varies according to region and vegetation type. The incidence of natural fires in the South may be lower in marshes constructed on reclaimed mine sites than in natural pine flatwoods or palmetto prairies, and prescribed burning may be a desirable technique to prevent these marshes from succeeding to thickets or swamps (Clewell 1984). A wetland type in which prescribed burning is not desirable, however, is the wet meadow (Murn 1993). Too little information is available to establish a protocol for the use of prescribed fire in prairie marshes of the northern glaciated region (Thompson 1992).

Prescribed burning is a potentially useful tool for vegetation maintenance, but it must be recognized that fire is indiscriminate between the native and introduced plants on a site. Fire is advantageous in those wetlands where the native plants recover more rapidly than the introduced or weedy species. It is particularly applicable to wet to wet-mesic prairies where prairie species have evolved under a regime of fire. The initial use of fire for weed control, during the first two or three growing seasons, can speed the establishment of many prairie species. After initial maintenance, prescribed burning can be used to control invasion by woody plants and to control weeds. For more information on the benefits of prescribed burning for weed control and for controlled burn protocols, see Thompson (1992).

Prescribed fire can be a useful tool to alter plant community structure or composition (e.g., increase grasses, decrease forbs), reverse or alter successional trends, reduce or eliminate accumulated dead plant material, restore hydraulic capacity, and modify animal populations (Hammer 1992). Van Horn et al. (1994) list the fire parameters which are ideal for woody plant control in Florida; they include heavy fine fuels, low target plant reserves, high ambient temperatures, and a head fire with winds of > 8 kph. They recommend mechanical control a few months prior to burning on sites having shrubs with a percent cover value of > 30 percent or where their average height exceeds 1 m. To produce a diverse plant mosaic, they recommend burning with wind speeds < 8 mph, fine fuel moisture > 15 percent and spot ignition.

The following generalizations apply to the use of fire in maintaining target species composition and diversity:

- Fire is helpful in controlling dense stands of many emergent species (e.g., cattails and common reed).
- Only a portion of a wetland should be burned at any one time.

- Fall burning of emergent cover of seasonally ponded basins in colder parts of the country, in the absence of water level control devices, reduces the wetland's ability to trap snow and may shorten periods of standing water in the following year.

## Mowing

The benefits of mowing include a reduction of weeds and weed seed production, exposure of remaining native seed to heat and light so that maximum germination is attained, and control of invasion by woody plants having the potential to lower light intensities and outcompete species requiring high light intensities.

Mowing is a good option for the management of wet meadows (Murn 1993), for meadows established on the drier aspects of stormwater detention basins, and for controlling competition between fast-growing weed species and slow-growing climax tree seedlings in riparian forested wetlands (Scheuler 1994). Annual mowing is required, either in the fall if maximum seed dispersal is the intention, or in late winter if maximum wildlife cover is the goal.

Meadow vegetation should be cut to a height of 10 cm (4 in.), and mowing equipment with the potential for minimal soil compaction should be used (Murn 1993). This type of mowing equipment is seldom available commercially .

Mowing with a flail-type mower, which generates a readily oxidized litter, which has been set to cut weeds above the height of the prairie plants (15 to 30 cm or 6 to 12 in.) or mowing and removing the mulch (i.e., haying) in late June or early July of the first year and again in May and/or June of the second year has been recommended as a method to maintain prairie plantings in Iowa. The techniques for prairie vegetation maintenance recommended by Thompson (1992) are based on the fact that growth and establishment of prairie plant species is largely underground in the first season or two, allowing repeated mowing for weed control without adverse impacts to immature prairie species.

Mowing is the least desirable method of weed control in forested wetlands, because of the high potential for damage to tree seedlings and failure to control competition from other plants at the root zone. Mowing around seedlings is recommended when combined with chemical treatment or mulching. Control of competition by mulch application, however, is probably practical only on small plantings. Mowing eliminates the protective cover for small animals having the potential to girdle tree seedlings during the winter months and makes seedlings easier to locate for monitoring purposes (Thompson 1992).

## Bushhogging

Bushhogging appears to have potential value for controlling weeds around direct seeded oaks in forested wetland restoration projects in the South, although apparently few land managers have used the method. One research trial indicated that bushhogging around seedlings improved seedling survival and growth by a reduction in the amount of competing vegetation. Competition was not totally eliminated, but the reduction in competition appeared to favor oak development.

Most studies have attempted to effect competition control in natural stand openings only after the oaks reached heights of 5 to 7 m (15 to 20 ft), which may be reached in 10 to 15 years after planting. This is the normal time at which individual oaks are released from competition by deadening or cutting competing trees. When individual oak trees are released earlier than this, the stand often reverts to a vine stage or releases sprouts from stumps of cut competitor species to regain dominance over the oaks (Johnson and Krinard 1987).

Johnson (undated) reports little need for post-planting weed control in bottomland hardwood plantings on old fields in the South. For that wetland type, he recommends no weed control measures for any species other than cottonwood. Bushhogging once or twice a year, where it can be practiced, induces early growth for most tree species. Five years is needed to get the trees above most competition in the absence of weed control.

## Cultivation

Mechanical removal of aggressive weedy and grass species is a relatively expensive but effective control measure. Mechanical methods are typically more expensive than some other methods because they are labor-intensive. Weed control can be accomplished by cultivation with a hoe (i.e., scraping the top 8 cm (3 in.) of soil and replacing it with topsoil).

Mechanical cultivation to control weeds also can be accomplished with a row cultivator, spring-tooth harrow, or other tractor-drawn device on sites where exposed soils are not subject to excessive erosion from wind or water. When using one of these tractor-drawn devices, a distance of 15 to 30 cm (6 to 12 in.) should be maintained between the blades and the seedlings. Cultivation should be to a depth of only about 8 cm (3 in.) and may need to be repeated 3 to 5 times per year for the first 5 years in hardwood wetlands (Thompson 1992).

The first and second cultivations of any given site are usually relatively deep. Succeeding cultivations should be relatively shallow and should proceed at a greater distance than 15 to 30 cm (6 to 12 in.) from the plants to avoid cutting the feeder roots just beneath the surface. For more information on cultivation, factors to consider for cultivation, and benefits and drawbacks of cultivation, see Edmond et al. (1957).

## Hand weeding

Hand weeding is a useful technique for control of weed species on very small prairie restoration sites. Hand weeding usually is not required for more than the first year or two (Thompson 1992).

## Light grazing

Periodic light grazing by livestock has the potential to increase species diversity and create structural diversity in prairie potholes. Grazing in fens, however, has the potential to destroy substrate properties and severely impact both plant and animal populations (Thompson 1992).

## Herbicides

Transplant survival, particularly survival of planted seedlings, is significantly affected by competition from weeds, drought, and animal predation in riparian forest buffer zones (Scheuler 1994). An effective method of control against weed competition is the use of herbicides. The land manager has numerous types of herbicides available for use, all of which are designed to injure or kill plants. Many herbicides are very selective in their action (e.g., Poast[R] eliminates grasses but not sedges; Velpar[R] kills broadleaf weeds but not grasses, etc.). Thus, a vegetation control program for a wetland restoration project may require several different herbicides (e.g., 2,4,-D, Roundup[R], etc.). Herbicide selection should also consider persistence in the environment and the manner of movement through soil and water. Herbicides having short half-lives are generally safest and most desirable. Chapter 7-2 provides more detailed information about herbicide utilization and selection. Before using any herbicides, however, check with an appropriate agency to make sure the selected herbicide has been approved for use in aquatic or wetland systems.

Weed control by herbicide application in wetland restoration projects must be approached with extreme caution. Precautions should be taken to narrowly confine the spray and to prevent drift from the area of desired effect. Removal of all competing vegetation around seedlings can be accomplished by ground herbicide applications in bands or strips of approximately 1 m (3 to 4 ft) wide and is recommended for use until canopy development has eliminated competition by weedy species (Thompson 1992).

Generally a pre-emergent herbicide is applied in early spring followed by additional post-emergent treatments, as necessary, for weed control in forested wetlands. The herbicide to be used is dependent on the type of vegetation that must be controlled (e.g., grasses, broad-leaved weeds, or woody plants). Herbicide treatment is one of the best, if not the most effective, methods of control for undesirable woody vegetation. Appropriate herbicides are available from most distributors of agricultural supplies and are labeled for use with broad leaved or coniferous trees. Methods of herbicide application include foliar application, stump application, or ground application of granules beneath unwanted vegetation (Thompson 1992).

## Mulching for weed control

In forested wetland restoration projects, mulch applications for weed control are probably impractical except in small-scale plantings (Thompson 1992). Chapter 7-2 provides additional information on mulches. Common types of mulches include sawdust, wood chips, bark, plastic, paper, straw, and compost.

## Control of Surface Debris

Litter and other deposits of surface debris, including sediment deposits, can kill transplants or seedlings unless removed promptly (Garbisch 1986). There are two general solutions to this problem:

- Exclude litter from the site

- Collect and remove litter from the site

## Maintenance of Site Topography and Hydrology

Maintenance of site topography is closely related to a site's erosion potential. Erosion typically is not a major problem on sites having high vegetation cover values. Any maintenance activity that promotes vegetation cover, therefore, will assist in maintenance of site topography.

Many of the erosion control techniques discussed in Chapter 7-2 are also applicable to a site after vegetation is established. The techniques discussed here have been found beneficial for treating erosion control problems. Some effective treatments include the following:

- In warm southern climates, vetiver grass (*Vetiveria* spp., especially *V. zizanioides)* planted in rills and gullies to slow down runoff and trap sediments (National Research Council 1993)

- Use of bioengineering techniques, including the installation of fiber plant carpets consisting of fiber blanket (jute mesh) planted with wetland plants (Allen and Klimas 1986; Cowan 1993)

- Use of rock, sandbags, cement bags, etc. as devices to reduce localized surface runoff

The manipulation of water levels in wetlands (i.e., both drawdown and flooding) is used to manage seed production, germination, and succession of selected wetland species. Timing (e.g., late spring drawdown), extent, and duration of drawdowns and flooding will depend on the hydrology and the desired species composition of the wetland or management objectives. Properly timed drawdowns, for example, can promote germination, stimulate growth, retard growth of invasive or exotic species, and significantly reduce the amount of revegetation and the labor required for revegetation (Warburton et al. 1985).

Drawdowns are particularly important to the germination of annual mudflat species such as *Cyperus erythrorhizos, C. flavicomus, Fimbristylis autumnalis,* and *F. vahlii*. For more information on the effects of timing of drawdown on germination and growth of these mudflat species see Baskin et al. (1993). In nontidal projects, water levels should be maintained well below the top growth of the seedlings during their development (Garbisch 1986). For more information on standard wetland habitat management, techniques and recommendations for water level manipulations see Fredrickson and Taylor (1982); Linde (1969); and Weller (1978).

## Damage by Wildlife and Waterfowl

Impacts on vegetation by wildlife and waterfowl can be of serious consequence. Control measures should be used at new planting sites where the potential for animal damage is high.

Potential control methods include fencing the site to exclude animals, trapping and removing animals, locating the site at a sufficient distance from problem species, and planning the project to avoid a known pest problem.

Waterfowl (e.g., Canadian geese) and small mammals (e.g., muskrats) sometimes consume large quantities of marsh and aquatic plants but seldom do permanent damage to established stands. Many of these animals can be serious problems, however, with new plantings (Kadlec and Wentz 1974). Canada geese (*Branta canadensis*), ducks (Scheuler 1994), and other waterfowl are known to cause significant depredation through grazing and uprooting of plant materials. Muskrats (*Ondatra zibethicus*) feed extensively on both stems and underground tubers (Warburton et al. 1985) and can compromise the integrity of earthen berms and levees.

Larger animals, such as beavers, can have devastating effects on both new and established vegetation. Also, beavers have the potential to adversely affect project success through alteration of site hydrology. Damage by deer and blackbirds to grain-producing species, such as Japanese millet (*Echinochloa crus-galli*), has also been well documented (Linde 1969).

In general, wildlife species tend to concentrate on isolated plants or individual clumps of vegetation rather than impacting a uniform stand of vegetation. Denudation of vegetation by wildlife depredation can be minimized by rapidly establishing a uniform ground cover at the site. Exclosure of wildlife from newly planted areas by fences may be needed as a means of reducing or eliminating depredation by wildlife (Garbisch 1986; Warburton et al. 1985). See Allen (1990) for an effective geese exclosure design.

Acorns have been treated with various repellents in an attempt to prevent rodent predation and damage in bottomland hardwood restoration projects in the South, but their use has generally resulted in little actual control of depredation. Johnson and Krinard (1987) report that the presence of large openings (250 $ft^2$) within the forest canopy helps to reduce acorn depredation by rodents.

Wildlife and feral animals (e.g., hogs and horses) can destroy newly planted vegetation or alter normal successional patterns by excessive grazing, trampling, or uprooting. These various pressures vary among regions and wetland types. Some trade-offs may need to be evaluated when considering whether control of grazing is desirable. For example, cattle grazing is known to affect dominance patterns, species composition, and biomass of restored marshes on reclaimed Florida mine sites, but grazing is beneficial in preventing the growth of woody thicket-forming species, such as willow, *Salix* spp. (Clewell 1984).

Consult a state wildlife agency for local information on potential problem animal species, control methods, and regulations related to wildlife species.

## Control of Plant Diseases and Insect Pests

Most plant diseases are caused by microorganisms (e.g., fungi, bacteria, and viruses), with fungi being of greatest significance. An individual plant may exhibit susceptibility, tolerance, resistance, or immunity to a specific disease. Various diseases affect plants in different ways.

Some diseases (e.g., dollarspot) only weaken plants, whereas others (e.g., *Fusarium*) will kill them. Some diseases infect only the leaf, and others infect only the stem, crowns, or roots. Some diseases are long persistent while others disappear with a change in weather conditions (Environmental Laboratory 1986).

Climate is a major factor in the prevalence of diseases and their control. In regions with high humidity and other stress factors, incidence of disease will be higher than in regions of low humidity and dry weather (Environmental Laboratory 1986).

Diseases are often secondary stresses induced by a previous environmental stress form such as unfavorable light, temperature, or moisture. Each plant has an optimum, minimum, and maximum set of environmental conditions under which it can grow (Environmental Laboratory 1986).

More than 850,000 insects have been identified throughout the world, and many are detrimental to good plant growth. Insects generally have a short life span, but also have the capability to reproduce at phenomenal rates. Populations of insects may flourish and then diminish as natural predators develop, food supplies become limited, or as extremes in climatic conditions reduce their numbers. Insect damage to plants is sometimes incorrectly attributed to disease, drought, or malnutrition (Environmental Laboratory 1986).

Contact your local Extension Service office for information on problem diseases and organisms and methods for their control.

## Control of Mosquito Population Levels

Almost any kind of wetland has the potential to support a mosquito population, although the particular species, population size, and associated public issues vary with wetland type and region of the country. In some areas, mosquito control programs are in place for disease control, and in others the primary concern is for public contentment and freedom from irritation. Local zoning ordinances place restrictions on wetland restoration projects in some parts of the country, because of the potential for mosquito problems (Hammer 1992).

Control measures suitable for many project sites include the following (Hammer 1992):

- deep flooding in the spring season to strand floating debris
- repeated dewatering to prevent metamorphosis of larvae into adults (i.e., on 5-day intervals)
- elimination of stagnant backwaters having no or limited connections to the main pool
- shading the water surface
- use of mosquitofish (*Gambusia affinis*) for control of larvae

- careful monitoring

- elimination of floating mats of *Lemna*, *Spirodela*, or other floating species

- implementation of bacterial control agents (e.g., *Bacillus thuringiensis*, *B. sphaericus*)

- as a last resort, chemical control (i.e., insecticides)

A number of simple and inexpensive mosquito prevention measures should be considered for wetland projects in areas where minor mosquito populations may create community problems. Basically, these control measures involve identification and elimination of any structure or object having the potential to hold water and serve as a mosquito breeding site. These potential breeding sites include hollow stumps, discarded cans, bottles, and tires, wooded depressions, etc. Elimination of these potential sites of standing water, in combination with appropriate design factors, minor vegetation or water level management, and the presence of mosquitofish, may provide effective and adequate mosquito control. For more serious mosquito problems, the services of a vector control specialist may be warranted (Hammer 1992).

## Checking and Maintenance of Fences

Exclosure fences should be maintained on a regular basis to ensure their integrity and effectiveness in eliminating human and/or wildlife impacts from the site.

## Re-firming Plants Loosened by Wind or Freeze Damage

The stems of plants that are not yet well established may be buffeted by winds, resulting in loosened root systems and causing the plants to lean. This problem is exacerbated by wet soils. Similarly, in areas of the country marked by extreme cold, root systems of plants are often loosened or raised above the surface by alternate freezing and thawing of the soil. In both cases, plants should be examined closely to see if they need to be re-firmed into the soil.

## Pruning or Removal of Dead or Diseased Plant Parts

Dead or diseased plant parts should be removed to discourage a proliferation of fungi or other disease organisms. Also, pruning or removal of these dead or diseased plant parts often stimulates the plant to produce new stems to compensate for the damage.

## Control of Vandalism

Plants may be lost to vandalism, particularly in urban or remote areas. There is probably no foolproof control method for vandalism, but the following measures may reduce the problem:

- erect signs
- engage the assistance of community leaders and organizations in trying to find solutions to a reduction in vandalism
- use the media to make people more aware of the purposes and values of a project's success
- placement of a log barrier network to prevent ORV access and use of the project site (Cowan 1993)
- contact local police or other law enforcement officials

## Assessment and Repair of Fire Damage

Fire has the potential to injure or kill vegetation of almost any kind. Whether or not a plant is injured or killed depends on plant characteristics, fire type and behavior, topography, wind speed, temperature, length of exposure, and season. Young, succulent, and actively growing vegetation is especially vulnerable, and damages/losses are generally greatest for seedlings or sprouts of any species. Damage from a severe burn is usually evident soon following the fire, but determination of the potential for recovery may not be evident until several weeks or months following fires of lesser magnitude (USDA Forest Service 1989).

# 7-6 Soils Handling Methods and Equipment[1]

Soils handling occurs when soil is to be excavated, removed and/or placed at a wetland restoration or creation project site. Throughout this chapter the term *soil* is used in the engineering sense, i.e., the unconsolidated, weathered rock fragments (regolith) forming the entire soil profile, from the ground surface down to contact with solid rock, and refers to either the organic topsoil or the underlying parent material or both.

When soils are to be handled, the earthwork is generally done in four phases:

*a. Excavation.* Soils are excavated (dislodged) at a wetland site to loosen them in preparation for removal or to aerate them for increasing the permeability to enhance plant growth.

*b. Removal.* Excavated soils are removed from their in situ location to decrease the existing grade, or elevation, of the ground surface at a specific location and/or for use as a fill material.

*c. Transport.* Excavated and removed soils are transported from the excavation area to the disposal area. This may be done mechanically (land haul) or hydraulically (pumped as a slurry).

*d. Deposition.* The excavated, removed, and transported soil may be deposited in a disposal area, may be placed in storage, or may be used in a fill. In the ideal cut and fill situation the amount of excavated soil is equal to, or balances, the amount of fill soil needed nearby because of the cost of transporting soil over long distances.

Equipment for this work may use either mechanical or hydraulic methods, or some combination of the two. The following discusses methods and equipment suitable for each phase of soil handling and criteria for selection among feasible alternatives.

There are several reference sources that should be consulted for more detailed information on soil handling methods and equipment than is presented here. The book by Peurifoy and Ledbetter (1985), *Construction Planning, Equipment, and Methods*, is an up-to-date text for land-based construction. F. H. Kellogg's (1954) *Construction Methods and Machinery*, although containing somewhat outdated equipment descriptions, presents many useful insights into land-

[1] By S. Joseph Spigolon

based construction. *Moving the Earth*, by H. L. Nichols, Jr. (1955), presents descriptive material written for the earthmoving contractor. Scott and Andres' (1986) *Principles and Practices of Heavy Construction* contains concisely presented useful information.

## Equipment Carriers -- Work Platforms

Self-propelled equipment for soils handling will be supported on one of three types of working platform: (a) crawler (track-laying), (b) rubber-tired wheels, or (c) floating. As shown in Table 7-11, each type has advantages and limitations.

**Table 7-11**
**Work Platforms for Self-Propelled Equipment**

| Platform | Advantages | Limitations |
|---|---|---|
| Crawler mount (track laying) | 1. High tractive effort, especially when operating on soft, loose, or muddy soil. 2. Can travel over muddy surfaces and/or rocky formations.<br>3. Can travel over rough surfaces, reducing cost of making and maintaining haul roads.<br>4. Less rutting and greater flotation because of low track pressure. | 1. Slow speed, as low as 1.6 kph (1 mph) when supporting cranes.<br>2. High operator fatigue because of lever operations. Maneuverability is slow.<br>3. Can damage paved roads.<br>4. Requires road transport (low boy trailer) to move on to job site. |
| Rubber-tired wheels | 1. High movement and travel speeds.<br>2. Hauling equipment not needed to move on to a new job site.<br>3. Low operator fatigue.<br>4. Can travel on paved roads without damaging surface. | 1. Low tractive effort in soft or loose soil.<br>2. Does not travel well in very soft or rocky terrain.<br>3. Requires smooth surfaced haul roads.<br>4. Contact pressure of wheels is high, causing rutting in all soft or loose soils. |
| Floating | 1. Can be used when there is as little as 0.6 to 1.0 meter (2-3 ft) of water depth.<br>2. Small units are highway and helicopter transportable.<br>3. Environmentally desirable. Does not leave tracks or ruts. | 1. Requires constant source of water for flotation and for slurry transport.<br>2. Requires pipeline for transport. Pipeline usually must be relocated frequently. |

## Soil Excavation and Removal

*Excavation* is the loosening or dislodgement of individual material grains or a cohesive aggregate of particles from their in situ position. *Removal* involves moving the excavated material from its in situ location. Excavation without removal is accomplished by plowing or sub-soiling. In soils handling, the *excavation process* invariably includes the dislodgement of the soil and its removal by either (a) movement in some sort of transport device or (b) movement of the soil along the ground surface by scraping and pushing to another location.

Excavation is classified as wet or dry excavation. *Wet excavation* involves dislodgement and removal of material from below water level. This is usually done by dredging methods and equipment. In addition to hydraulic dredging equipment, all of the crane-mounted equipment described below, including backhoes, clamshells (grabs), and draglines, can be barge mounted to allow scooping excavation of underwater soils. *Dry excavation*, done by land-type equipment, may actually include saturated clay or sand if no major problem of handling water is involved.

In the construction industry, excavation is classified as machine excavation or grading. *Machine excavation* means the use of heavy machinery for large-scale excavation and removal. This is sometimes referred to as *rough grading*. Because it is difficult to end up with a smooth surface to the desired final grade using high-production equipment, the last few centimeters (inches) of excavation are done by scraping, a process called *fine grading*.

## Sources of material to be moved

The soil material to be moved at a wetlands site may originate at any one of several sources:

*a.* *Onsite excavations.* When site grading (decrease in elevation) is required as part of a modification plan, or material is needed for fill, the excavated material must be removed and transported to a deposition site for disposal, storage, or fill.

*b.* *Offsite borrow pit.* When there is not sufficient soil available from onsite grading, or the quality of the available soil is not acceptable, an offsite source of material must be developed.

*c.* *Commercially supplied, specially manufactured materials.* Materials having special plant growth qualities not available naturally at the site may be purchased and delivered and temporarily stored at the project site. The materials must then be picked up, transported, and deposited at the desired locations.

*d.* *Mixed materials.* Materials from on- or offsite may be mixed in temporary storage locations or at fill sites to produce a soil of the desired composition and properties. As an example, a high plasticity (fat) clay may be made more friable and more easily compacted if it is mixed with lime.

## Mechanical excavation methods and equipment

Equipment for mechanical excavation is used for loosening or dislodging soil. It is accomplished by one of several processes:

*a.* *Cutting or ripping.* This includes such devices as plows, subsoilers, and rippers. The objective is to simply loosen the soil, without removal, to (a) increase plant growth potential by increasing aeration and/or permeability, or (b) to make removal easier.

*b.* *Scraping and pushing.* For fine grading, a motor grader or a tractor with a dozer blade may be used to scrape soils and move them by pushing along the ground surface. Tractor-mounted bulldozer blades are also used extensively in land clearing operations, preparatory to placement of a dike (see discussion of dikes in a later section).

*c.* *Scooping or digging*. When removal of the soil is required, scooping or digging equipment is used to remove the soil to a transport device. Scooping equipment includes front-end loaders, loader-scrapers, power shovels, backhoes, clamshells (grabs), and draglines.

**Cutting or ripping equipment.** Virtually all equipment used for loosening soil to a shallow depth is common agricultural equipment. This includes plows, harrows, discs, and ripper-type subsoilers. The deep soil loosener shown in Figure 7-4 is, in effect, a series of thin vertical blades drawn behind a tractor. The blades are inclined in the pulling direction and are held in vertical position. The net effect is one of loosening or swelling the soil by 20 to 30% without creating a furrow, resulting in aeration and increased permeability to a depth of up to 1 meter (3 ft) or slightly more. This device works best in fairly dry, friable soils.

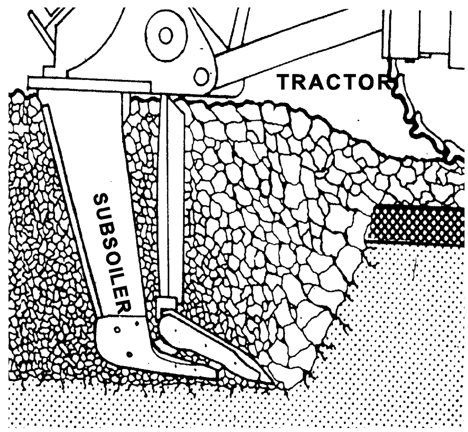


Figure 7-4. Deep soil loosener (agricultural subsoiler).

**Grading and land clearing equipment.** Grading equipment uses a blade, mounted transverse to the line of travel, that causes a scraping and pushing of the soil. Typical grading equipment includes (a) the self-propelled, or motor, grader (Figure 7-5) and (b) the tractor with a bulldozer blade (Figure 7-6).


Figure 7-5. Self-propelled grader (motor patrol).

On the *motor grader* the blade is mounted between the front and rear wheels. This unit is designed for fairly high speed, light grading work such as road maintenance, slope smoothing, and mixing of materials. Much better mixing can be achieved, however, by a pair of disc harrows drawn by a tractor.

A dozer blade may be mounted in front of a crawler-mounted or wheeled tractor, as shown on Figure 7-6. A crawler-mounted machine has an advantage on short hauls with soft, muddy ground and the wheel-mounted unit has the advantage on longer hauls and firm ground. The term bulldozer is commonly used, even though the bull blade may be exchanged with an angle blade (angle dozer) or any of the other special blades that are available for land-clearing operations.

When used for land clearing, the tractor-mounted bulldozer or special blade is indispensable. Land clearing includes removing trees and stumps, removing and moving above-ground vegetation, and scarifying the ground to remove roots.

Figure 7-6. Bulldozer blade mounted on crawler tractor.

**Front-end loaders.** If the crawler- or wheel-mounted tractor is fitted with a shovel or bucket blade mounted in front, the *front-end loader* can scoop (dig) and then pick up the excavated material, as shown in Figure 7-7. Although the major function of a front-end loader is loading excavated material onto trucks, it is a versatile machine that can be used for excavating, hauling short distances, and even for fine grading.

Figure 7-7. Wheel-mounted front-end loader.

**Loader-scrapers.** The *loader-scraper* is a machine that combines the functions of scraping (excavating), loading, hauling, and discharging. The large container body has a scraper blade at the bottom so that the scraped soil enters the storage area as the device is pulled forward. It is used primarily when there are large volumes of soil to be moved from large areas. The loader-scraper may be towed by a crawler tractor or by rubber-tired wheeled tractors, as in Figure 7-8. The crawler tractor has good traction in soft ground, but is a relatively slow mover. The wheeled tractor, which may need the assistance of a pusher tractor during loading, can travel at speeds of 65 kph (40 mph) or more on relatively smooth, firm surfaces.

Figure 7-8. Wheel-mounted loader-scraper.

**Power shovels.** The *power shovel* is a crane-mounted machine with a forward-acting scoop. Shovels are used mainly to excavate soil and load it onto trucks or other containers or onto a nearby storage pile. Power shovels may be mounted on crawler tracks or on wheels at the rear of a truck or tractor. A power shovel is intended to operate against a face or bank, which it excavates and removes by upward motion of the shovel as it slowly moves forward. As a result, it cannot dig very far below the supporting ground surface.

The crawler-mounted unit has a very slow travel speed, often as slow as 1.6 kph (1 mph), and can be fitted with wide tracks for low ground pressure on soft ground. Crawler units cannot travel on roads because of their slow speed and the damage the treads do to the surface. Truck-mounted cranes generally have a much lower digging power because of lesser traction at the wheels. However, a truck-mounted unit can operate over paved or firm soil roads at reasonable speeds, and can move to various parts of a project rapidly.

**Backhoes.** The *backhoe* is similar to the power shovel except that the bucket is reversed. It digs by pulling toward the crane power unit rather than away from it as the power shovel does. The linkage of the crane arm and dipper is designed to dig below the grade of the support unit, remove the material, and load it onto a transport unit.

Figure 7-9. Backhoe mounted on farm tractor.

Backhoes can be either crawler- or wheel-mounted. When wheel-mounted, they can be an integral part of a small unit, such as a small farm-type tractor, as in Figure 7-9, or be mounted on the rear of a prime mover such as a truck. The small, integral units can dig as much as 3.6 to 4.3 meters (12 to 14 ft) below support grade. The larger crane-rigged units can reach up to 9 meters (30 ft) below grade. These units can be of particular benefit on a wetlands site because of their versatility for clearing ditches and watercourses, excavating in an area with a high water table, cutting and grading slopes, and generally any excavation and removal from below grade.

**Clamshells (grabs).** A crane with a long boom can have a hinged bucket, called a *clamshell*, attached to the end of the line. The value of such an arrangement is its ability to excavate vertically below ground level, and even below water, and for handling bulk granular soils. Clamshells may be either wheel- or crawler-mounted, or loaded on a barge, as with other crane-operated units.

The hinged bucket is open until it is lowered into contact with the material. The clamshell bucket is made of two opposed scoops, hinged at the center. The tagline is tightened and the clamshell bucket closes as it is retrieved, picking up the loose material. The crane is then swung to the deposition area where the process is reversed, the tag line is loosened, bucket swings open, discharging the material. The digging power of the bucket is due only to its own weight and is, therefore, limited by size.

**Draglines.** When a crane is fitted with a *dragline* bucket, Figure 7-10, and the supporting line is slackened, the bucket can be cast a substantial distance horizontally. As the dragline bucket rests on the ground, the cable is on top and opening is on the side, toward the crane. The lower edge of the opening is the cutting blade. The dragline is operated by pulling the bucket toward the crane, filling the bucket. The depth of cut is regulated by the tension on the lifting cable.

Figure 7-10. Crawler-mounted dragline.

The dragline is capable of operations that cannot be done by any other excavating machine. The crane unit can remain on firm ground, or on a barge, and dig below and away from its position. Because it casts rather than places, the dragline deposits cannot be located as accurately as with other excavating devices. However, the casting ability makes it possible to dig materials that are too soft or loose to support the machine.

## Hydraulic (dredging) excavation methods and equipment

Small, transportable dredging machines are available that use a rotary cutterhead or a transverse auger to excavate and use hydraulic suction to remove the soil-water slurry to the surface. Hydraulic slurry systems require large quantities of water and are generally (but not necessarily) mounted on floating platforms, such as barges or self-propelled vessels.

Figure 7-11 shows a small-sized, transportable dredge with a conventional rotary cutterhead. The cutterhead arm can be lowered to the bottom where the blades cut by rotary action. The dislodged (excavated) material is then suctioned to the surface by the on-board pump and then discharged into a pipeline or other disposal system.

Figure 7-11. Small rotary cutterhead dredge (Courtesy of Ellicott Machine Corp.)

Figure 7-12 shows a road-transportable dredging unit with a horizontally mounted cutter head. Similar units use horizontal augers for cutting.

Portable dredges of this type range in weight from 3,600 to over 9,000 kg (8,000 to over 20,000 lb). They can operate in fairly shallow water. Operating drafts range from 0.38 to 0.56 meters (15 to 22 inches), depending on weight.

All that is needed for operation is sufficient water for flotation of the dredge and water for slurrying and moving the soil. The water can exist as a stream, a pond, or a specially created pool at the excavation site with sufficient dredge water pumped in to permit operation.

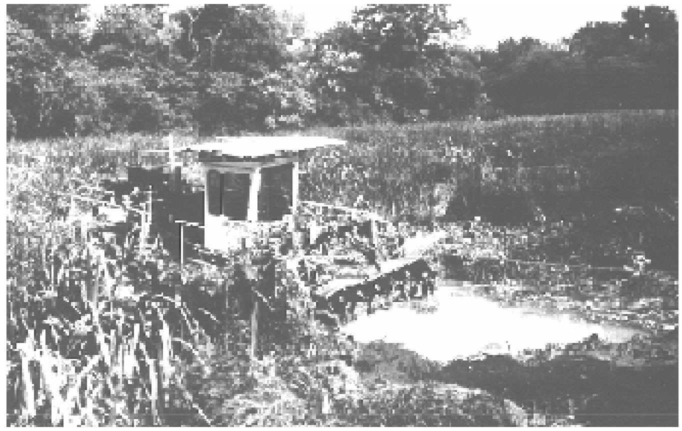


Figure 7-12. Dredge with horizontal cutterhead (Courtesy of Innovative Material Systems, Inc.)

## Transport of Excavated Material

The movement of the excavated and removed soil to the deposition location may be done in a number of ways, including (a) pushing or scraping (grading), (b) casting from a dragline bucket, (c) hauling, using containers such as a land-based loader-scraper, truck, or conveyor belt, or floating equipment such as a bottom-dump barge, and (d) hydraulic pipeline, by pumping a slurry of soil particles, clumps of material, or clay balls.

Conventional wheeled transport is normally done on prepared roadways, although any firm, smooth soil surface can usually be used. Trafficability of the excavation site and of haul roads will determine the necessary type and contact pressure of the hauling equipment. In a wetland, the creation of a roadway or travel path on the surface may not be suitable because of environmental damage to the site or simply the lack of a firm, dry surface. Where soil is to be moved over an environmentally sensitive wetland location, a temporary conveyor belt system can move the soil from the borrow area to a deposition area economically and with minimum damage to the site. If the soil is excavated by hydraulic dredge methods, then a pipeline may be the only feasible transport method.

### Mechanical transport methods and equipment

Mechanical transport systems include all those methods in which the soil being moved is at or near its natural moisture content, i.e., without added water. Mechanical transport methods include grading, dragline casting, hauling, and conveying on a belt. Hauling methods use equipment such as loader-scrapers, front-end loaders, trucks and wagons, and bottom-dump barges.

**Grading transport.** Motor patrols and bulldozers (tractors with dozer blades), as discussed above, move shallow cuts of soil as part of grading operations. If a grader or bulldozer is used for moving soil, the feasible haul distance is generally less than 100 meters (300 ft). The amount of soil that can be moved in this manner is small for the effort of moving the machine itself and is, therefore, not economical for large volumes of soil.

**Dragline casting.** Excavation with a dragline bucket, although not as efficient as excavation with other types of equipment, has the advantage that the bucket and its contents can be cast into locations where the equipment cannot go. The crane may be resting on firm ground, but the deposition area may be a short distance away at the top of a mound of soil, under water, or on a very soft foundation. Because of the swing of the bucket, the precision of the dump depends greatly on the skill of the operator.

**Loader-scraper.** Where surface soil conditions are favorable, the loader-scraper can be a very efficient machine for soils handling, although it is a compromise between the best loading and the best hauling machine. The same unit can excavate, remove, transport in its hull, and then deposit in layers of uniform thickness. This is a useful function for general soil spreading over an area or for spreading a layer, or lift, to be compacted in a dike.

**Front-end loader.** Although intended primarily as a combination excavation and fast loading unit for trucks or other hauling units, a limited amount of soil (a bucket full) can be transported fairly long distances. Because the soil is scooped and carried rather than simply pushed, this is a more definite and more efficient transport than a grader or bulldozer.

**Trucks and wagons.** Trucks (self-propelled units) and wagons (trailers) serve only one function: as a bulk hauling unit. Most trucks can be operated over any haul road for which the surface is firm and smooth, or reasonably so, and on which the grades are not too steep. Deposition from a truck can be by rear dumping or bottom dumping, with the latter being more efficient for granular, free-flowing materials. Soils can be deposited in layers of controlled thickness. With a rear dump truck operating in reverse, the dumped material is placed in front of the direction of travel, allowing the placement of a layer of soil before the wheels traverse it. This allows placement of satisfactory material over a foundation of much softer soil, permitting movement of the placement truck that could not otherwise travel over the soft surface.

**Barge haul.** Excavated, removed, and transported soil can be deposited in a barge, as an alternative to a truck, if the barge can be floated to within placement distance. This is particularly valid if the excavation equipment (backhoe, dragline, or clamshell) is also barge mounted, or has been moved into position in shallow water. The operating depth of a barge is a function of its size and its payload. However, loaded drafts of 30 to 60 cm (12 to 24 inches) are feasible. Many barges are bottom dump, which means they can be loaded while floating in a wetland, be floated to the dump site by a work boat, and then dump their soil cargo into an underwater deposition site.

**Conveyor belt.** A conveyor for transporting materials a short distance may be a portable installation that can be suited to a wetlands site. Conveyor systems can be environmentally desirable because they do not require a roadway and will operate over any terrain provided the slopes do not exceed those that will allow the material to slip. When the project is completed, the machine is removed and a very minimum of damage is done at the supports.

A conveyor system, because it is fixed until purposely moved, requires that both loading and unloading be done at fixed locations. Loading can be done by an excavator such as a front-end loader, power shovel, backhoe, clamshell, or dragline. Unloading is done by spilling onto a truck, barge, or on the ground. If on the ground, then a bulldozer or front-end loader can be used to distribute the material.

### Hydraulic pipeline transport methods and equipment

The pumping of a soil-water slurry in a pipeline has been extensively studied, particularly with regard to navigation dredging. Reference sources that should be consulted for detailed discussions of slurry pumping include J. B. Herbich's (1992) *Handbook of Dredging Engineering*, and Tom Turner's (1984) *Fundamentals of Hydraulic Dredging*.

There are two matters that are of primary concern in the selection of a hydraulic pipeline as a means of soil transport at a wetlands project: (a) pumpability of the soil, and (b) for clayey soils, the degradation of clay balls in the pipeline.

**Pumpability.** The energy required to pump a soil-water slurry in a pipeline, its *pumpability*, has been studied both theoretically and empirically. The following general statements are applicable: (a) the larger the typical, or median, grain size the less pumpable is the sediment, i.e., the greater the pumping energy needed; and (b) a uniformly graded sediment is easier to pump than a well graded (dispersed grain sizes) sediment of the same median size.

Sediment type is only one of the factors influencing the energy needed for pipeline transport of sediments. All other factors being held constant, such as the nature of the transporting fluid, the equipment geometry, and the slurry factors, the energy required to pump a slurry in a pipeline depends on the median grain size, $d_{50}$, of the sediment. The dispersion of grain sizes (uniform vs. well graded) also affects pumping energy. The greater the dispersion (well graded) the greater the tendency for segregation of grain sizes in the pipeline, with the larger grains traveling along the bottom of the pipe. Grain shape affects the ease with which individual coarse grains will slip past each other in the slurry. The greatest slurry fluidity occurs with rounded grains. The energy required to pump a granular, dispersed sediment in a pipeline is dependent on several factors:

*a.* *Factors of the sediment SOLIDS*: Typical (median) grain size; maximum grain size (must be capable of passing through the pump); degree of dispersion, or uniformity, of the grain size distribution (which indicates the relative amounts of the various grain size fractions present); grain shape; amount of silt and clay (which affects the rheologic properties of the slurry); and plasticity of the -0.42 mm (No. 40 screen) grain size fraction (which determines the tendency to form clay balls).

*b.* *Factors of the transporting FLUID*: Density and viscosity.

*c.* *Factors of the EQUIPMENT GEOMETRY*: Pipe diameter; pipe length; configuration (number of elbows); surface texture (pipe roughness); and pipe material.

d. *Factors of the SLURRY*: Concentration; distribution of grain sizes over the pipe cross-section; presence and amount of clay balls (lumps); and velocity profile of the fluid.

**Degradation of clay balls.** During excavation, clays will tend to stick together in small clods or lumps rather than separating into individual grains as with a sand or gravel. As they are removed and transported in a pipeline, the clods or lumps will naturally rotate and become ball shaped. Their stickiness will cause other clayey particles to stick to them; sand, gravel, and even shells will also stick to the surface of the clay balls. Some clays will degrade in the pipeline and form a very fine-grained slurry and others will retain their ball shape. The clay balls in a pipeline can, in certain circumstances, coalesce and plug the line. However, in the formation of dikes from clay balls, or of geotubes filled with clay balls (discussed in a later section), the non-degradation of the clay balls is necessary. A set of behavior characteristics is shown in Table 7-12 based on a U.S. Army Engineer Waterways Experiment Station report (Richter and Leschinsky 1994).

**Table 7-12**
**Degradation of Clay Balls in a Pipeline**

| Plasticity Index | Low Initial Strength; Low Initial Density | High Initial Strength; High Initial Density |
|---|---|---|
| Less than 25 | Friable; clay balls will degrade. | Friable; clay balls will degrade. |
| 25 to 35 | Clay balls will degrade. | Clay balls will not degrade. |
| Greater than 35 | Highly cohesive; clay balls will not degrade. | Highly cohesive; clay balls will not degrade. |

# Low-Ground-Pressure Equipment

When the surface of a proposed or existing wetlands site is extremely wet and soft, or is even partially under water, the land-based soils handling equipment described above will either cause highly disruptive rutting or will not be able to move at all. Machines should be capable of traversing the site during initial site evaluations, including surveying and geotechnical subsurface investigations, as well as other sampling missions. During earthwork construction, the machines should not only be capable of movement but be able to exert substantial drawbar pull and/or do excavation and removal work.

The U.S. Army Engineer Waterways Experiment Station (WES) has evaluated a number of commercially available low-ground-pressure machines. Several WES publications present information of value in the selection of low-ground-pressure vehicles. These include Green and Rula (1977), Willoughby (1977), and Poindexter-Rollings (1990).

The application of a vertical load over a finite area on the ground surface is identical in effect to a shallow spread footing. If a footing is loaded to beyond the bearing capacity of the under-lying soil, a punching failure will result. This applies equally well to a footprint, a crawler-track (long footing), or a wheel, when it is called a rut. A typical adult male will apply around 28-35 kPa (4-5 psi) contact pressure on the ground when walking. Conventional crawler-mounted equipment will have ground contact pressures of 70 to over 200 kPa (10 to over 30 psi), depending on the machinery being carried, and wheeled construction equipment will exert pressures of 200 to over 400 kPa (30 to over 60 psi).

Figure 7-13. Low-ground-pressure cargo carrier.

The low-ground-pressure equipment for soils handling described in the publications listed above consist of tracked (crawler-mounted) and wheeled vehicles that can be used to haul personnel or cargo, or to pull or carry construction machinery. Contact pressures range from 10 to 35 kPa (1.5 to 5 psi) for both tracked and wheeled machines. For example, the unit shown in Figure 7-13 can be used to support a subsurface investigation drill rig, operate a push blade, pull a plow, or support a crane-mounted unit such as a dragline.

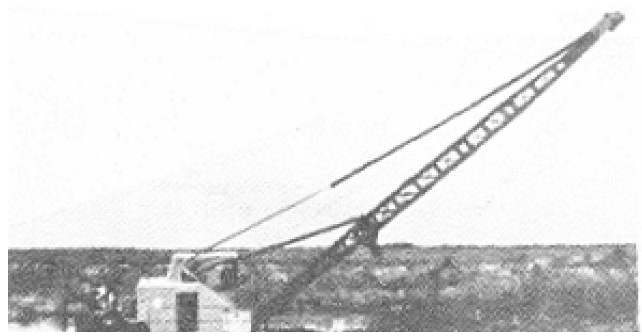


Figure 7-14. Dragline-fitted crane on low-ground-pressure carrier.

Cargo can be carried on either tracked or wheeled vehicles at speeds up to 48 kph (30 mph). The unit shown in Figure 7-14 can carry a payload of 2.25 tonne (2.5 tons) with a loaded ground pressure of 22.7 kPa (3.3 psi). Other wheeled units can carry payloads up to 13.6 tonnes (15 tons) with a contact pressure of 27.5 kPa or less (4 psi or less). By using wide tracks, crawler-mounted units can carry payloads of 27 to 36 tonnes (30 to 40 tons) with contact pressures of 27 to 38 kPa (4 to 5.5 psi) and at speeds of 14.5 to 19 kph (9 to 12 mph). Some of the tracked equipment is amphibious due to large water-tight tanks placed alongside and between the tracks. Therefore, this equipment can travel and work in soils so soft that they will not support a person on foot.

## Uses for Excavated Material

Deposition at a disposal, storage, or fill site may be by mechanical or hydraulic methods, depending on the transport method. If the excavated and transported soil is to be simply discarded, then mechanical dumping or hydraulic slurry placement on a land or water disposal site, with or without manipulation, is suitable. The only geotechnical concern will be the possible sticking of moist clayey soils to the container and the turbidity of the water for underwater disposal. Placement in a storage area may require manipulation of the soil after deposition to move the soil to the desired location and/or to provide a needed grade or slope. The deposited soil may be used as a fill. The fill may be used (a) for area fill to raise level of a wetland bottom, (b) to create islands or landform buffers, (c) to augment new impoundment subgrades, or (d) in the creation or modification of retention dikes. If a fill is to be made, then the amount and type of compaction required will determine the type of processing methods and equipment, as described in Chapter 7-8.

### Requirements for disposal sites

When the amount of soil excavated and removed from a wetlands site, for whatever reason, exceeds the amount that can be placed in temporary storage or as fill, the excess must be disposed of. The disposal site can be on land, in open water, or in a created-island disposal area. Selection of a disposal alternative should be based on both economic and environmental considerations.

If the soil to be discarded contains contaminants that may be harmful to the environment, then the various Corps of Engineers requirements for land and/or open water disposal should be followed. In general, however, it is expected that most excess material removed from wetland sites will not contain contaminants. Therefore, only the environmental consequences of a land fill in a disposal site need be of concern. For example, erosion of the disposed material may cause clogging of streams. The aesthetics of the disposed soil should also be a consideration; vegetation should be planted as soon as possible on the raw fill. Disposal in open water needs approval of government agencies.

### Requirements for temporary storage sites

Temporary storage of soils may be needed to accommodate the limitations of the construction plan for time and space. Depending on the needs for temporary storage, three or more separate storage areas should be considered at each storage location. Because of differences in the character of the materials, strippings from the A- and E-horizons should be stored separately from the B-horizon, if at all possible. And the total A-, E-, and B-horizon material should be stored separately from the parent C-horizon material. In this manner, a selective replacement may be made.

Both the chemical and physical character of the materials to be stored should be known for the design of a stable dump. In this manner, any possible toxicity or stability problems can be dealt with. It may even occur that some layer within the C-horizon may be a more suitable plant growth medium than the existing solum materials. Other considerations include the erodibility of the stored material, drainage of the stored fill, and the effect of leachates on ground and surface waters.

Access to and from the storage site is essential. The storage site, obviously, should be capable of supporting the load of the stored material without base failure or excessive settlement. The effect of the stored material on nearby locations should also be considered.

### Areal fill, islands, and landform buffers

The placement and compaction of fill for a long, narrow fill, such as a dike, is discussed in Chapter 7-7. For a wide area, such as an areal fill, an island, or a landform buffer as part of a wetland project, the feasible methods of fill placement on land or in shallow water include simple dumping or casting (uncompacted) and equipment compaction (semicompaction). Mechanical densification, or compaction, of soil (discussed in Chapter 7-8) is used to increase strength, decrease compressibility, and decrease permeability when these factors are critical. Full, or specification, compaction is the mechanical densification, using vibrators or rollers, in thin layers, to achieve a specified compaction amount for dikes or as backfill around concrete structures.

**Simple dumping or casting.** Soil can simply be dumped from the transport container, such as a loader-scraper, a truck, a barge, or a pipeline and then spread using a grading machine. Only minimal mechanical manipulation of the grading machinery is used. The soil is *uncompacted*, i.e., there is no attempt at densification and excess water drains away or evaporates. This technique is used only when the strength and compressibility of the area fill is not of concern and when hydraulic conductivity is. The fill will eventually compress under its own weight (see below). This fill method may be used, for example, when it is desired to raise the elevation of the bottom of a pond or small lake to accommodate a particular group of plants and/or animals.

**Equipment compaction.** For aboveground facilities such as created islands and landform buffers, some mechanical densification may be necessary to provide shear strength for stability and to decrease erodability at the surface. This can be economically accomplished by using the wheels or tracks of the hauling equipment to *semicompact* the soil in moderately thin layers. No attempt is made to densify to a specification value. The densification methods appropriate for mechanical semicompaction depend on the soil type.

Cohesionless (clean granular) soils can only be densified with vibratory equipment. Crawler tractors have often been used, especially if the engine is purposely made to run rough to create a vibration of the machine. Cohesive (clay, silty clay) and friable mixed grain soils are best semicompacted by repeated passage of wheeled or crawler mounted machines. Excess water content may prevent achievement of desired amount of densification and may simply lead to continued rutting.

## Substrate Sealing

Excessive seepage losses can occur through the subgrade that will support the substrate of a planned new, or newly deepened, impoundment if subgrade permeability is too high. The permeability, or hydraulic conductivity, of the subgrade will have been determined during the initial subsurface investigation or as part of the detailed, or specific, subsurface investigation (see Chapter 2-3).

The obvious solution to this problem is to reduce the permeability to a level where the losses become acceptable. Subgrade permeability can be reduced by either mechanically compacting the surface of the existing subgrade or by modifying the texture of the surface layer with clay from a nearby excavation, with a high plasticity bentonite, or by use of a chemical treatment such as lime or a dispersing agent. These methods assume (a) that compaction will be done in accordance with the concepts and methods discussed in Chapter 7-8 and (b) that suitable new substrate material will be placed or created on the surface of the modified subgrade. They are discussed below more or less according to increasing cost.

### Compaction of existing subgrade surface soil

This method is feasible only if the soil at the existing subgrade surface has a texture that may be readily compacted and whose permeability can be decreased by one or two orders of magnitude. This includes soils from the Unified Soil Classification System (see Appendix A) classes GM, GC, SM, SC, CL-ML, CL, ML, and MH. Soil types GW, GP, SW, and SP (clean gravel and/or sand) do not contain sufficient fines to permit a significant reduction in permeability by compaction. Soil type CH (high plasticity clay) generally forms clods that are very difficult to break down and compact, without chemical modification, with typical compaction equipment.

The subgrade surface should first be cleared of all trees, vegetation, and humic (highly organic) soil. Stump holes and other depressions should be filled with compacted and relatively impervious soil. The subgrade surface should then be scarified to a depth of about 20 to 25 cm (8 to 10 in.) with a disk, tiller, or similar device. All large roots, stones, and other debris should be removed.

The water content of the soil should be modified, by wetting if needed, to permit compaction at a degree of saturation above 80 to 90 percent, as discussed in Chapter 7-8. The objective is to cause a breakdown of the flocculent structure of the clay and cause it to become dispersed, thus lowering the permeability. The achievement of structural strength in the compacted soil layer is rarely a concern in the sealing of the substrate.

The soil should then be compacted with a sheepsfoot or other suitable roller with sufficient passes to form a firm, relatively impervious layer. The necessary compactive effort can be determined by laboratory permeability tests of laboratory compacted soil. Or, preferably, field permeability tests can be made to determine the effectiveness of the compaction and the compactive effort adjusted to achieve the desired result.

If a greater thickness of compacted subgrade is needed than can be achieved in one layer, then a second layer of compacted soil may be needed. The top 20 to 25 cm (8 to 10 in.) of scarified soil can be removed and stockpiled. The new surface can be scarified and compacted. Then, the stockpiled material can be returned, spread evenly, and compacted. Alternately, the second (uppermost) layer can consist of soil hauled in from another nearby borrow area.

### Modification of subgrade soil with clay

If the existing subgrade soil is too clean (lacking in fines) and coarse grained to be compacted in place, as described above, three simple alternatives are feasible if a source of clayey soil is available nearby: (a) mixing clay from a nearby excavation with the existing subgrade soil, (b) applying a clay blanket over the subgrade, or (c) mixing bentonite clay with the existing subgrade soil.

*Mixing with nearby clay.* Fine-grained soil, silt and clay, may be excavated from a nearby borrow area, hauled to the subgrade modification site, and spread uniformly over the surface. The scarifying process, enhanced by blade mixing or other form of soil mixing such as the use of road building pug mills, will then create the desired texture in the uppermost layer. The subgrade surface can then be compacted as described above.

*Clay blanket.* If a sufficient supply of fine-grained soil is available from a nearby source, it may be cost-effective to simply clear the existing subgrade, remove one compacted layer thickness from the surface, and replace it with a layer of hauled-in clay. The clayey blanket layer should then be compacted as described above, i.e., at a sufficiently high water content to permit degradation of the flocculent structure into a dispersed, and less permeable, structure.

*Mixing with bentonite.* If a clay mixture with the existing subgrade soil is desired, but a source of clayey soil for mixing is not available at an economic distance, the commercially available bentonite may be used. Bentonite is a naturally occurring clay formed from the decomposition of volcanic ash and occurs in deposits in several locations in the U.S. and other countries. It is composed almost entirely of the clay mineral sodium-montmorillonite. Therefore, bentonite is characterized by having a very high liquid limit and plasticity index with the associated high swell-shrink potential. When saturated it can swell to over 10 times its original volume.

The proportion of bentonite to be used should be determined by a laboratory test of the compacted mixture. Application rates are typically 5 to 15 kg/sq m. (1 to 3 lb/sq ft.). Because of the great affinity of bentonite for water, the existing subgrade soil to be mixed should be thoroughly wetted before mixing and the mixture may require additional wetting after mixing to achieve the desired water content for compaction.

### Modification of subgrade soil with chemicals

Common chemicals mixed with clayey soil will modify the compactibility of the soil by either (a) reducing surface tension resulting from partial saturation, or (b) changing the clay mineral formulation by addition of lime. These materials will be useful only in subgrade soils containing an appreciable amount of clay. This topic is discussed in detail in Chapter 7-8, Mechanical Compaction of Soils.

## Self-Weight Consolidation of Dredged Material

When fill soil is dumped or cast in a very wet, nearly slurry condition, either on land or under water, the mass will settle, or decrease in volume, due to two factors: (a) the pressure of it own weight and (b) desiccation at the exposed surface. An analysis procedure was developed at the U.S. Army Engineer Waterways Experiment Station (WES) to deal with the settlement of dredged material in a confined disposal area (Cargill 1985). A computer program was developed to deal with the calculations, with the latest upgrade being by Stark (1991).

When soil is placed at a very high water content, it first begins to settle out of the slurry. This process occurs naturally in any body of water receiving suspended sediment and occurs in man-made confined disposal areas. As the sedimenting soil reaches the bottom, it overlies previously sedimented soil. The weight of the new soil serves as a consolidating pressure increment for the underlying soil. At each lower level, the compressing force is the effective pressure of the overburden. The rate of placement of the overburden pressure increments is not uniform. To this is added the effect of desiccation drying if the surface is exposed to the air. The mathematical model attempts to quantify these effects to predict the total change in volume of the soil mass at any given time.

The application to wetlands soils handling occurs whenever soils are dumped or cast into an area fill, as a high water content slurry or under water. With self-weight consolidation comes a change in volume that causes an increase in strength and a decrease in hydraulic conductivity that varies with depth.

## Criteria For Selection of Soils Handling Methods and Equipment

The selection of the appropriate method and equipment for soils handling at a wetlands project site is important if the project is to be conducted in an economical and environmentally acceptable manner. Four main factors affect the selection:

*a.* *Material factors.* The type, properties, and variability of the soils to be moved. The type of end-product desired: disposal, storage, or fill.

*b.* *Terrain factors.* The volume and location of the materials to be moved and the location to be deposited. The availability of haul roads or haul areas. The condition of the haul roads, including grade and trafficability. Environmental factors limiting temporary and/or permanent changes in the site due to soil movement operations.

*c.* *Equipment factors.* The types of equipment available, their operating characteristics, rolling resistance, cost of mobilization, and cost of operation.

*d.* *Environmental factors.* Legal, contractual, or environmental limitations on the method and type of equipment that can be used.

**Material considerations.** The soil handling equipment must, of course, be adapted to the type of soil and the handling needs. If it is necessary to remove and transport the various soil horizons, or even layers within the substratum, or parent material, then the machinery must be capable of scooping in thin layers and transporting without extensive mixing of the soil. Clamshells are best adapted to handling granular materials above water. If used to excavate granular materials from below water, clean sand will tend to wash out of the bucket. Firm clayey materials are best excavated in bulk with a backhoe or power shovel because of their high scooping force.

**Terrain considerations.** The volume of soil to be moved will affect the efficiency of the hauling equipment. The surface condition and relative elevations of the various parts of the site will affect the type of carrier, or work platform, that is suitable for any given equipment. This includes shear strength (bearing capacity) and drainage for the combination of the excavation site, the transport locations, and the deposition site.

Trafficability, or the ability to support a vehicle without severe rutting, is a major concern. When a loaded wheel or track moves over a surface, it deforms itself and also presses into the supporting surface. Therefore, it is always trying to climb a small hump that is always in front of it. The force required to overcome the resistance of the hump is called *rolling resistance.* The effect of moving up or down a slope, changing elevation, is called *grade resistance.* Obviously, it takes more energy to move a vehicle and its cargo up a slope than it does to move it horizontally or down a slope. Therefore, an excavation site that is higher than the deposition site, with no steep grades in between, is the ideal situation. Because of rolling resistance, movement of bulk soils by water is more efficient than movement by land vehicles.

**Equipment factors.** Table 7-13 shows a listing of soil handling equipment according to various categories of use. Obviously, any combination of the four phases of soil handling (excavation, removal, transport, and deposition) can be accomplished with a variety of combinations of equipment. Each of the various transport methods has advantages and limitations, as summarized in Table 7-14.

**Table 7-13**
**Categories of Soil Handling Equipment**

| Excavation Only | Grading | Excavation and Loading | Hauling and Deposition | Excavate, Load, Haul, and Deposit |
|---|---|---|---|---|
| Plow<br>Ripper<br>Soil loosener | Bulldozer<br>Motor grader | Backhoe<br>Clamshell<br>Cutterhead dredge<br>Dragline<br>Front-loader<br>Power shovel | Barge<br>Conveyor belt<br>Dump truck<br>Pipeline | Dragline<br>Front-loader<br>Loader-scraper |

Conventional wheeled vehicles generally have the highest contact pressures and, therefore, require the firmest working surface. Because of fairly narrow tires, rolling resistance on a given site tends to be the highest of all types of equipment. However, if the site is firm, their higher speed and maneuvering ability make them a primary choice.

**Table 7-14**
**Methods of Soil Transportation**

| Method | Advantages | Disadvantages |
|---|---|---|
| Land-based Hauling | 1. May use central borrow areas.<br>2. Permits use of high-speed, high-capacity equipment.<br>3. Allows better selection of soil type. | 1. All traveled surfaces must be firm to support equipment.<br>2. Cannot be used in soft, wet areas or underwater.<br>3. May require specialized low-pressure equipment. |
| Dragline Casting | 1. Dragline bucket can move very soft, wet soils.<br>2. Can operate on soft foundation. | 1. Low speed and low capacity.<br>2. Requires frequent movement of dragline equipment.<br>3. Short casting distance. |
| Hydraulic Pipeline | 1. Move large quantities of soils from above or below water.<br>2. Permits use of dredged materials in dike.<br>3. May be used on soft foundation and roadway. | 1. Requires dredge pump and pipeline.<br>2. Soils cannot be compacted without drying. Requires large sections with very flat slopes unless confined in geotubes. |

Tracked, or crawler-mounted, equipment spreads the load out over the tracks and has a lower contact pressure than a comparable wheeled vehicle. As a result, they can work and travel on muddier sites than wheeled equipment. The effect of rolling resistance is usually less than for wheeled carriers. However, speed is much lower and grade resistance tends to be higher. Most tracked equipment is powered to work on level surfaces.

If the site is too wet and soft for wheeled or tracked machines, low-ground-pressure equipment can be used. The cost of this specialized equipment is expected to be higher than for conventional construction machines, but this may be the only way to accomplish the work within project cost and environmental constraints. As an alternative, if the travelway is environmentally restrictive, a temporary, portable conveyor system should be considered. If the site contains a considerable amount of waterway, especially if a continuous water route can be found or created between the excavation site and the deposition site, then dredging excavation equipment and barges or pipeline can be used.

**Environmental factors.** Environmental concerns at a wetland site must always be considered. Soils handling invariably involves disruption of the ground surface of the excavation itself, and of the surrounding work area. The removal of surface vegetation exposes the surface to possible erosion as does rutting caused by excavating and hauling machinery .

If a natural haul road exists and is firm and well drained, then the highest and best form of short distance transport is by wheeled vehicles. If, however, a satisfactory pre-existing road does not exist, the environmental effect of creating one, or a group of roads, must be determined. Alternatives to roadways are conveyor systems, pipeline, or barge. Lightweight excavators, including dredging units, and conveyor systems and pipelines can be airlifted and moved by helicopter.

# 7-7 Construction of Retaining Dikes[1]

The general construction sequence for a retaining dike involves, in order, (1) foundation preparation, (2) material source (borrow area) operations, (3) transportation and placement of the dike materials in the embankment, and (4) manipulation and compaction of the materials to the final form and shape. Requirements and methods for soil compaction are discussed in detail in Chapter 7-8.

The choice of construction methods and equipment for a retaining dike will be governed by the character of the available construction sites and type of embankment materials. Additional factors are the availability of specific construction equipment, trafficability of haul roads and the dike foundation, environmental concerns, and project economics. Equipment commonly used for the construction of retaining dikes is listed in Table 7-15.

## Foundation preparation

The preparation of a dike foundation usually involves clearing, grubbing, and stripping. Some degree of foundation preparation is desirable to help insure the stability of the structure and inhibit underseepage. Clearing and grubbing should be a minimum treatment for all dikes and other retaining structures. However, in marshy areas where a surface mat of marsh grass and roots exists over a typically soft clay layer, experience has shown that it is often more beneficial from a stability and construction standpoint to leave the mat in place rather than remove it, even though this will leave a high pervious layer under the dike. The underseepage can then be reduced by other design methods.

**Clearing.** Clearing consists of the complete removal of all above-ground matter that may interfere with the construction and/or integrity of the dike. This includes trees, fallen timber, brush, vegetation, abandoned structures, and similar debris. Clearing should be accomplished well in advance of subsequent construction operations.

**Grubbing.** Grubbing consists of the removal of below-ground matter that may interfere with the construction and/or integrity of the retaining dike. This includes stumps, roots, buried logs, and other objectionable matter. Shallow depths of very soft, highly organic, or otherwise

[1] By S. Joseph Spigolon

**Table 7-15**
**Equipment Commonly Used in Dike Construction**

| Operation | Equipment | Application |
|---|---|---|
| Excavation | Loader; Scraper | Firm to stiff soils.  Requires firm roadway. |
| | Dragline | Very soft to soft soils that cannot support scraper. |
| | Dredge | Granular or cohesive soils located below water. |
| Transport | Scraper | Hauling firm, moist soils on firm roadway. |
| | Truck | Hauling firm, moist soils on firm roadway. |
| | Dragline | Casting soft  or loose, wet soils. |
| | Dredge pipeline | Hydraulic pumping of soil slurry. |
| Scarification | Disc | Scarifying surface of foundation or compacted soil. |
| Spreading | Scraper | Haul and spread firm soils from same machine. |
| | Grader | Spread truck-hauled soils. |
| | Crawler dozer | Used on soft soils. |
| | Rubber-tired dozer | Used on firm soils. |
| Compaction | Sheepsfoot roller | Cohesive soils--clays, silts, dirty sands. |
| | Rubber-tired roller | Cohesive soils--clays, silts, dirty sands. |
| | Vibratory roller | Only on clean, cohesionless sands and gravels. |
| | Crawler tractor | Semicompaction on all soil types. |
| | Hauling equipment | Semicompaction on all soil types. |
| Shaping | Grader | Firm to stiff soils. |
| | Crawler dozer | All soils; useful on soft soils. |
| | Dragline | Rough shaping in very soft soils. |

unsuitable soils may also be removed.  All holes and/or depressions caused by grubbing or excavation operations should have their sides flattened and should be backfilled to foundation grade in the same manner proposed for embankment filling.

**Stripping.**  After clearing and grubbing, the retaining dike area is usually stripped to remove all low-growing vegetation and the organic topsoil layer (A-horizon).  This will (a) permit bonding of the embankment fill soil with the foundation, (b) eliminate a soft, weak layer that may serve as a translation failure plane, and (c) eliminate a potential seepage path.  Stripping is normally limited to the dike location proper and is not usually necessary under stability berms (Chapter 4-3).  All stripped material suitable for re-use as topsoil should be stockpiled for later use on the dike and/or borrow area slopes.  Stripping is not normally required for dikes on soft, wet foundations or for dikes built by other than full, specification compaction.

**Disposal of debris.** Debris from clearing, grubbing, and stripping operations, not gainfully used elsewhere in the wetland site, can be disposed of by burning in areas where permitted. Where burning is not feasible, disposal is usually accomplished offsite in accordance with applicable regulations. Debris should never be placed where it may be carried away by streamflow or where it may block drainage of an area. Material buried within the water-filled area being retained must be placed so that no debris may escape and damage or block the outlet structures. All buried debris should be covered by a minimum of one meter (3 ft) of earth.

**Foundation scarification.** For compacted retaining dikes on firm foundations only, the prepared foundation should be thoroughly scarified to provide a good bond with the embankment fill.

## Compaction of soils

Soils may be placed in the dike cross section with various degrees of mechanical compaction, ranging from (a) specification compaction, to (b) semicompaction, to (c) simple dumping and shaping. Details about the concepts, methods, and equipment for soil compaction are given in Chapter 7-8.

*a.* *Specification compaction.* Materials are selected to exclude highly organic soils or high plasticity soils. Soils are placed in thin layers, or lifts, and machine compacted using suitable compaction equipment until a specified degree of compaction is achieved. In some soils, the water content may be controlled. Field density tests are made to check on specified densification.

*b.* *Semicompaction.* Material selection is similar to compacted soils, but not as severe. Soils are placed in fairly thin layers and compacted by the action of hauling and spreading equipment. In some soils, the water content may be controlled.

*c.* *Simple dumping and shaping.* The fill material is dumped, cast, or dredged into place and then shaped. May be used for displacement filling when foundation is extremely soft.

The degree of compaction determines, for any given soil, the resulting shear strength, compressibility, and hydraulic conductivity. The requirements and methodology for compacted fill are discussed in detail in Chapter 7-8.

## Hydraulic fill

For those situations where the available fill soil is sandy, with considerable fines content, and is being transported in a pipeline as a slurry, a hydraulic fill dike should be considered. As

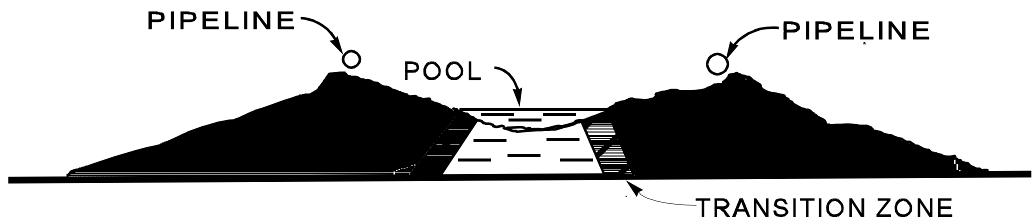



Figure 7-15. Cross section of a hydraulic fill dike during construction.

described by Taylor (1948), the soil and water are carried by rapidly flowing water in pipelines to one end of the dike, as shown in Figure 7-15. The soil-water slurry is discharged at the inside top of the slope. The slurry then flows toward the center of the section. The water loses velocity as it approaches the pool. As a result, the deposited soil is coarsest at the outer boundaries and is increasingly finer at points nearer the pool. When the remaining slurry reaches the pool edge, its velocity is checked, and all the remaining fine sand and coarser silt sizes are deposited in the narrow transition zone. Only the finest particles reach the pool, where they settle slowly. With time, the sedimented fine soil experiences self-weight consolidation and forms an impervious central core.

The coarse sandy outer shells will stand on a slope equal to the angle of repose of the sand. For loose sand this will range from about 1.75V:1H to 2V:1H. The strength of the sand, and therefore steeper slopes, can be improved by vibratory compaction, as discussed in Chapter 7-8. For compaction, the sand should be vibrated in fairly thin layers formed by machine spreading during the hydraulic filling operations.

The total base width of the hydraulic fill dike will be about six to eight times its height. As a comparison, if the same material had been placed mechanically (assuming careful separation and placement of the impervious central core material) with side slopes of 2V:1H, the base width would be about five to six times the height.

# 7-8 Mechanical Compaction of Soils[1]

Soils are mechanically compacted, or densified, to increase shear strength to a desired value, to reduce compressibility, and/or to reduce permeability. Mechanical compaction may be done on (a) hauled or dredged fill soils, one layer at a time, or (b) on the surface layer of existing soils. The most common way to densify soils is by mechanical methods, using special rollers or vibrators. Alternately, the wheels or tracks of heavy hauling equipment may be used. Mechanical densification, or decrease in porosity, is the result of expulsion of air from the void spaces. Except in clean gravels and coarse sands, water is not expelled from the soil mass during densification because of the soil's low permeability combined with the brief time of application of the mechanical force.

## Factors Affecting Mechanical Compaction

There are several factors that interact to affect the amount of compaction and that determine the suitability of compaction equipment and of processing method. The major factors are: (a) soil type, (b) water content, (c) type of compaction equipment, (d) magnitude of the compactive effort, and (e) thickness of soil layer (lift) to be compacted.

When a compactive effort is applied to a soil mass, the magnitude of the compressive force is dissipated with depth. The distribution of pressure with depth, under a rigid footing, the tire of a rubber-tired roller, or the foot of a sheepsfoot roller, may be approximated by the $60^o$ rule shown in Figure 7-16. For a load *P* applied to a rigid footing of width *b* and great length, the pressure directly under the footing, although not uniform, will have an average pressure reasonably approximated as *P/b* per unit of length. At the depth z, the average pressure is very nearly *P/(b+z)* per unit of length. For example, a long footing 30 cm (1 foot) wide will have, at a depth of 30 cm (1 foot), only 50 percent of the surface pressure. At a depth of 60 cm (2 feet) it will have an average pressure only 33 percent of the surface pressure. If the footing is square (or round), then the pressure diagram approximates a pyramid. The average surface pressure is then about $P/b^2$ and at depth $z$ is about $P/(b+z)(b+z)$.

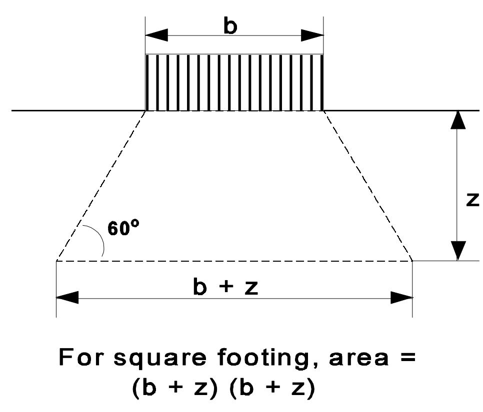



Figure 7-16. Pressure distribution with depth for a long footing.

[1] By S. Joseph Spigolon

For a small, nearly square footing, such as the tip of a foot on a sheepsfoot roller, the contact pressure at one roller foot width below the foot is only 25 percent of the surface pressure.

The two major soil type groups, cohesionless and cohesive, react differently to the compactive effort. Clean, cohesionless soils are best densified with vibration. Cohesive soils are best compacted by means of weighted rollers.

## Compaction Behavior of Cohesionless Soils

Cohesionless soils are defined as gravel or sand containing less than five percent by weight of material finer than the No. 200 screen (0.074 mm). Cohesionless soils have very little or no plasticity, because of a very low clay content, and do not exhibit cohesion in shear. In one series of tests by the writer, a dredged sand from the Mississippi River having 16 to 20 percent silt sizes, and no measurable plasticity, indicated cohesionless behavior.

The shear strength of a confined cohesionless soil varies directly with the vertical pressure. Increased strength leads to a resistance to compression by a direct force. The simple, direct compression force of a roller will not cause appreciable compression of the granular soil. Therefore, a loose cohesionless soil is primarily densified by vibration, which causes the pressure on the grains to momentarily decrease, permitting the grains to slide past each other into a denser mass. A similar effect is obtained by using a steel wheel roller on thin lifts, or layers. The concentrated load of the rigid wheel first pushes the soil, shearing it, and then compresses it as it passes.

### Effect of water content

Clean granular soils are generally insensitive to compacting moisture. However, vibration-induced densification occurs best on completely dry or completely saturated soils. Partial saturation of a clean, granular soil causes a negative pore water pressure to exist in the voids. This causes an internally induced normal force between the grains that somewhat increases the shear strength beyond that due only to external forces plus the self-weight of the soil. Since natural soils are rarely dry, it is best to completely saturate the granular soil, if possible.

### Magnitude of vibratory compactive effort

Vibratory compactive effort acts throughout the soil mass with a magnitude as shown in Figure 7-17 and causes a lifting and lateral motion. Because the grains near the surface do not have a large vertical

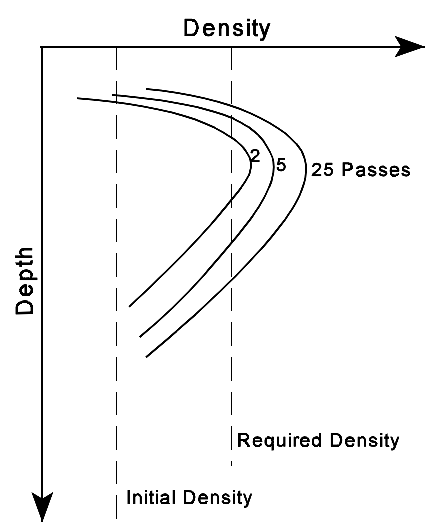



Figure 7-17. Variation of density with depth for vibratory compaction.

self-weight force, they tend to lift and return without appreciable densification. As a result, the maximum densification occurs, not at the surface, but at a short distance below as shown in Figure 7-17. The depth of maximum compaction is a function of roller weight and number of passes. A typical value is 20 to 30 cm (8 in. to 1 ft).

The effectiveness of vibratory compaction depends on several factors involving the interaction between the vibratory compaction equipment and the soil being compacted. The factors include:

*a.* *Operating frequency*. The operating frequency of the vibrator should be above the resonant frequency of equipment and soil combination. Generally, the lighter the vibrator, the higher the operating frequency.

*b.* *Magnitudes of static weight and dynamic forces.* In cohesionless soils, the higher the static weight, the greater the compaction and at a greater depth. At below the resonant frequency, dynamic soil pressure is proportional to the dynamic force. Above the resonant frequency, increasing the dynamic force does not produce a proportional increase in soil pressure.

*c.* *Relation of dynamic force to static weight*. For most rollers, dynamic force is 2 to 3.5 times the static weight; for vibratory plates, dynamic force is up to 10 times static weight.

*d.* *Amplitude of vibration displacement.* High displacements produce high vibratory velocities and large impact or tamping forces. Therefore, there is greater compaction at higher amplitudes. However, this requires greater power and/or lower frequencies.

*e.* *Speed of travel.* Roller speed affects the number of vibrations applied to the soil mass at a given point for each pass of the vibrator. Most self-propelled rollers operate at 1.5 to 3 km (1 to 2 miles) per hour. Manually operated vibratory plates operate at 1 to 2 km (0.6 to 1.2 miles) per hour.

*f.* *Properties of soil to be compacted.* Vibratory compaction is best suited for clean granular soils (sand and gravel). When vibration is used for compacting cohesive soils, the heavy roller weight and large amplitude cause a tamping effect.

## Compaction Behavior of Cohesive Soils

Cohesive (clay, silty clay) and friable mixed grain soils contain a significant amount of clay. The clay content is sufficient to prevent the frictional shear strength derived from grain-to-grain contact. Therefore, cohesive soils behave as though their shear strength derives only from cohesion and the shear strength is not dependent on the magnitude of the vertical force. Because of the cohesion, vibration alone will not cause a significant amount of densification.

Weighted rollers are used to compact cohesive fill soils in layers by means of direct compression. When vibratory rollers are used, the major effect is due to the static weight of the roller and the tamping effect of a high vibratory amplitude. The compaction behavior of cohesive soils is highly sensitive to water content, compactive effort, and to the plasticity of the clay.

The required roller energy to achieve a given density in a given cohesive soil is directly related to the water content. A high water content may prevent achievement of desired amount of densification. *Compactive effort* is defined as the work input of the equipment, measured in foot-pounds per cubic foot of soil. The work input depends on the size and type of equipment, the number of passes, and the thickness of the layer (lift) to be compacted. "Optimum" densification occurs when the combination of water content and roller energy produce a degree of saturation in the soil of 80 to 90 percent. This interrelationship of density, water content, and compactive effort may be best illustrated by means of an example.

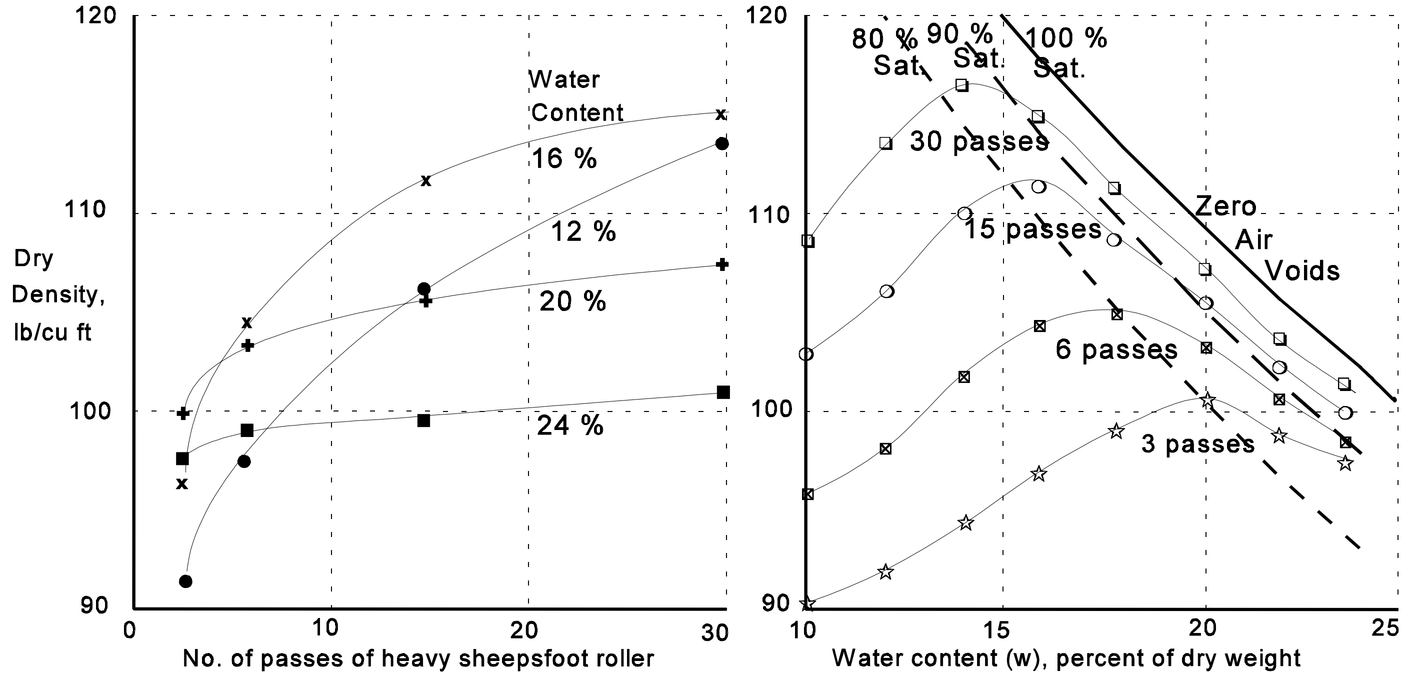
Assume that a rectangular test fill has been made of a silty clay soil using a heavy sheepsfoot roller. Transverse strips of loose soil, about 23 cm (9 in.) thick, are prepared at several different water contents. The roller is operated in several longitudinal strips, each strip subjected to a different number of passes of the roller. Field density tests are made in each area of a different combination of water content and number of passes of the roller, or compactive effort. The results of the tests may be plotted on a three-dimensional surface. Two views of the surface are shown in Figure 7-18, (a) density vs. number of passes of the roller, and (b) density vs. water content.

As shown on the right side of Figure 7-18, the *zero air voids* line is the focus of all points where, for any given dry density, there is a *water content* (expressed as a percentage of the dry weight of the soil) that will result in 100 % saturation. As a loose, partially saturated soil is rolled, the compactive effort overcomes the shear strength due to negative pore water pressure, squeezes air from the voids, and the soil becomes denser. With densification, the degree of saturation increases, and the shear strength decreases, making compaction easier. However, the air permeability lessens, less air is expelled, and more of the compaction energy goes into the pore water. When the *zero air voids* curve, or 100 % saturation density, is approached, further densification becomes virtually impossible.

At a low initial water content, such as 12 % as shown on the left side of Figure 7-18, continued compaction by the roller causes a continued increase in density because the degree of saturation is relatively low. With a slightly higher initial water content, such as 16 % in Figure 7-18, shear strength is lower and the compactive effort is more efficient, resulting in a higher density for a given number of passes of the roller. At an even higher initial water content, such as 24 %, the density quickly reaches the point of almost 100 % saturation and further compaction is ineffective in producing greater densification although the density at a low number of passes is higher because of the lower shear strength. Therefore, for a reasonable number of passes of this roller on this soil, say 4 to 6, the highest density is reached with 16 to 20 % water content, which will approach a degree of saturation of about 80 to 90 percent.

## Effect of Compaction on Soil Properties

The water content and compactive effort at which a given soil should be compacted to achieve a desired shear strength and/or permeability depend on (a) the suitability of the soil,




EXAMPLE OF FIELD DENSITY TESTS MADE OF A TEST FILL OF SILTY CLAY COMPACTED WITH A HEAVY SHEEPSFOOT ROLLER.

Figure 7-18. Effect of variation of water content and compactive effort on the density of a cohesive soil.

(b) the ease of modifying the existing water content, particularly in an area of high rainfall, and
(c) the availability of compaction equipment of a given weight.

## Shear strength and compressibility

The shear strength of soil may be modeled by the Coulomb equation which states that the shear strength $s = c + (\sigma - u) \tan \phi$. In this equation, *c* is the cohesion, independent of external stresses, $\sigma$ is the normal force on the shear plane, *u* is the pore water pressure, and $\tan \phi$ is the coefficient of internal friction.

**Cohesionless soil.** The shearing resistance of a clean, granular soil is a function of the coefficient of internal friction and the effective normal force on the shear plane, i.e., the difference between the total stress and the pore water pressure. The coefficient of internal friction is directly affected by the gradation of the soil, the angularity of the grains, and the relative density. Vibratory compaction increases the relative density. Partial saturation provides a slight increase in the apparent shear strength by increasing the effective normal force. The compressibility of a cohesionless soil is inversely related to shear strength.

**Cohesive soil.** At any specific density and water content, a compacted cohesive soil will have a shear strength that depends, in part, on the negative pore water pressure, a function of the degree of saturation. The lower the degree of saturation for a given density, the greater is the shear strength. However, if the compacted soil is to be used in a water retention structure and is likely to become nearly saturated after compaction, then the strength will eventually become lower, at a constant density, as the amount of saturation increases (Proctor 1933). This effect is shown in the lower half of Figure 7-19. The example soil shown in Figure 7-19 is the same as that shown earlier in Figure 7-18.

For a desired density, the maximum compaction efficiency occurs when the soil is compacted at a water content that will reach about 80 to 90 percent saturation (optimum water content for that soil and compactive effort) at the desired density. Further application of compactive effort produces only a decreasing rate of densification because of increased saturation. No additional saturation appears to be possible when the degree of saturation reaches about 95 to 97 percent Because compaction imparts a pre-consolidation pressure to the soil, the greater the densification, the lesser the compressibility of the soil.

## Permeability (hydraulic conductivity)

Permeability, or hydraulic conductivity, is the rate at which water will flow through a soil. The *coefficient of permeability* is defined as the rate at which water will flow through a unit cross-section of soil under a unit head (pressure). Permeability is not only a property of the soil but also of the permeating fluid. When the fluid is water, the permeability is often designated the hydraulic conductivity.

**Cohesionless soil.** The most significant index of the permeability of cohesionless soils is the 10 percent grain size, $D_{10}$. This is the equivalent spherical diameter for which 10 % of the

Soil, by weight, is finer. An increase in relative density, or degree of packing, causes only a minor change in permeability.

**Cohesive soil.** The hydraulic conductivity of a clayey soil is best understood by considering the structure of the clay. Clay particles exist mainly as flakes or platelets rather than in a roughly spherical shape. Because of electrical charges imparted by ions in the pore water, some clays exist in nature with a highly disorganized, or *flocculated*, structure, in which the platelets have an end-to-flat, random orientation. In a *dispersed* structure, the clay flakes, or platelets, are all roughly parallel and can exist closer together than in the flocculated structure. Clays having a flocculated structure exhibit lower shrinkage, greater swelling, greater permeability, and higher strengths at low strains than samples of the same density and water content but having the clay particles arranged in the dispersed, or parallel, orientation.

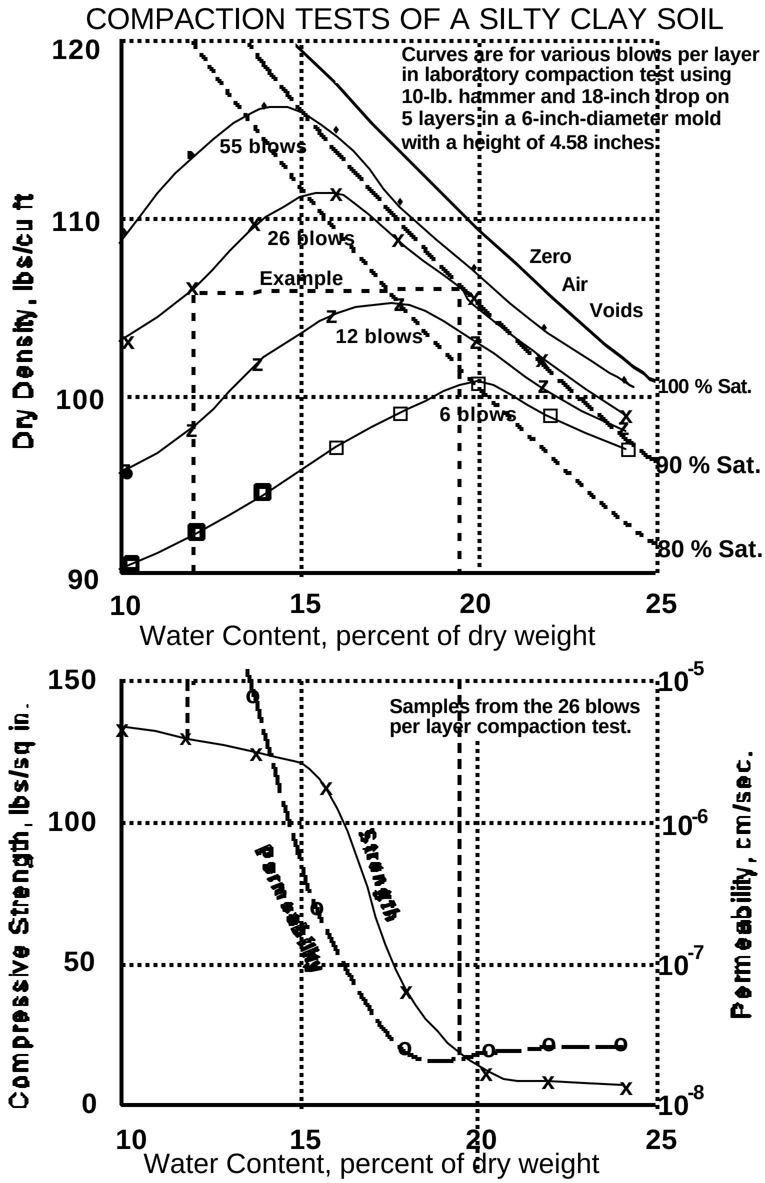



Figure 7-19. Effect of compaction on the strength and permeability of a silty clay soil.

The flocculated structure occurs in soils that have been deposited out of suspension in sea water or ion-bearing fresh water. This includes nearly all sedimentary deposits of clay. The dispersed structure is typical of mixed or remolded soils, whether natural or man-made. Natural sources include glacial till and soils sedimented in the presence of a dispersing agent.

For the example compacted fill described above, and shown in Figures 7-18 and 7-19, assume first a fairly low water content, say 12 percent. Initially, the clay has a highly flocculated structure with low strength but high permeability. At a constant 12 percent water content, as the compactive effort is increased the density increases and the degree of flocculation decreases, the clay platelets become more parallel, but the strength increases and permeability decreases due to the closer arrangement of the flocs. If, now, the water content of another section of fill is raised uniformly to 18 percent, for example, the initial degree of saturation is higher. As increasing compactive effort is applied, the energy needed to break down the flocculent structure and create a dispersed structure is much less because clay platelets in the flocs are farther apart (less strong) because of the higher water content. This effect is especially noticeable when the degree of saturation is on the order of 80 to 90 % or more. Because of the dispersed structure, the permeability is greatly reduced, as shown in Figure 7-19, sometimes by a factor of 100 times or more from samples compacted to the same density but at a lower water content.

The formation of a dispersed structure apparently does not occur when a clay is compacted well dry of optimum (< 80-90 % saturation) and then saturated. Therefore, the strength, and to a great degree, the permeability of a compacted cohesive soil can be controlled by controlling the initial water content and the compactive effort.

### Modifying compactibility with chemicals

Common chemicals mixed with clayey soil will modify the compactibility of the soil by either (a) reducing surface tension resulting from partial saturation, or (b) changing the clay mineral formulation by addition of lime. These materials will be useful only in subgrade soils containing an appreciable amount of clay.

**Surface tension reduction.** Surfactants, primarily sodium phosphates (soap), may be used to reduce surface tension in the water in clayey soils. These include such products as tetrasodium pyrophosphate (TSPP), sodium tripolyphosphate (STPP), and sodium hexametaphosphate (commercially known as Calgon).

These “dispersing” agents cause a reduction in the surface-tension-induced strength of clay particle aggregations, reducing the energy needed for densification by compaction. The applied compactive effort, if the soil degree of saturation is sufficiently high, can then more easily break down the flocculent structure of the clay and cause it to become dispersed, dramatically decreasing its permeability, as described above. Surfactants are typically applied at the rate of 0.25 to 0.5 kg/sq m (0.05 to 0.10 lb/sq ft) by spreading the liquid surfactant on the surface, mixing it in, and the mixture compacted as described above. The actual amount of surfactant used should be determined by laboratory test.

**Addition of lime.** If the clay soil is a CH (in the USCS classification), it has a high plasticity index and high swell-shrink potential. At a normally low water content, such a soil tends to be hard and form clumps or clods that are difficult to crush by normal compaction energies. This generally results from the sodium ions in the montmorillonite clay mineral. The replacement of most of the sodium ions by calcium ions will result in an increase in the plastic limit of the clay, greatly reducing the plasticity index and the swell-shrink potential, and greatly reducing the clod strength of the clay. This form of ion exchange occurs most effectively with the addition of calcium hydroxide, $Ca(OH)_2$, although the addition of calcium chloride, $CaCl_2$, seems to have little effect.

The addition of lime causes flocculation rather than assisting dispersion, as in the case of the surfactants. However, it is one of the most cost-effective methods available for permitting compaction of high plasticity clays by reducing needed compactive effort. Hydrated lime is typically applied by spreading on the surface, mixing in, and compaction as described above. The actual amount to be used should be determined by laboratory test.

## Compaction Specifications

The specified compaction of a soil fill, or the surface layer of existing soil, at a wetland site may consist of fill that is (a) *uncompacted*, or simply dumped and shaped, (b) *semicompacted,* in which lift thickness is unspecified, the soil is placed at natural water content, and compaction is done by uniform coverage of the wheels or tracks of hauling equipment, or (c) *compacted*, involving control of lift thickness, type of compaction equipment, and water content to achieve a specified density. The following discussion deals only with specifications for *semicompaction and compaction*.

Specifications for compacted fill will usually contain requirements for (a) the soil types that may be used or that are to be excluded, (b) the amount of compactive effort or the degree of compaction to be achieved, based on either (for granular soils) a relative density or (for cohesive soils) a percentage of the maximum density from a laboratory Proctor compaction test, (c) the type of compaction equipment that may, or must, be used, and (d) the maximum lift thickness for the selected soil type and equipment.

### Proctor compaction test

In August-September, 1933, Raymond R. Proctor published a series of four articles (Proctor 1933) describing the relationships shown in Figure 7-18. Proctor indicated that, for a given size of roller and a given number of passes, i.e., for a given compactive effort, variation of the water content of a soil in a test fill resulted in a curve similar to the ones shown on the right side of Figure 7-18. For that constant compactive effort, there was a unique water content that resulted in *maximum density*. He termed that water content the *optimum water content*.

Proctor's main concern was with the effect of near-saturation *after* compaction on the strength of a compacted soil. As shown in the lower portion of Figure 7-19, at a density and water content below optimum, the strength is higher than at *maximum density* because of negative pore water pressure from partial saturation. However, the subsequent increase in saturation at the lower density, and higher porosity, from permeating water would cause a greater decrease in strength than saturation would at maximum density. He therefore advised that soils be compacted at or near the optimum water content for the given compactive effort, i.e., at a degree of saturation of about 80 to 90 percent.

In Proctor's time (early 1930's) it was very common to specify compaction by requiring a given size of roller, lift thickness, and number of passes. Proctor and others recognized the effect of water content on density at the specified constant compactive effort and the effect of subsequent saturation on a soil that was compacted at a low density and high strength (because of low degree of saturation). Test fills, using the multiple water content and multiple strip procedure described in the example given above, were used to determine the optimum water content for the contractor's specific equipment and desired number of passes for a given soil. This was a tedious but essential process, particularly with the naturally dry soils being used to construct water retention dams in southern California.

Proctor (1933) described a laboratory test that could be used to define the moisture-density relationship for a given soil that would provide the same optimum water content as that obtained from the very expensive test fill procedure. Proctor selected a compactive effort, in Newton-meters per cubic meter (foot-pounds of energy per cubic foot) of soil, that would closely match the compactive effort of roller weights and number of passes commonly used at that time. With some minor, later modifications to Proctor's test device, this resulted in the now standardized Proctor compaction test. Because the maximum density and optimum water content are sensitive to soil composition, this test was later adopted as a specification standard for quality assurance testing of fill compaction. The maximum density is greatest for coarse grained, well-graded soils and decreases, as the optimum water content increases, with finer soils and with increasing plasticity of the fine fraction.

The Standard Proctor Compaction Test, ASTM (1994) Method D 698, is made by compacting a soil in a cylindrical mold, 102 mm (4 in.) in diameter and about 115 mm (4.5 in.) high. The soil is first uniformly mixed to a given water content. The soil is placed in the mold in three equal layers. Each layer is compacted by 25 blows of a 2.5-kg (5.5-lb) metal rammer falling freely a height of 30.5 cm (12 in.) for each drop. The test is repeated at several different water contents, below and above the *optimum* value to develop a curve similar to those of Figures 7-18 and 7-19.

With the later development of heavier compaction equipment, used for airfield pavements, subgrades, embankments, and earth dams, Proctor's original concept of adapting the laboratory compactive effort to match commonly used field compactive efforts resulted in a Modified Proctor Compaction Test, ASTM (1994) Method D 1557. In this test, the soil is placed in the Proctor mold in five layers, with each layer compacted by 25 blows of a 4.5-kg (10-lb) metal rammer falling freely a height of 45.7 cm (18 in.). Compared to the Standard Proctor moisture-density relationship, the higher compactive effort, for a given soil, results in a higher maximum density at a lower optimum water content, as demonstrated in Figure 7-19.

## Compactive effort requirement

**Cohesionless soils.** The purpose for compaction of a cohesionless soil is to increase shear strength by increasing its relative density. Therefore, specifications for cohesionless soil compaction usually require that the soil be densified to at least a stated relative density. Typical requirements are for the relative density to exceed 60 to 80 percent. Vibration densification is generally insensitive to moisture content; therefore, water content limits are rarely specified.

Because the maximum and minimum densities used for reference are sensitive to gradation changes, the laboratory reference tests must be made for each significant soil gradation change.

**Cohesive soils.** The compactive effort requirement for cohesive soils is sometimes stated by specifying the type, size, and weight of the compaction equipment to be used and the minimum number of roller passes. More commonly, however, a required density is specified, based on the results of a laboratory Proctor compaction test of the selected soil. Sometimes, water content limits are also specified. A typical cohesive soil specification for embankments requires that the soil be compacted to a density at least 95 % of the maximum density determined for that soil in the Standard Proctor Test, ASTM (1994) D 698. This usually results in a higher density than the soil had in its natural, unexcavated state.

When an end-result, density specification is used, acceptance of the work is based primarily on obtaining the required density. The choice of equipment, initial water content, and most procedures are under the contractor's control. Generally, the maximum loose lift thickness is specified. The suitability, or lack of suitability, of certain types of compaction equipment may be specified. For example, it is unrealistic for a contractor to attempt to densify a coarse sand with a sheepsfoot roller. In those instances where the properties of the compacted soil, particularly the permeability, are important, an initial water content range may also be specified. Care must be taken by the specification writer not to require a situation that cannot be met, such as specifying that a given density be attained with too high a water content, or by also specifying the type or size of equipment or the number of passes of the roller. This would, in effect, be an unfair mixing of methods-type and end-result specifications.

## Types of compaction equipment

**Cohesionless soils.** Equipment for vibratory compaction of cohesionless soils consists of rollers or plates and may be self- or manually-propelled. Commonly used types are:

*a*. *Vibrating rollers.* This category includes self-propelled tamping, smooth-wheel, and pneumatic-powered rollers having weights ranging from one to over 15 tonnes (1-15 tons). A typical self-propelled vibratory roller is shown in Figure 7-20.

*b.* *Self-propelled vibrating plates or shoes.* This category also includes crawler-mounted tractors, especially if poor timing makes the engine run roughly, vibrating the tractor.

*c.* *Manually propelled vibrating plates*. These are always sufficiently lightweight to permit manual operation in restricted areas. Used only with very thin (2-5 cm, 1-2 in.) lifts.


Figure 7-20. Self-propelled vibratory roller.

**Cohesive soils.** Compaction equipment for cohesive soils consists of rollers of various types which may be either towed or self-propelled. For use in space restricted areas, various designs of impact tampers are used. The most common equipment types for cohesive soils are:

*a.* *Tamping rollers (sheepsfoot).* The tamping feet, Figure 7-21, are generally on the order of 23 cm (9 in.) long, with an enlarged foot or they may be in the form of elongated prisms.

Figure 7-21. Sheepsfoot roller.

*b.* *Smooth-wheel rollers.* Because of the rigidity of the metal wheel, the contact area tends to be small and the load highly concentrated. Therefore, these are used mainly on mixed grain soils where a high compactive effort on thin layers can be achieved.

*c.* *Pneumatic-tired rollers.* The contact area of the rubber tires depends on tire pressure, the number of tires, and the total load on the roller.

*d.* *Hand-held tampers (jumping jacks).* These are hand-held devices that are powered by pneumatics or a small gasoline engine to deliver a vertical impacting motion. This will tamp, or compact, cohesive soils in thin layers in areas of limited access.

The suitability of various types of compaction equipment for use with various soils, classified according to the Unified Soil Classification System (USAEWES 1960), in embankments and foundations is shown in Table 7-16.

## Lift thickness

**Cohesionless soils.** Typical lift thicknesses for clean granular soils subjected to vibratory roller compaction are shown in Table 7-17. Motorized vibrating base plate units are generally able to effectively compact layers several centimeters (inches) thick. Manually propelled units are usually limited to layers about 5-8 cm (2.-3 in.) thick.

**Cohesive soils.** Lift thicknesses for mechanized rollers used to compact cohesive soils are generally limited to about 23 cm (9 in.) loose to result in a 15 cm (6 in.) thick compacted layer. For steel wheeled rollers and hand-held tampers, the lift thickness is generally held to no more that 5-8 cm (2-3 in.) thick.

**Table 7-16**
**Equipment Suitability for Compacting Soils ***

| Soil Type | USCS Class. | Compaction Equipment |
|---|---|---|
| Clean gravels or clean sands, with low percent fines. | GW, GP<br>SW, SP | Vibratory roller; crawler-tractor; steel wheel roller (thin lifts) |
| Mixed-grain soils with non-plastic fines (free flowing). | GM, GW-GM, GP-GM, SM, SW-SM, SP-SM | Vibratory roller; crawler tractor; rubber tired roller; steel wheel roller. |
| Mixed-grain soils with low- to medium plasticity fines | GM, GC, GW-GM, GP-GM, GW-GC, GP-GC, SM, SC, SW-SC, SP-SC, SC-SM | Rubber tired roller; sheepsfoot roller |
| Low plasticity fine-grained soils | CL-ML, CL, ML | Rubber tired roller; sheepsfoot roller |
| Medium to high plasticity fine-grained soils and organic soils | MH, CH, OL, OH | Sheepsfoot roller |

* Based on Table A1 of "The Unified Soil Classification System," of the USAE Waterways Experiment Station Technical Memorandum No. 3-357 (USAEWES 1960).

**Table 7-17**
**Typical Lift Thickness For Clean Granular Soils**

| Vibratory Roller Weight | | Lift Thickness | |
|---|---|---|---|
| Tonne (metric) | Tons | Meters | Inches |
| 0.9 | 1 | 0.2-0.3 | 8-12 |
| 1.8 | 2 | 0.30-0.46 | 12-18 |
| 4.5 | 5 | 0.46-0.61 | 18-24 |
| 9.1 | 10 | 0.61-0.76 | 24-30 |
| 13.6 | 15 | 0.76-1.22 | 36-48 |

# Tests of Compacted Soils

Tests may be made of the mechanically compacted soils to determine the soil's compliance with a density specification. Laboratory strength tests of field-compacted soil may be made on undisturbed cohesive soil samples. It should be recognized that undisturbed samples of cohesionless soils are nearly impossible to obtain. However, if the field density is known, the laboratory sample can be re-compacted to the field density and tested. Much more commonly, however, field tests of the density and water content are made. A summary of commonly used field density and water content test methods is given in Table 7-18.

**Table 7-18**
**Field Density and Water Content Test Methods**

| Test Method | ASTM Method | Discussion |
|---|---|---|
| Field Density Test Methods | | |
| Undisturbed tube sample | D 2937 | Uses a short section of thin-wall sampling tube. Driven into cohesive fill and retrieved. Weight of soil in tube is determined. |
| Sand cone | D 1556 | A small hole, 15 cm (6 in.) deep is excavated. The soil is carefully retrieved and is weighed. The volume of the hole is measured by filling with sand from a container having a cone-shaped end. The weight of calibrated sand is used to calculate volume. |
| Water balloon | D 2167 | A small hole, 15 cm (6 in.) deep is excavated. The soil is carefully retrieved and is weighed. The volume of the hole is measured by inserting a rubber balloon in the hole and then filling the hole with water from a calibrated container. |
| Nuclear density gauge | D 2922 | A radioactive source of gamma rays is placed in contact with the soil. A Geiger counter a short distance away measures the intensity of gamma rays passing through the soil. The intensity is proportional to the bulk density. |
| Rapid Water Content Test Methods | | |
| Microwave oven | D 4643 | A computer controlled standard microwave oven is used to dry a soil sample to constant weight. |
| Calcium carbide gas pressure | D 4944 | Water in a soil sample combines with calcium carbide in a closed container. The pressure of the acetylene gas is proportional to the water content. |
| Rapid heating | D 4959 | Soil sample may be dried in a pan on a hot plate or burner. Temperature is not controlled, therefore a slight error may be introduced. Useful for coarse grained soils . |
| Nuclear moisture gauge | D 2922 | The radioactive source of the nuclear density gauge also emits neutrons. When the neutrons strike a hydrogen atom, the velocity is halved (thermalized). A counter measures only the fast neutrons. The reduction is proportional to the water content. |

The density and water content of each layer of compacted fill should be measured, as construction proceeds to determine the effectiveness of the compaction method and the contractor's compliance with specifications. Because all of the commonly used test methods measure the total, or bulk, density of the soil, it is necessary to also measure the water content so that the dry density can be calculated. Commonly used methods for rapidly measuring the density and water content of samples of compacted fill were discussed in detail in an earlier section of this handbook. Rapid methods are used in the field to obtain results as construction is proceeding.

# Section 7
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# Wetlands Engineering Handbook

## Section 8

## Monitoring and Evaluating Success

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# 8-1 Introduction[1]

## Background

As wetland projects increase, so does information and debate on the extent that such projects can be expected to duplicate natural wetlands (e.g., Kusler and Kentula 1989, Thayer 1992). Increasing emphasis has been on the need for functional equivalency of wetland projects and natural wetlands lost (e.g., Thayer 1992). This emphasis is in keeping with general concern that management of ecosystems worldwide involve maintenance of ecological processes, preservation of genetic diversity, and sustained utilization of species, populations, and ecosystems (Lubchenco et al. 1991). With emphasis on functional equivalency comes a responsibility both to identify realistic goals for wetland projects and to conduct monitoring evaluations to determine if or to what extent goals have been met.

Long-term evaluations of structural and functional equivalency of project wetlands and natural wetlands are generally lacking (Kusler and Kentula 1989, Thayer 1992). In some instances, no monitoring is conducted at all nor are records kept or checked to ensure that a wetland mitigation project is completed (Kentula et al. 1992). Not surprisingly, consensus views of projects' success are difficult to obtain and will remain so until a more systematic approach is taken to evaluations of wetland projects. More importantly, carefully planned and conducted project evaluations will yield information that will provide a basis for improved enhancement, restoration, and creation technology.

## Purpose and Scope

This section provides a conceptual guide for developing evaluation criteria and monitoring programs for projects aimed at wetland restoration and creation. Local expertise and data bases for particular wetland types must be used along with this guide in order to tailor criteria and monitoring plans to a specific project. Wetland projects typically involve several agencies, organizations, and individuals at local, state, and federal levels. Systematic and thorough monitoring should promote greater consensus as to what constitutes a successful project.

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[1] By Barry S. Payne

## Organization

This section presents monitoring and success evaluation guidance on basic monitoring concepts, assessing wetland hydrology, evaluating soils and vegetation, and fauna usage. Chapter 8-2 defines and discusses basic terms and concepts, outlines a logical approach to determining project goals and evaluation criteria, and presents basic considerations related to monitoring. Chapters 8-3, 8-4, and 8-5, respectively, provide detailed information on how to assess wetland structure and function with respect to hydrology, soils and vegetation, and fauna.

Chapter 8-3 reviews the components of a water budget and how they are assessed and includes specific sections on evaluating water levels and circulation, groundwater recharge and discharge, and floodflow alteration. Chapter 8-4 addresses assessments of soil organic content, particle size and texture, hydric condition, sedimentation rates, basic components of plant community structure, and shoreline and bank stabilization. Chapter 8-5 guides direct assessment of faunal communities in wetlands, including methods of monitoring macroinvertebrates and fishes (indicative of aquatic habitat) and birds (inclusive of terrestrial habitat).

# 8-2 Basic Concepts[1]

## Terminology

To avoid confusion, a few terms used throughout this section need to be discussed at the onset. They are:

*a.* *Reference wetland* - A reference wetland is defined as a natural wetland that sufficiently represents the range of variation in wetland structure likely to be encountered in a specific wetland project. Reference sites are only useful if they are suitably matched to the wetland project site in proximity, size, and function. Comparisons of natural to project wetlands are not the only basis of an evaluation. Indeed, wetland projects can function with considerable success within a particular context even if they have not been intended to duplicate natural wetlands (e.g., Phillips et al. 1993, Pomogyi 1993).

*b.* *Wetland function* - In an ecosystem context, a wetland fulfills roles such as providing habitat for plants and animals, retaining sediments that otherwise would be transported downstream, or protecting banks and shorelines from erosion. These are examples of wetland functions. Monitoring allows evaluation of important aspects of structure and process that bear directly on wetland functions. Table 8-1 presents a comprehensive list of specific wetland functions and values proposed by Smith (1993). Specific lists of wetland functions, especially those related to ecological processes, vary among sources (e.g., Brinson 1993, Marble 1990, SCS 1992). For example, Marble (1990) breaks ecological functions into production export, maintenance of aquatic diversity and abundance, and provision of wetland dependent bird habitat diversity. Chapter 13 of the Engineering Field Handbook of the USDA SCS (1992) on wetland restoration and creation considers ecological functions to include provision of habitat for fish and shellfish, food and timber production as well as habitat for threatened and endangered species and other wildlife. The broadly stated function, maintenance of intra- and inter-ecosystem integrity (Table 8-1), allows monitoring to be tailored to whatever is most important in a particular setting.

*c.* *Performance criteria* - Criteria are used to determine if a wetland project attains specific structural or functional goals as intended by design. Performance criteria should be developed during project design and construction; criteria can be quantitative or qualitative.

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**Table 8-1**
**Functions of Wetlands and Their Value**

| Functions of Wetlands | Value of the Functions of Wetlands |
|---|---|
| Store and/or convey floodwater | Reduce flood-related damage |
| Buffer storm surges | Reduce flood-related damage |
| Recharge groundwater | Maintain groundwater aquifers |
| Discharge groundwater | Maintain base flow for aquatic species |
| Stabilize shorelines | Minimize erosion damage |
| Stabilize streambanks | Minimize erosion damage |
| Detain/remove/transform nutrients | Maintain/improve water quality |
| Detain/remove/transform contaminants | Maintain/improve water quality |
| Detain/remove sediments | Maintain/improve water quality |
| Maintain intra/inter-ecosystem integrity | Maintain plant and animal populations<br>Preserve endangered species<br>Maintain biodiversity<br>Provide renewable food and fiber products |
| Setting for cultural activities | Provide educational/research opportunities<br>Provide recreational opportunities<br>Provide aesthetic enjoyment<br>Preserve archeological and historical sites |

## Performance Criteria

Performance criteria can come from several sources. Criteria can be based on literature values, previous projects, reference site data, or data from the wetland the project was designed to replace, depending on what is most appropriate for a given situation. Carefully planned wetland projects are designed with the intent of creating specific structural and functional features. Performance criteria **must** be based on project goals.

Criteria must be used flexibly enough that unforeseen benefits can be fostered or project expectations (or features) revised if unforeseen factors limit or prevent realization of planned wetland functions (SCS 1992). The technology of wetland restoration and creation is imperfect. Unforeseen benefits of projects (e.g., Landin et al. 1989) should lead to reconsideration of performance criteria prior to judging a site as unsuccessful or deciding to make modifications that might be deleterious to beneficial but unplanned functions.

Scientists that study wetlands, like most scientists, are reluctant to be specific in making recommendations if available information does not allow nearly complete understanding of wetland structure and function in relation to project design. Data on reference sites, whether natural wetlands or enhancement, restoration, or creation sites, are not always sufficient to allow confident development of performance criteria. Uncertainty during planning and design of a project negatively affects confidence with which performance criteria can be developed and used. Nonetheless, trade-offs must be made between the longer process of scientific discovery and investigation and the immediate needs of project managers who must make decisions. Criteria must be developed, but then must be used flexibly, especially if reference information for project planning is unavailable or unclear.

Nearly all project evaluations should include assessments of the basic structural components of a wetland -- water, soils, plants, and animals. Holistic assessment of ecosystem integrity is not practical, but reasonably straightforward measurements can be made of hydrologic and soil characteristics and process as well as numbers and relative abundances of plant and animal species that indicate development and maintenance of a desirable ecosystem (e.g., Roberts 1991). It has been argued that species lists for ecosystems offer the cheapest and most useful approach to answering questions about ecological function (Slobodkin et al. 1980). Within a geographic region, it is appropriate to depend on adaptations of species to indicate environmental conditions (Brinson 1993).

Performance criteria and baseline information may be simple for some wetland projects with highly specific goals. For example, if the goal of a project is sediment retention, then baseline information is needed on initial basin elevations and criteria should focus on sedimentation accretion. Then monitoring can be conducted to determine if the depth of sediment accumulation satisfies performance criteria. However, most projects will involve multiple and more complex goals, and, thus, more complex criteria and monitoring plans.

## Basics of Monitoring

Goals or objectives of a particular project must be related to aspects of wetland structure and function that are capable of being monitored within the manpower, cost, and other limitations. Monitoring of wetland performance in strict relation to performance criteria allows evaluation of a particular projects's “success.” In contrast to such success monitoring, diagnostic monitoring is aimed more at basic research of wetland structure and function. Although both types of monitoring ultimately can help improve wetland restoration and creation methods, diagnostic monitoring should be distinguished clearly from success monitoring tied in a very utilitarian way to a particular project.

Nearly all detailed studies of wetland restoration and creation projects have included among their conclusions that intensive and extensive research is needed to thoroughly understand factors affecting the development of wetland structure and function (e.g., Simenstad and Thom (1992) and Seneca and Broome (1992)). Despite continuing need for research on restored, created and natural wetlands, success monitoring must be carried out for projects now being planned and built. The characteristics that lead to success as well as the causes of less than full attainment of project goals need to be understood. More systematic monitoring of projects (and reference wetlands if appropriate) should augment research-oriented monitoring, with both leading to improved restoration and creation technology.

The scope of a monitoring plan must be concordant with the complexity of a project as well as personnel, time, and funds available. Complete evaluation of functional equivalency of project to natural wetlands generally is not a practical objective. Seneca and Broome (1992), in their review of saltmarsh restoration in North Carolina and France, pointed out that evaluations to determine functional equivalency of restoration projects to natural wetlands are not easy and are likely to be impractical for many small projects. Similarly, Fonesca (1992), with respect to seagrass restoration, noted that determining functional equivalency of restored sites in anything approaching the complete meaning of the phrase is not affordable for many projects and probably is not technically possible.

Frequency and duration of monitoring depend on project complexity, funding, and the specific attributes and functions being assessed. Monitoring should look at both short- and long-term development of a site. Short-term monitoring is generally accepted to include approximately the first six years of development. Within that time span, it is possible to determine if hydrologic function and vegetation establishment are appropriate to design. In general, no less than every three years and no more than quarterly sampling is an appropriate range for the first six years of development, when conditions are changing most rapidly. During this period, site modifications can be made in response to monitoring results.

Long-term is difficult to define with respect to a wetland project. Without doubt, natural wetlands have features and processes that develop over centuries. However, Sacco et al. (1988) demonstrated equivalency of invertebrate communities in salt marsh projects 15 years old. Newling and Landin (1985) reported plant communities at six dredged material marsh creation sites were equal to or more productive than natural reference marshes after an eight-year period.

A timespan of two decades is not an unreasonable one for long-term monitoring efforts. As a wetland project ages, the rate of change in its characteristics and functions should decrease, reducing the required frequency of monitoring during long-term assessments. Ideally, projects should be monitored by organizations that are committed in perpetuity to restoration of wetland resources (although a given project need not be monitored forever).

Monitoring implies periodic observations to observe changes from “baseline conditions.” What constitutes baseline conditions depends on the type of project. If an existing wetland is being enhanced, pre-alteration conditions at the enhancement site must be documented. If a wetland is being created where one never existed or restored where one has not existed for a long time, then baseline conditions probably are the “as-built” conditions of the project. As-built conditions are those that exist when work is completed.

Standardization of methods, to the extent feasible, is important. Methods used to assess baseline conditions must be comparable to methods used in subsequent monitoring. Although specific project goals will determine the precise needs of baseline characterization, a complex and well-funded project could include detailed planimetric and contour maps, an assessment of site hydrology, sediment and water quality data, a complete description of vegetation, and data on invertebrate, fish, and wildlife use. Photographic records are also valuable (Kentula et al. 1992).

A site plan should be made that shows the location, shape, and area of open aquatic, semi-aquatic, and adjacent upland areas, water inflow and outflow structures, dikes built or removed, and general design components. Any uncorrected deviations from original site design should be documented. Site construction maps can often be modified to serve as a base map for sketches or data overlays.

## Multidisciplinary Working Groups

Evaluation of practically any wetland enhancement, restoration, or creation project requires expertise in engineering, hydrology, soils, nutrient dynamics, plant ecology, and animal ecology. A multidisciplinary technical working group should be comprised of regional experts in wetland modification projects and their evaluation. Different participating or concerned agencies and organizations should be represented. A working group of civil engineers, hydrologists, soil scientists, and ecologists with experience in wetland botany and zoology should allow decisions based on the best available information on wetland restoration.

Such technical working groups must form and operate at a regional or local level. It is at these levels that project goals, evaluation criteria, and monitoring programs have much in common. There cannot be a simple cookbook approach to wetland projects. Each project will have its own special aspects, constraints, and subtleties. Regional and local expertise must be consulted to maximize the use of information based on related projects and experiences.

Working groups should be formed with the intent of operating for many years. The longer a group remains operative the greater will be their development of detailed familiarity with enhancement, restoration, and creation technology.

## Information Transfer

A systematic approach to a wetland modification project requires periodic compilation, review, and synthesis of existing information on related projects and natural reference wetlands. National symposia have been very useful in providing overviews of wetland projects. Published proceedings of these symposia are an important source of information that may not otherwise be widely available (e.g., Kusler and Kentula, 1989; Thayer 1992). However, it is important that similar exchanges and publications of information occur at local and regional levels.

Publication of wetland project design, construction, and monitoring results is encouraged. Many projects, especially small mitigation sites, go largely unreported (Kentula et al. 1992). Information transfer is often not a priority at the project level. Improved reporting is greatly needed. Both government technical reports and refereed scientific publications are desirable. Such publications should be considered in addition to project files and other essentially internal working documents that are not designed to broadly disseminate information.

# 8-3 Monitoring of Hydrologic Functions[1]

## Groundwater Recharge and Discharge

Groundwater recharge and discharge may be principal components of inflow and outflow from a wetland and thereby be instrumental to other wetland functions such as sediment and pollutant retention, nutrient transformation, and aquatic productivity. Comprehensive monitoring of groundwater flow to evaluate the contribution to wetlands requires a series of piezometer nests. Optimum locations and depths of piezometer nests should be determined by a qualified hydrogeologist familiar with the area. Such a hydrologist should assist in developing a data collection schedule and system for keeping records. Methods for compiling and analyzing data, such as flow nets and hydrographs, should be determined.

Similar piezometric tests are also required in the design stage to gather data on the direction and rate of groundwater flow (see Section 8-2). Where possible, the location of these piezometers should be satisfactory for post-construction monitoring and evaluation success. If a monitoring program involving piezometers or observation wells cannot be implemented, the next best course of action is to determine the location of nearby meteorologic and hydrologic monitoring stations, and acquire proxy data from them. These data, along with more qualitative measures such as water temperature surveys, hand-held stage surveys, and vegetation mapping, can serve to characterize the role of groundwater in a wetland's water budget (see Figure 8-1 and accompanying discussion).

## Flood-Flow Alteration

Temporary storage of peak flow from runoff, channel flow, groundwater discharge, and precipitation in wetlands may delay movement of potentially damaging floodwaters. The capacity of a wetland to alter flood flow in part depends upon its position in the watershed. Wetlands in the upper watershed are more likely to comprise a significant portion of the drainage.

[1] By Barry S. Payne

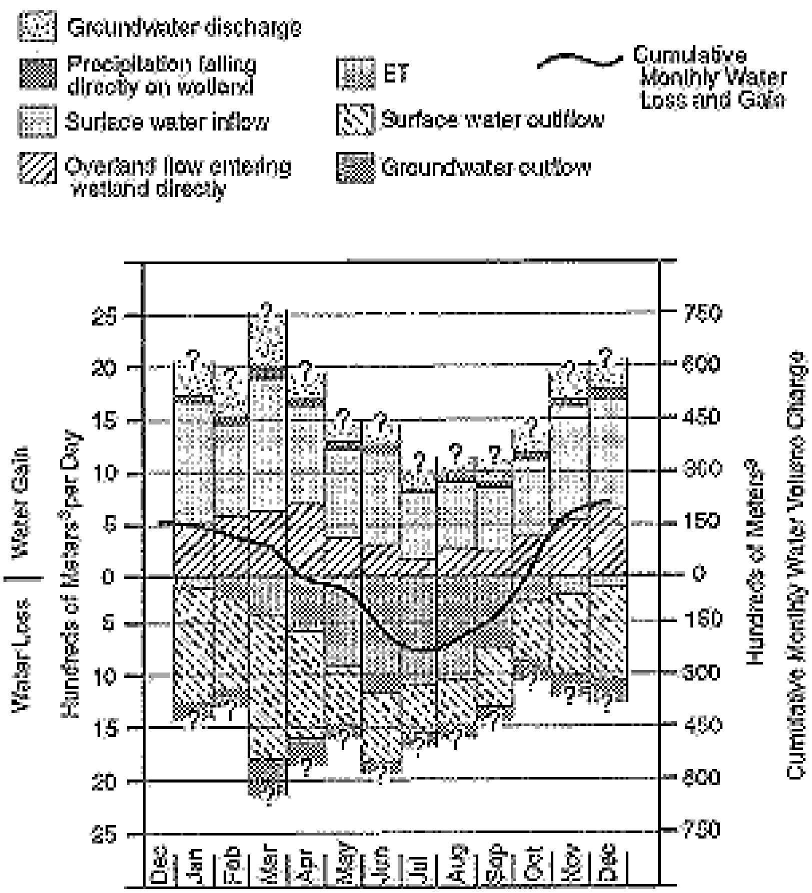


Figure 8-1. A hypothetical wetland water budget. The volume of water involved in a particular wetland water budget will vary widely from the numbers shown here, depending on the size of the watershed, position in the watershed, climate, hydrogeology, etc.

However, because many wetlands are often at or near saturated conditions, their capacity to alter flood flow is questionable. Wetlands probably do not significantly affect floods with frequencies greater than 25 to 100 years.

Stream stage must be monitored (using methods earlier described) to ascertain a wetland's affect on flood flow. Ordinary stage gauges may be ineffective and sites inaccessible during floods. A crest stage gauge, which measures the highest water level since last reading, is needed. Crest gauges operate by depositing cork dust along the sides of pipe which is open to the aquatic system. Cork dust is available through the Water Resources Division offices of the USGS.

Degree of saturation just prior to flooding largely determines the capacity of a wetland to alter flood flow. If wetland water level is low at the onset of flooding, more potential exists to alter flood flow. Emergent vegetation at crest stage creates drag, reducing water velocities and thereby altering flow. Density of such emergent vegetation can be measured as an indicator of a wetland's capacity to alter flood flow. Plant densities can be measured using aerial photographs or field surveys. Monitoring by aerial photographs alone measures canopy density rather than stem and trunk density which controls flood-flow alteration. Stem and trunk densities are best measured by counts along established transects. Techniques for establishing transects and taking plant counts are described in Chapter 8-4. When taking plant counts for analysis of flood-flow alteration, only those plants which would remain emergent at crest stage should be counted.

The shape and degree of bottom roughness also influences flood-flow alteration. Broad, rough, shallow areas reduce water velocities and thereby slow downstream progress of flood flows. In addition, bottoms that are morphometrically complex disrupt and thus lengthen flow paths. The relative proportion of shallow water areas available during floods should be mapped amd the extent of inundation during floods inspected. Mapping may be done using either aerial photography if canopy is not too thick, or by field surveys. Mapping the extent of inundation can also be used to calculate the volume of water stored during flooding. Maps showing the extent of inundation for major floods (return frequency of 2 years or longer) should be kept on file for comparative analysis.

Degree of constriction at the surface water outlet influences the capacity of a wetland to alter flood flow. Determining degree of constriction of surface water outlets during flooding is often difficult due to access limitations. Post-flood inspections of the scoured area swept free of debris in the lower portions of a wetland can provide qualitative evidence of the extent and rate of surface water outflow during floods.

Stage information before, during and after floods, and maps of extent of inundation can be used to evaluate the volume of water temporarily stored during crest stage (using methods earlier described). Comparison of water volumes, crest stage height, and areas of inundation with previous flood information provides a means to analyze how a wetland responds to different depths of inundation.

The ultimate measure of the capacity of a created or restored wetland in altering flood flow is determined by a perceptible reduction in crest stage downstream from the wetland. This can be evaluated by comparing recent flood stage readings with historical records of the USGS or State Water Resource Division (WRD) offices. A list of state WRD offices may be obtained from the EISC (800-USA-MAPS).

When comparing recent and historical floods, rainfall and snowmelt amounts must be taken into account. This information is available in newspapers which are archived in public libraries. Moisture conditions prior to flooding should also be considered. Antecedent conditions can be assessed by examining stream stage records for the week leading up to a flood.

The ratio of rainfall to runoff is strongly controlled by land use. In particular, conversion to residential, commercial or industrial markedly increases runoff relative to infiltration, and thereby increases flood peaks and decreases baseflow. If a significant portion of land in a watershed is altered such that the amount of runoff relative to infiltration increases, downstream flooding may increase even if a wetland is effectively altering flood flow. Therefore land use change, both present and past, must be considered. If land use changes have decreased infiltration, water tables and baseflows have most likely declined. Comparison of recent and historic baseflow records should indicate the impact of land use change.

# 8-4 Monitoring Soils and Vegetation[1]

## Soils and Sedimentation

The condition of soils in a wetland system largely affects many functions, including groundwater recharge and discharge, pollutant retention, and biotic diversity and abundance. Sedimentation rate and soil characteristics can be highly indicative of pollutant and nutrient retention and can provide for indirect assessment of this wetland function. Sedimentation rate is often closely coupled to nutrient and pollutant removal and its measurement provides at least an indication of a wetland's potential to perform these other functions. Organic soils enhance pollutant capture by supporting biological and chemical removal processes. Extremely clayey or sandy soils are less effective at trapping pollutants than are intermediate soils. Also, medium texture soils allow infiltration but not rapid transport into the groundwater.

Important aspects of soil condition to monitor include organic content, texture and particle size, sedimentation rates, and whether or not hydric soils are present. Soil samples must be taken throughout the wetland to determine these soil properties. For properties which change with time such as organic content, sedimentation thickness, and hydric state, samples must be taken periodically to evaluate temporal changes that may occur.

Soil cores should be taken in random transects from the wetland approximately according to the following schedule: initial characterization, one year after project completion, and approximately every three years later to evaluate soil conditions. The same samples should be used for organic content as well as texture and particle size analysis. The size, configuration, and variability of soil types present should determine the total number of samples to be taken. In a small, homogeneous wetland, approximately 10 samples are likely to be enough. Large complex wetlands may require a stratified random design for sampling, with 5-10 samples taken within each stratum. Cores should be taken to at least a 7.5-cm depth, unless deeper topsoil has been placed in a created wetland. If at least 100 g of soil are not obtained at a given sampling location, a second core sample should be taken in proximity to the first (i.e., a few inches away). Approximately 100 g of soil are needed for analysis of organic content; approximately 40 g are needed for particle size analysis.

[1] By Barry S. Payne

## Hydric Condition

Anaerobic conditions that develop in inundated or saturated soils cause chemical reduction of soil components, such as iron and manganese oxides, and lead to characteristic colors and other physical properties that are indicative of hydric soils (Federal Interagency Committee for Wetland Delineation 1989). Hydric soils can be organic or mineral. Nearly all organic soils are hydric and readily identified. Mineral soils that are hydric are identifiable by gleying and mottling that accompanies reducing conditions. Procedures summarized here for identifying hydric soils are a digest of detailed information provided in the federal wetland identification and delineation manual (Federal Interagency Committee for Wetland Delineation 1989). These procedures are useful not only for delineation of wetlands but also for determining the suitability of sites for wetland restoration or monitoring the changing soil conditions in restored and created wetlands.

Sampling involves digging of soil pits 1 foot in diameter and two feet deep or to the water table, whichever occurs first. In small, homogenous sites a single pit suffices. In larger and more complex sites, several pits will be needed to characterize different microhabitats. Ideally, pits should be dug seasonally rather than just once a year.

The water table depth per pit should be measured and the soil horizon's characteristics described. Samples should be collected from each identifiable layer in the soil horizon or at regular intervals down the pit wall. Organic soils are readily identified as either peats (original plant material being barely decomposed) or mucks (original plant material so decomposed that it is not recognizable) or a combination of peats and mucks. Mucky soil feels greasy and will leave the hands much dirtier than peaty soil. If the soil horizon is peat, muck, or a combination to a depth of 18 inches, it is classified as organic and is almost certainly hydric.

Mineral soils should be evaluated using the Munsell color chart noting texture, moistness, and presence of roots and pores. Gleyed (sticky clay) mineral soils are usually neutral gray but can be bluish gray if soluble ferrous iron has been removed. A mineral soil that is hydric will be gleyed to the surface except for oxidized zones around penetrating roots and pores. Nonhydric soils can also be gleyed (not to the surface), but will be interlayed by reddish or brown layers. Where soils are periodically inundated or saturated, alternate periods of reducing and oxidizing conditions will lead to mottling. Mottles are spots of different colors interspersed with the dominant color. Abundance, size, and color of mottles indicate the duration of saturation and indicate if a soil is hydric. Hydric mottled soils tend to be greyish with brown or yellow mottles.

## Sediment Retention

Retention of sediment is a widely recognized wetland function and often a goal of restoration and creation projects. Sedimentation rate is important to the soil-building process, alters water storage capacity and thus the flood-flow alteration function of wetlands, and colonization, growth, and survival of plants and animals. Natural wetlands vary greatly in their sediment accretion rates; annual rates range 100-fold, from slightly less than 0.01 to slightly more than 1 inch (e.g., Shepard and Moore 1960, Rusnak 1967, Walker 1970, Eckblad et al. 1977, Nanson 1980, and Cooper et al. 1986). Unless sediment trapping (or pollutant and nutrient retention associated with sediment trapping) is a specific design goal of a wetland, sedimentation rates in the lower half of this range are probably preferable.

Many approaches can be taken to measuring sedimentation rates. Sediment traps are most often used. These vary greatly in design, but all are containers of some type that are open at the top. Drawbacks of sediment traps are artifactual effects of trap design (especially in flowing water). Another approach to sedimentation measurement involves using graduated reference stakes or rods driven into the ground. Limited access and inability to see the portion of stakes underwater are disadvantages of this second approach. Photographic records of alluvial fans that form at inlets can be used to qualitatively assess sedimentation.

Sediment traps are probably the most convenient monitoring method for sedimentation rate in most wetlands. The height:mouth ratio of sediment traps is an important variable, especially in flowing or turbulent water. Trays or cakepan-like traps (low height:mouth ratios) work well in still water, while cylinders (high height:mouth ratios (>5)) are preferred in flowing water. In wetlands, water is usually calm, and tray-type traps will work in most applications.

Placement of traps depends on study objectives and access. If a goal is to build a data set for predicting declines in water storage capacity, then an array of traps will be needed to represent conditions throughout the wetland. Emphasis should be given to trap placement near inlets, as these are often the sites of highest sediment accretion. If the comparative performance of a project to a reference wetland is desired, then only a few traps in inlet areas of high sediment accumulation may suffice.

A typical cakepan-type trap is shown in Figure 8-2. The pan is attached to a PVC pipe that is placed over a stake driven into the sediment. A wedge driven into the top of the pipe will prevent the pipe and attached pan from pivoting around the anchor stake. To remove the pan, it simply must be covered, the wedge removed, and the pipe and pan lifted up. A ruler can be used to measure sediment accumulation in the field, or the pan's contents can be returned to the laboratory and dried and weighed. Pans measured in the field can be emptied and reset on the bottom. If monitoring cannot be done often, then traps should be retrieved annually after the high water season that typically occurs in late winter/early spring. If seasonal irregularities of sedimentation need to be quantified then a more rigorous schedule is needed.

## Vegetation

The rate, extent, and community composition of plants that become established in a restored or created wetland bear greatly on function. Monitoring of plant communities is essential to evaluating the success of a wetland project. Interactive effects of wetland hydrology, soils, and vegetation largely determine ecosystem characteristics and function. As has been mentioned, vegetation affects hydrology (e.g., evapotranspiration and flood-flow alteration), sedimentation, and shoreline stabilization, and influences habitat suitability with respect to wildlife, birds, fish, and macroinvertebrates.

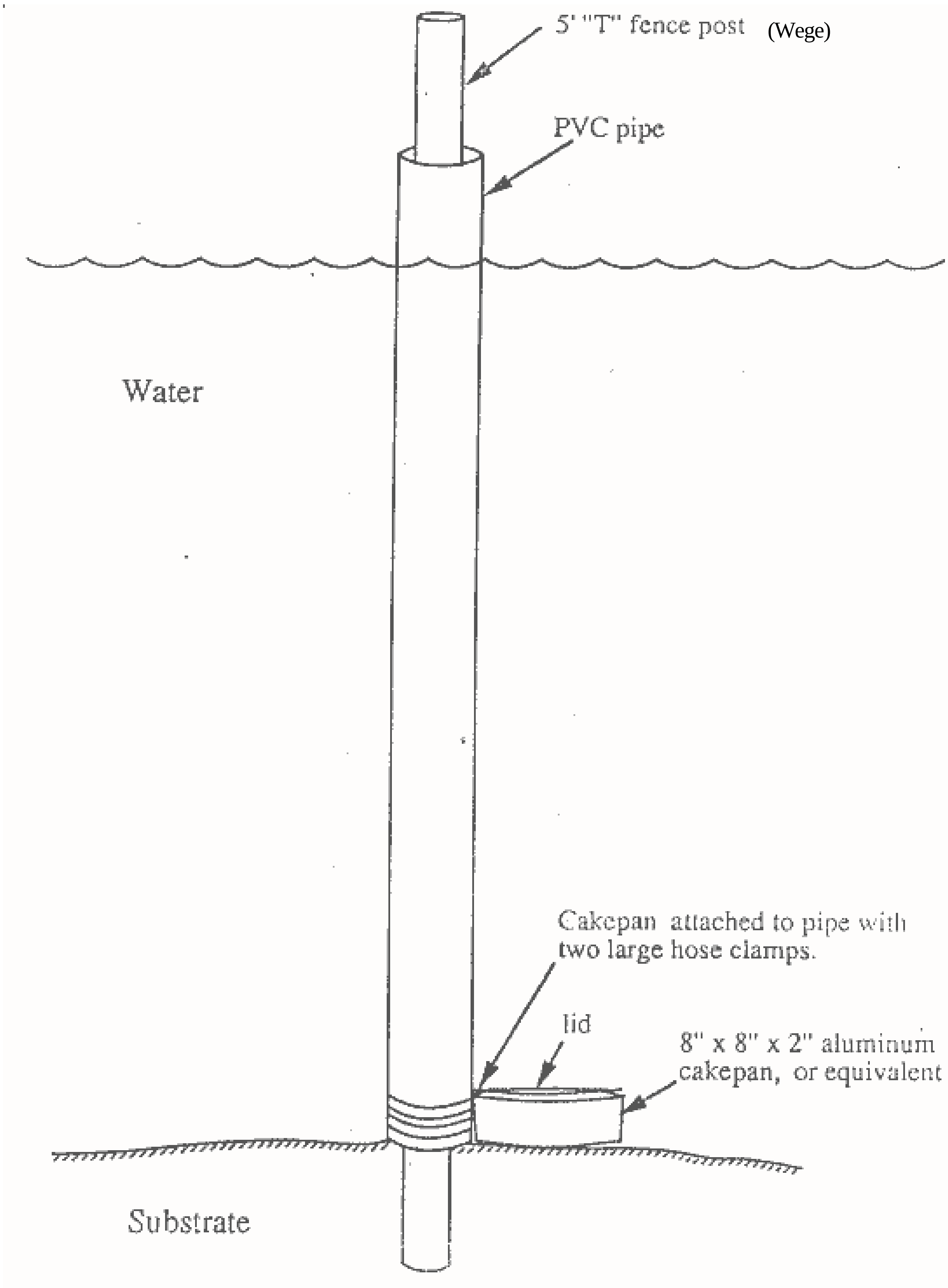


Figure 8-2. Cakepan-type sediment trap assembly.

Hydrophytic plants require continual or sustained, periodic inundation by water and are important in delineating a wetland (Federal Interagency Committee for Wetland Delineation 1989). The U.S. Fish and Wildlife Service has classified plants based on their probability of occurring in wetlands using five categories: obligate, facultative wet, facultative, facultative upland, and upland (Reed 1988). This list should be consulted by botanists involved in project monitoring.

Essentially three approaches are used to quantify plant communities in wetlands. The canopy coverage method is used to determine the relative abundance of vegetation less than 1 m tall. The line intercept method is used to determine the relative abundance of small trees and shrubs less than 2 m tall. Lastly, for mature wetlands, the belt transect method is used to assess relative abundance of larger trees and shrubs. Each method requires taxonomic expertise: plants are identified to the species level. Any plants that cannot be identified in the field are bagged and pressed, and brought back to the laboratory for subsequent identification.

All three methods involve measurements made along transects (each transect is typically 60 m long). Permanent transects are usually used such that precisely the same areas are sampled during each monitoring effort (if trampling or destruction of plants is problematic, then sampling of permanent transects may not be the best approach). Sampling is usually conducted when the canopy is fully developed within the growing season. For comparisons among years it is important to sample on approximately the same date such that plants are in the same phenological stage each year.

The canopy coverage method (Daubenmire 1959) uses a series of 0.25-$m^2$ quadrants (0.5 m x 0.5 m) placed along a transect (Figure 8-3). Spacing of quadrants is determined according to wetland size and the number of transects being sampled. In very small wetlands (< 0.3 hectares), quadrants are typically spaced at approximately 3-m intervals along each transect. Spacing of quadrants at 6-m intervals is more appropriate in larger wetlands. A minimum of 40 quadrants is recommended. A 60-m tape is laid to define each transect, and quadrants are positioned to the right of the tape. If water is present, the depth should be recorded in the same corner of each quadrant along the transect. Canopy coverage is estimated by imagining a vertical projection from the undisturbed canopies to the ground within the quadrant (plants do not have to be rooted in the quadrant). Canopy coverage of each species in the quadrant is estimated using a range from a series of canopy coverage classes; the cover class for bare ground also must be estimated.

The line-intercept method (Canfield 1941) is used along the same 60-m transects, with the investigator staying to the left of the tape to avoid trampling the canopy coverage transect. Each small tree or shrub for which a vertical projection of its canopy intercepts the transect is included. Intercept lengths are estimated as the portion of the transect intercepted by the vertical projection of foliage.

The belt transect method (Phillips 1959, Daubenmire 1968, Mueller-Dombois and Ellenberg 1974) is used in mature, forested wetlands. All trees with at least one half of their trunk inside a 2-m belt (using a 1-m photo pole) to the left and right of the tape are included. Again, the investigator walks along the left of the tape to avoid stressing the canopy coverage sampling plots. Trees exactly bisected by the boundary of the belt should be counted as one half. The species

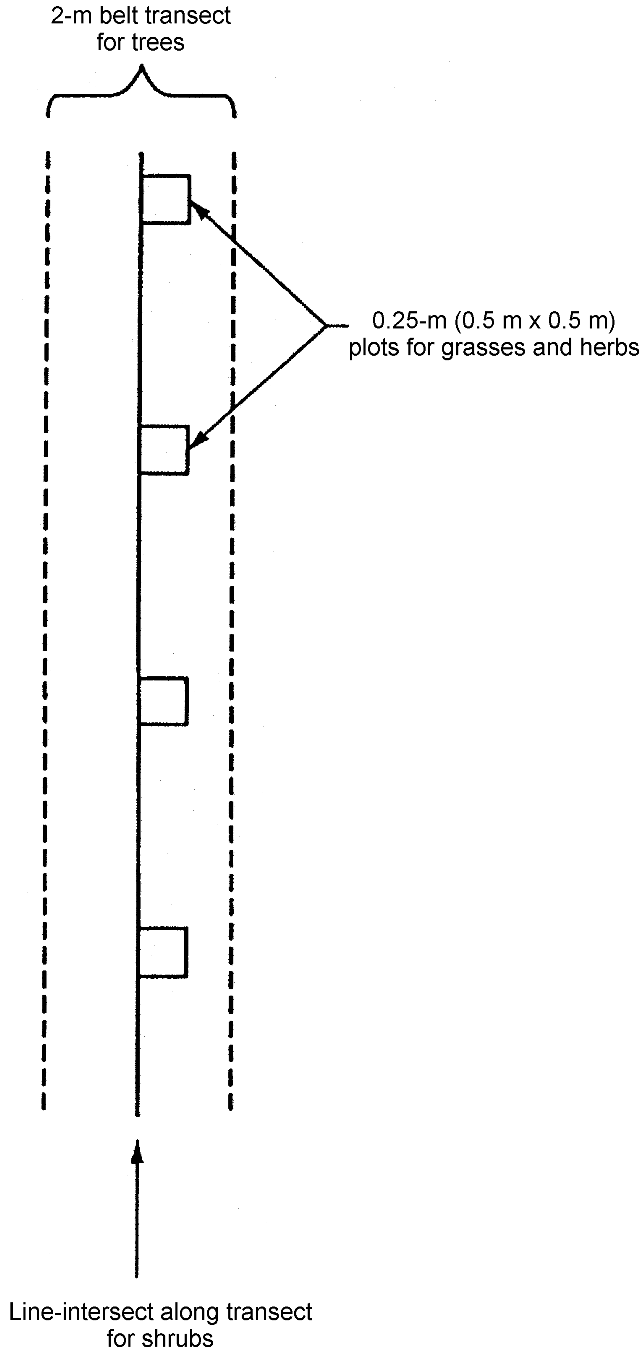


Figure 8-3. Plant sampling along a 60-meter tape

and diameter at breast height (DBH) of each tree encountered are recorded. The 10-cm division of the photo pole can be used to measure DBH.

Dominant species within each of the three canopy strata can be identified from the results of this sampling effort. Transformation of raw data from each method is required to determine species relative abundances.

Transformation of data collected by the canopy coverage method involves summing the average canopy coverages per species. This value frequently exceeds 100 -- both because it is based on raw coverage values and there can be multiple canopy layers. Canopy coverage of a single species is the sum of midpoint values recorded for that taxon; average coverage per species equals the sum of midpoint values divided by the number of quadrants sampled. Total coverage by all species is simply the sum of average coverage of the individual species. Relative abundance of a particular species equals its coverage divided by the total coverage of all species. Another useful measure is percent bare ground.

Transformation of data collected by the line-intercept method involves summing the intercept lengths for each species. Species relative abundances are computed as species-specific intercept length divided by intercept length of all species combined. Relative abundances are computed similarly from the belt-transect data, except that trunk basal areas are used instead of intercept length.

Once relative abundance data are compiled it is useful to construct a dominance-diversity plot (species-specific relative abundances plotted against dominance rank from most to least abundant). Tabulation of the total abundance of all obligate, facultative wet, and facultative plant species is also useful, serving as a quantitative indication of the degree to which wetland vegetation is dominant (relative abundances of some or all such species are likely to be included as success criteria for a restoration or creation project). A variety of diversity indices can be computed using species relative abundance data (see Magurran 1988 for discussion). Two of the most commonly used diversity measures are the Shannon-Weaver Index (H ) and Pielou's evenness index (J ):

$$H = p_i \log(p_i) \qquad (8\text{-}1)$$

and

$$J = \frac{H}{\log(S)} \qquad (8\text{-}2)$$

where S = total number of species and $p_i$= relative abundance of species i.

Another aspect of community analysis worthy of mention is the difficulty of sampling all species actually present. Typically, the cumulative number of species increases as a linear function of the logarithm of sampling effort - whether effort is measured in cumulative area or individuals sampled. Thus, species lists or estimates of species richness should never be presented nor analyzed without an accompanying statement of the sampling effort (see Magurran 1988 for additional information and advice on richness estimation).

## Shoreline and Bank Stabilization

Most vascular wetland vegetation stabilizes shorelines, with the degree of stabilization being largely a function of vegetated area width and emergent plant density. Both can be measured using aerial photographs or field surveys. Monitoring by aerial photographs alone measures canopy density rather than stem and trunk densities. Stem and trunk densities are best measured by counts along established transects (see section on vegetation characterization). Dean (1978) provides formulae for calculating expected reduction in wave height and energy from measurements of stem density, spacing of emergent plants, water depth, width of the vegetated area, and incident wave height. Recording and graphing plant densities and vegetated area width over time is a means to monitor wetland shoreline stabilization capacity.

Soil particle size determines the capacity of waves and currents to transport sediment (Figure 8-4). In a restored or created wetland, the substrate (soil) will adjust to the new biogeochemical conditions. These changes should be monitored to determine if these alterations enhance or detract from the wetland's capacity to stabilize sediment. Likely changes will be in soil cohesiveness and ability to support vegetation.

Shape and degree of substrate roughness influence shoreline stabilization. Broad, flat shallow water areas dissipate potentially erosive wave and current energy. Wetland bathymetry and topography should be periodically surveyed. More than one survey per year may be required if a wetland's morphometry changes with season.

Fetch influences coastal wave and current regimes as well as height of storm surges. Changes in fetch on water bodies adjacent to wetlands could modify a wetland's capacity to stabilize its shoreline. Fetch can be monitored by aerial photography or field observation. Any changes in fetch should be compared to wave and current regimes and height of storm surges.

Most shoreline and bank erosion occurs during storms and floods. Frequency of intense storms or large floods and their effects on wetland shoreline stability must be monitored. Meteorologists and climatologists can provide information on the frequency of recurrence of intense storms or large floods. The likelihood of occurrence of storms and floods decreases with their magnitude. When analyzing storm recurrence, it is customary to think in terms of storms with the probability of occurring once in a one-, two-, five-, ten-, twenty-five-, fifty-, and one-hundred-year period. This enables the analyst to evaluate how common such a storm or flood may be and, in the case of shoreline stabilization, how successful a wetland is in providing that function.

After an intense storm, some shoreline and vegetation damage is expected. Long-term shoreline stability becomes a function of the rate at which the shoreline and vegetation reestablishes, and whether the shoreline and vegetation are able to sufficiently recover so that succeeding storms do not compound shoreline instability. Recovery time can be monitored by field observation. A series of photographs taken from designated locations in designated

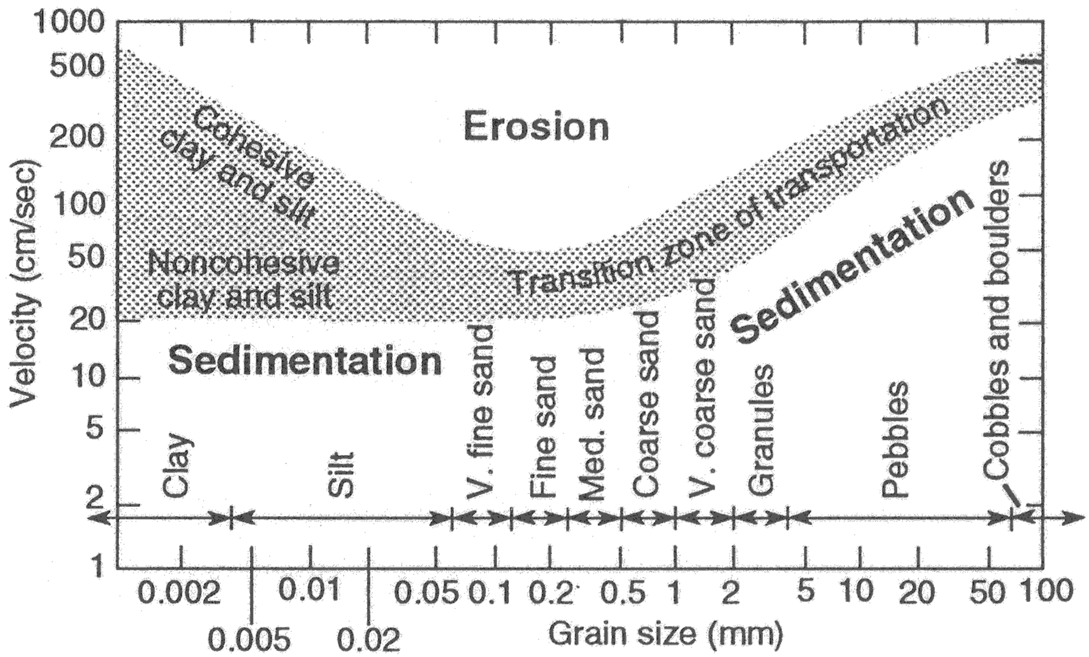


Figure 8-4. General relationship between sediment size, water velocity, deposition, and transport. Measurements were made on flat granular bed of quartz sand. For a specific grain size, the lower limit of the gray zone demarcates the velocity at which all particles of that size fall to the bed. The upper limit of the gray zone demarcates the velocity at which all particles of a particular size continue to be reentrained from the bed. The gray zone is broad because many of the physical properties of the water and grains are not accounted for by size and velocity alone. The gray zone in the silt and clay size portion is especially broad because of the electrostatic forces binding clay minerals.

directions provides a consistent record of shoreline stability over time. Photograph locations should be recorded on the appropriate topographic map with an arrow indicating direction of view. The location, direction of view, and date should be recorded for each photograph, and the photos kept in a file. The ground photographs can be supplemented with aerial photographs to monitor shoreline stabilization over time.

Successful shoreline or bank stabilization is probably best measured by comparison to nearby natural shorelines not protected by wetlands. A logical approach to monitoring is to install or establish benchmarks that can be used as references for judging whether erosion is occurring, and, if so, at what rate. Photographic records are also valuable. Vertical benchmark posts should be driven into the ground to a point deeper than that to which erosion is anticipated; emphasis during placement of benchmarks should be on probable sites of erosion. Monitoring then is relatively simple and can be done during each site visit. The most important season for monitoring will be soon after winter/spring storms. Measurements should be made to determine the distance from the benchmark references to the shoreline. Depending on the nature of the shoreline and the erosion, this may be vertically down the benchmark post or along a sloping bank.

# 8-5 Faunal Utilization[1]

## Faunal Diversity and Abundance

Wetlands support diverse and abundant faunal communities. Wetland vegetation provides a source of nutrients, cover, feeding and egg-laying surfaces, and substrate for locomotion for many freshwater invertebrates. The high productivity of invertebrates among wetland plants or on shallow flats with productive algal mats that provide trophic support to many freshwater and saltwater fishes depends on shallow wetland habitats during some stage of their life cycle. Partially submerged wetland plants provide important habitat for juvenile fish communities (Turner 1977; Boesch and Turner 1984). Birds associated with wetlands, because of their mobility, visibility, and diverse habitat utilization patterns, can be surveyed to indicate overall habitat diversity and quality.

## Macroinvertebrates

Quantification of macroinvertebrate abundance and diversity in wetlands is necessary for direct evaluation of aquatic diversity and abundance. Such quantification will be useful in developing empirical bases for judging wetland quality based on macroinvertebrate community composition. Although macroinvertebrate-based indices of biotic integrity have been developed to indicate quality of different aquatic habitats (e.g., Hilsenhoff 1982, Modde and Drewes 1990, Guhl 1987, and references within these), no such indices have been specifically adapted to wetland evaluation. Until such indices are developed, the most appropriate way to evaluate the degree of successful wetland function is in comparison to macroinvertebrate community characteristics of carefully selected reference wetland sites (i.e., sites representing the goal for aquatic habitat development in a restored, enhanced, and created wetland project).

Aquatic macroinvertebrates, as discussed in this section, are invertebrates that are large enough to be seen by eye, can be retained on a U. S. Standard No. 30 sieve (0.595 mm openings), and live at least part of their life in or on substrates in a body of water. Major taxonomic groups in freshwater include insects, annelids, molluscs, flatworms, nematodes, and crustaceans. In saltwater, the major taxa are molluscs, crustaceans, coelenterates, poriferans, and bryozoans. The abundance of species varies greatly seasonally, especially in freshwater habitats, and this potentially great seasonal variation should be taken into account in designing sampling programs.

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[1] By Barry S. Payne

Macroinvertebrates are important members of the food web, and the health of these communities is usually reflected in the health of vertebrate communities, including fish.

However, only cursory evaluation of macroinvertebrate utilization of wetlands has typically been included in even relatively detailed monitoring of restored and created wetlands (e.g., Landin et al. 1989).

Selection of sampling sites for macroinvertebrate assessments may be systematic or at random. Systematic samples are often used for qualitative evaluations such as synoptic surveys and reconnaissance studies. Such systematic surveys are useful for estimating sampling precision and appropriate numbers of replicate samples for subsequent quantitative surveys. Line transects across a channel or wetland sampled at a set interval is an example of a systematic sampling technique that is useful in mapping and delimiting habitat types. Another form of systematic sampling is when an investigator, sometimes using a variety of gear, consciously selects and intensively samples all recognizable habitat types. This survey technique is useful for comparative studies where qualitative comparisons are being made (e.g., to compare taxa richness but not density among habitats).

Quantitative studies provide a measure of sampling precision, and thus allow use of inferential statistics for comparisons among sites. Some type of randomization procedure must be used in selecting sampling sites. Often, the wetland should be stratified into distinct habitat types (based on factors such as substrate, velocity, depth, vegetation, and, in estuaries, salinity). Then random sampling is conducted within each habitat type. Alternatively, systematic random samples can be taken. For systematic random sampling, placement of a transect or grid cell array, for example, is at random within a site or site stratum, and subsequent samples along the transect or within the grid cell array are taken systematically. To avoid the problem of pseudoreplication (Hurlbert 1984), replicate sites, each sampled in turn in replicate, for each habitat type are needed if quantitative comparisons are to be made between habitat types. The question of how many samples must be obtained depends on characteristics of the site, community, and the degree of precision desired. However, a minimum of three replicate samples must be obtained per site to obtain a measure of sampling precision.

Quantitative or qualitative methods can be used to obtain samples. Quantitative methods are those that provide an estimate of number of individuals and taxa per unit area. Qualitative sampling relies on devices such as sweep nets, dip nets, rakes, tongs, shovels, trowels, hands, and forceps. The advantages of quantitative methods are: a measure of standing crop density is provided, replicated sampling provides a measure of precision that allows use of inferential statistics for comparative evaluations, and data of different investigators can be compared. Disadvantages of quantitative methods include: different devices are required in different physical habitats, sample precision is frequently low and thus a high number of replicates can be required, and sample processing is time-consuming. Qualitative methods offer the advantages of wide latitude in collecting techniques and usually can be tailored to minimize sample processing time. The limitations of qualitative methods are the lack of accurate estimation of standing crop density and minimal ability to compare data taken by different investigators.

Quantitative sampling devices useful in plant-free habitats include benthic grabs, coring devices, Surber samplers, artificial substrates such as rock-filled baskets and trays or multiplate samplers, and drift nets. Used carefully, corers can also be used among plant beds to sample sediments without incorporating plant stems and leaves (Beckett et al. 1992). Among plant beds, the density of macroinvertebrates on plant surfaces can be estimated per surface area of bottom using stovepipe samplers or quadrants. This approach often results in an extensive sample processing effort. Thus, alternative methods have been developed to quantify invertebrates on plants, including estimates of number and taxa per unit length, area, or biomass of clipped plant fragments.

Sample processing is a major consideration in macroinvertebrate studies. Substrate samples must be sieved through a U.S. Standard Number 30 or finer sieve (if finer sieves are used they should be nested under a number 30 and sample fractions sorted separately because of the wealth of published data based on use of a number 30 sieve). The number 30 sieve is not sufficient to capture often abundant benthos such as many oligochaetes and small instars of chironomids. If possible, sieving should be done in the field prior to sample fixation and preservation. Sample fixation should be in dilute formalin (5 %) followed by preservation in 70 % ethanol. The addition of vital stains such as rose bengal, ideally prior to fixation, greatly facilitates sample processing.

Sediment samples for wetlands often include much detritus that makes sample processing especially time-consuming. If densities of macroinvertebrates are relatively high (> 1,000 per square meter), then subsampling prior to sorting is a must (unless small diameter corers are used). Commercially available sample splitters may be used or material to be processed may be homogeneously spread in a shallow tray and divided into fractions of which a few are randomly selected for sorting. Unused fractions should be recombined and stored until it is certain that they are not needed.

As organisms are sorted from the debris they should be counted and separated into major taxonomic groups. The appropriate level of taxonomic sorting at this stage depends greatly on the expertise of individual laboratories, project needs, and available resources. A typical sorting sheet for a generally skilled laboratory is provided in Figure 8-5. Reference collections should be maintained for comparative purposes and quality control. Sorting to order and family can usually be done using a stereoscopic microscope with up to 50X magnification. Identification to genus or species often requires considerable taxonomic expertise and the use of high powered compound microscopes with up to 100X magnification.

Both abundance and diversity of macroinvertebrates can be evaluated from the results of quantitative sampling methods. Abundance can be considered in terms of numbers of individuals per square meter, or, and of greater use, in terms of biomass per square meter. Biomass estimates can be in terms, in order of utility for evaluating production, of wet weight, dry weight, or ash-free dry weight. Diversity can be evaluated in a number of ways. Generally, diversity is considered to be a combined function of taxa richness and relative abundance, and the latter can be based on numbers of individuals or biomass. Measurement of both richness and relative abundance of taxa requires decisions concerning the level of taxonomic description, and it is often appropriate that taxonomic identification be to different levels for different major groups. For example, nematodes are typically identified only to phylum, but chironomid larva are often identified to genus or species. Evaluations of diversity should be restricted to taxonomic groups for which a similar level of identification has been made.

PROJECT:________________ SITE:__________ DATE:__________
INITIALS:_________

| | | Rep. 1 | Rep. 2 | Rep. 3 | Rep. 4 |
|---|---|---|---|---|---|
| 10 | Amphipoda | ________ | ________ | ________ | ________ |
| 20 | Bivalvia | ________ | ________ | ________ | ________ |
| 30 | Chaoborus | ________ | ________ | ________ | ________ |
| 40 | Chironomidae | ________ | ________ | ________ | ________ |
| 50 | Coleoptera | ________ | ________ | ________ | ________ |
| 60 | Collembola | ________ | ________ | ________ | ________ |
| 70 | Ephemeroptera | ________ | ________ | ________ | ________ |
| 80 | Gastropoda | ________ | ________ | ________ | ________ |
| 90 | Hemiptera | ________ | ________ | ________ | ________ |
| 100 | Hirudinea | ________ | ________ | ________ | ________ |
| 110 | Hydra | ________ | ________ | ________ | ________ |
| 120 | Hydracarinidae | ________ | ________ | ________ | ________ |
| 130 | Isopoda | ________ | ________ | ________ | ________ |
| 140 | Microturbellaria | ________ | ________ | ________ | ________ |
| 150 | Nematoda | ________ | ________ | ________ | ________ |
| 160 | Nemertea | ________ | ________ | ________ | ________ |
| 170 | Neuroptera | ________ | ________ | ________ | ________ |
| 180 | Odonata | ________ | ________ | ________ | ________ |
| 190 | Oligochaeta | ________ | ________ | ________ | ________ |
| 200 | Other Diptera | ________ | ________ | ________ | ________ |
| 210 | Platyhelmintha | ________ | ________ | ________ | ________ |
| 220 | Plecoptera | ________ | ________ | ________ | ________ |
| 230 | Tardigradia | ________ | ________ | ________ | ________ |
| 240 | Trichoptera | ________ | ________ | ________ | ________ |
| 250 | Turbellaria | ________ | ________ | ________ | ________ |
| 260 | Megaloptera | ________ | ________ | ________ | ________ |
| 270 | Decapoda | ________ | ________ | ________ | ________ |
| 280 | Copepoda | ________ | ________ | ________ | ________ |
| 290 | Ostracoda | ________ | ________ | ________ | ________ |
| 300 | Cladocera | ________ | ________ | ________ | ________ |
| 310 | Arachnida | ________ | ________ | ________ | ________ |
| 320 | Lepidoptera | ________ | ________ | ________ | ________ |
| 330 | Hymenoptera | ________ | ________ | ________ | ________ |

Figure 8-5. Example of laboratory data sheet for enumeration of macroinvertebrates by major taxa.

# Fishes

A diverse array of sampling approaches can be taken to qualitatively or quantitatively assess fish abundance and diversity in aquatic habitats. Excellent overviews of various fish sampling methods and the advantages and disadvantages of each in different habitats is available elsewhere (Nielsen and Johnson 1983). An attempt is made here to provide a synopsis of those qualitative and quantitative methods that are most applicable to the shallow and/or plant-filled habitats that are typical of most wetlands. Special emphasis is also given to the assessment of juvenile and larval fishes in such habitats, because the spawning and rearing function of wetlands is often among the most important aspect of wetland contribution to the health of fish stocks.

Although created, restored, and enhanced wetlands are often essentially aquatic habitats, even relatively intensive monitoring typically involves little attention to fisheries utilization and considerable attention to vegetation and birds (e.g., Landin et al. 1989, Kentula et al. 1992). Fisheries evaluations at and near natural and created wetlands can take advantage of a variety of gear including a variety of nets, traps (including larval light traps), and electroshockers (e.g., Killgore and Hoover 1992).

## Larvae and juveniles

Direct assessment of larval and juvenile fish abundance and diversity in shallow, structurally complex wetlands presents a sampling challenge. Towed plankton nets, diaphragm pumps, seines and dip nets, and traps are potentially useful for evaluating larval and juvenile fish stocks (see detailed review by Snyder 1983). All of these techniques are relatively labor-intensive and require trained personnel. Light traps are among the least demanding means of obtaining estimates of catch per unit effort and species composition of larval/juvenile assemblages in shallow, structurally complex wetland habitats. These traps have been used recently for wetland evaluations in flooded bottomland hardwoods, agricultural land, and among and adjacent to dense plant beds (Morgan et al 1992).

Light traps take advantage of the common phenomenon of fish attraction to light (Verheijen 1958, Nagiec 1975, Faber 1982). Figure 8-6 shows a plexiglass light trap with a chemical light stick that has been used to assess juvenile/larval fish utilization of wetlands. Four 5-mm entrance slits allow fish to enter the inner chamber. Once inside, it is difficult for them to escape back through the narrow slit. A chemical light stick is used as the light source to attract fish, eliminating the need for any electrical power. In moderately turbid water (14 NTU), light transmission viewed at night was approximately 2.3 m.

Typically, light traps are set at dusk. They can be set at any depth by using anchor and float lines tied to the bottom and top of the trap, respectively. After predetermined time periods (two hours is appropriate for high density larval communities), the traps are retrieved. During retrieval, a plankton net is carefully placed under the trap, the trap is lifted, the stopper is removed, and trap contents are washed several times to transfer fishes into the net. The plankton net is then washed into the cod-end and fishes are transferred to a jar for preservation.

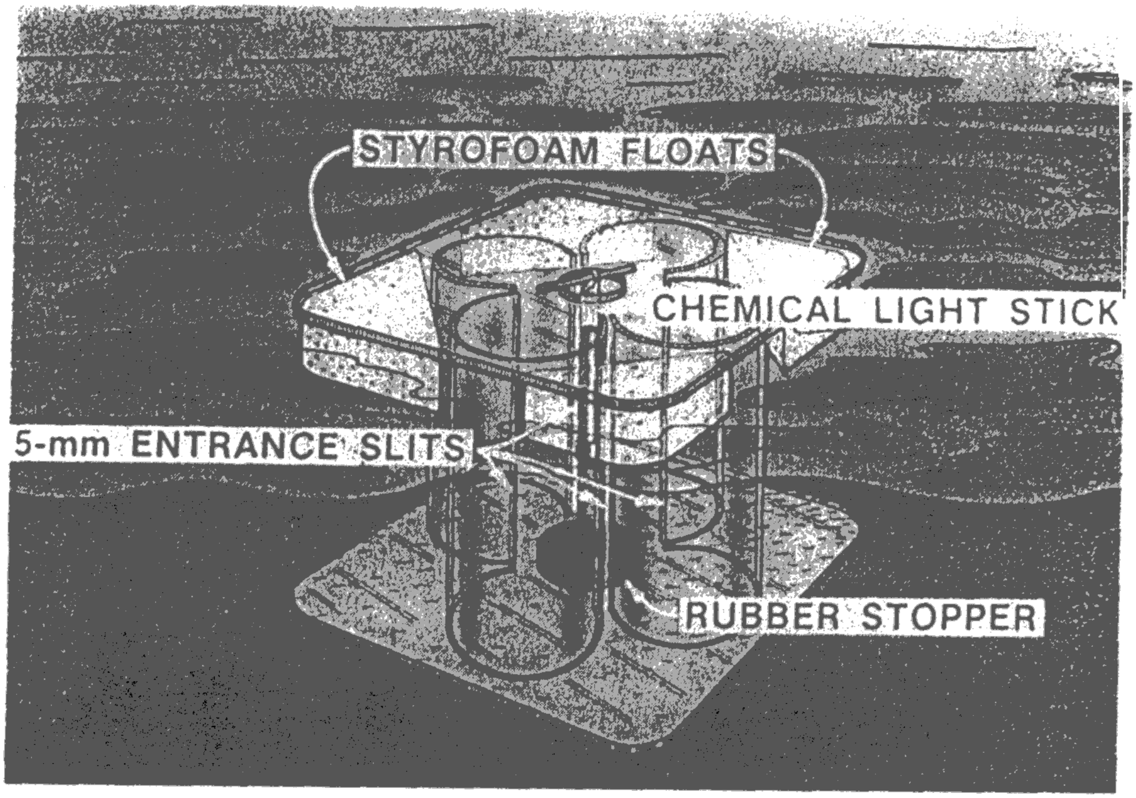


Figure 8-6. Schematic diagram of larval light trap.

Samples should be fixed (rapid killing and chemical stabilization of tissues) in 5 to 10 % neutral formalin (2 to 4 % formaldehyde buffered with calcium carbonate), and preserved in 3 to 5 % solutions. Alcohol should not be used because of dehydration and association morphological deformation that makes identification difficult. A review of preservative additives to reduce loss of nonmelanin pigments (color loss hinders identification) is provided by Hubert (1983). It is advisable to identify specimens as quickly as possible after collection using appropriate larval keys and guides (e.g., Auer 1982, Berry and Richards 1973, Colton and Marak 1969, Drewey 1979, Elliot and Jimenesz 1981, Hogue et al. 1976, Lippson and Moran 1974, May and Gasaway 1967, Scotton et al. 1973, Snyder 1981 and 1983, Wang 1981, Wang and Kernehan 1979).

## Adults

The most commonly used and generally appropriate passive gear for sampling adult fishes are fyke nets, gill and trammel nets, and hoop nets. Active methods of fisheries evaluation most applicable to wetland monitoring include electroshocking (both from boats and using backpacks) and use of popnets. Detailed descriptions of these fish sampling methods are available elsewhere (e.g., Hubert 1983, Reynolds 1983 and references within; see Morgan et al. 1988 for popnet description) and are only briefly described here. All of these methods, including popnets, require trained fisheries biologists, specialized equipment, and are labor-intensive.

Fyke nets can be used in shallow, relatively lentic conditions. However, setting and retrieval of fyke nets is relatively labor-intensive and catch is biased toward larger fishes. Fyke nets are modified hoop nets with one or two wings of a leader of webbing attached to the mouth to guide fish into the hoop net (Figure 8-7). The wings and leader are positioned to intercept moving fishes that in attempting to swim past the barrier are funneled into the hoop net. These nets are probably most appropriate for use in shallow open water, but can be deployed in marshy environments if a path is cut through vegetation to allow the net to be set. Damage to these nets by small mammals can be extensive in marshy environments. Mobile species that seek cover, such as centrachids, appear to be especially susceptible to fyke nets.

In shallow, open, still or slowly flowing water, trammel and gill nets can be used. Trammel nets consist of three panels of netting suspended from a float line and attached to a single lead line (Figure 8-8). Two outer panels are large mesh netting, and the inner panel is of small mesh netting. The inside panel has greater depth and hangs loosely between the two outer panels. Fish pass, from either side, through an outer panel, contact the small mesh inner panel, and carry this panel through the larger openings of the other outer panel. Thus, a pocket of netting, in which the fish is entangled, is formed. In addition, larger fish may become wedged or gilled. Trammel nets are most effective when set around an aggregation of fish, with the fish being subsequently frightened or driven into the net. Multiple trammel nets can be set around beds of aquatic plants from which fish are driven into the nets. In addition, drifted or set nets can be used to capture fish in slow-moving open channels. Gill nets are comprised of a single panel of mesh in which fish become tangled (often by their gills) as they pass through the net (Figure 8-8). Trammel nets are somewhat selective toward larger fishes, but not to the extent that simpler gill nets are size selective.

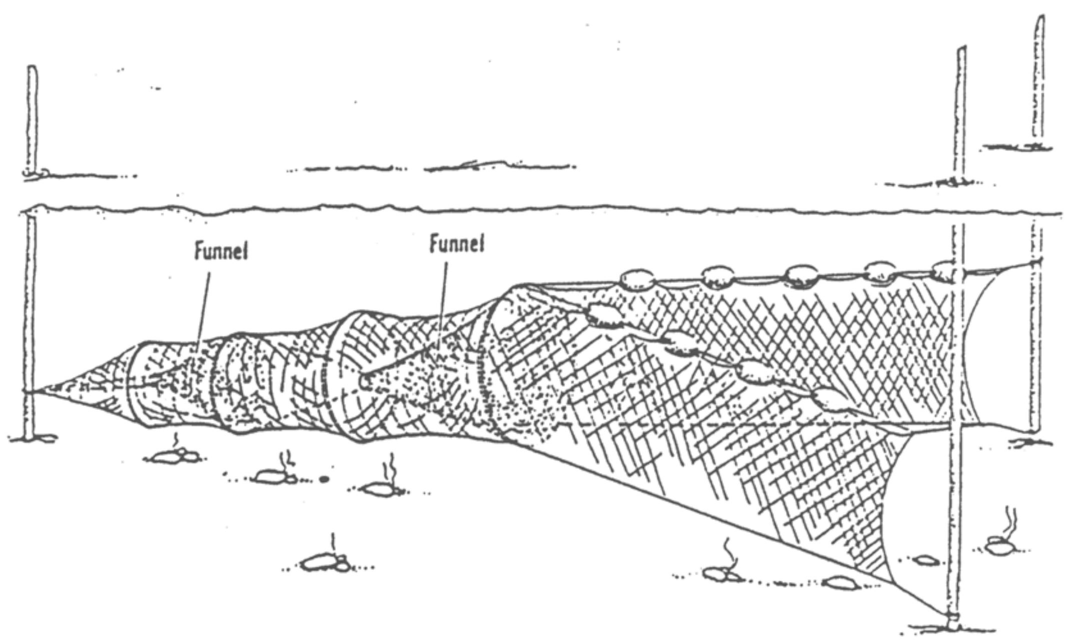


Figure 8-7. Fyke net.

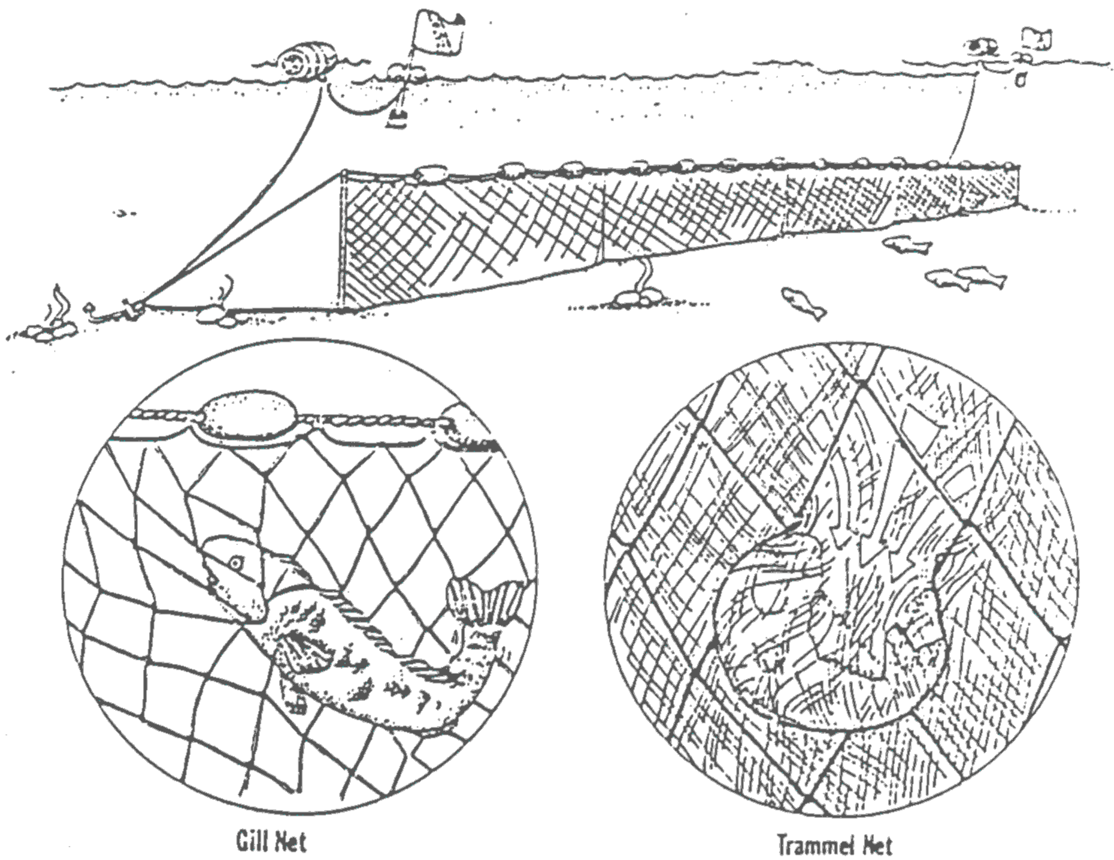


Figure 8-8. Gill and trammel nets.

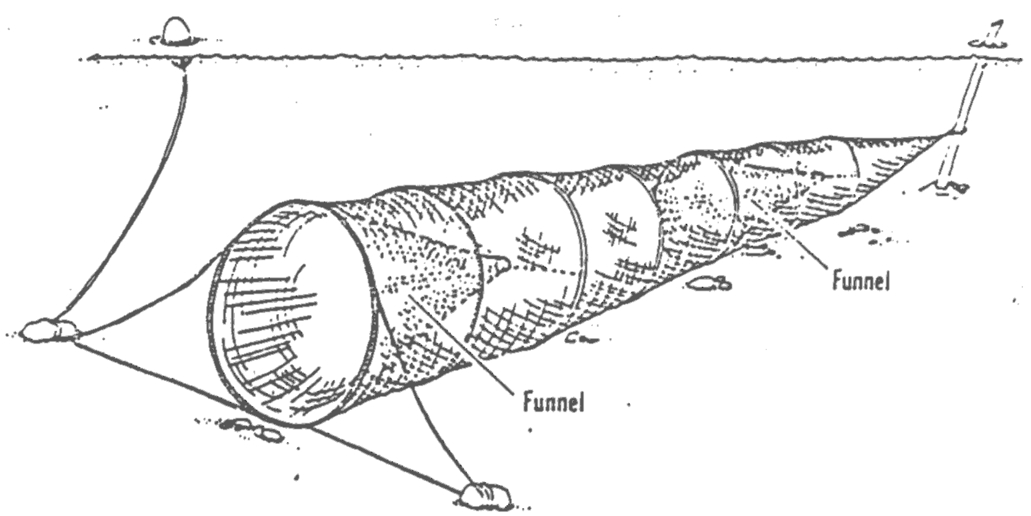


Figure 8-9. Hoop net.

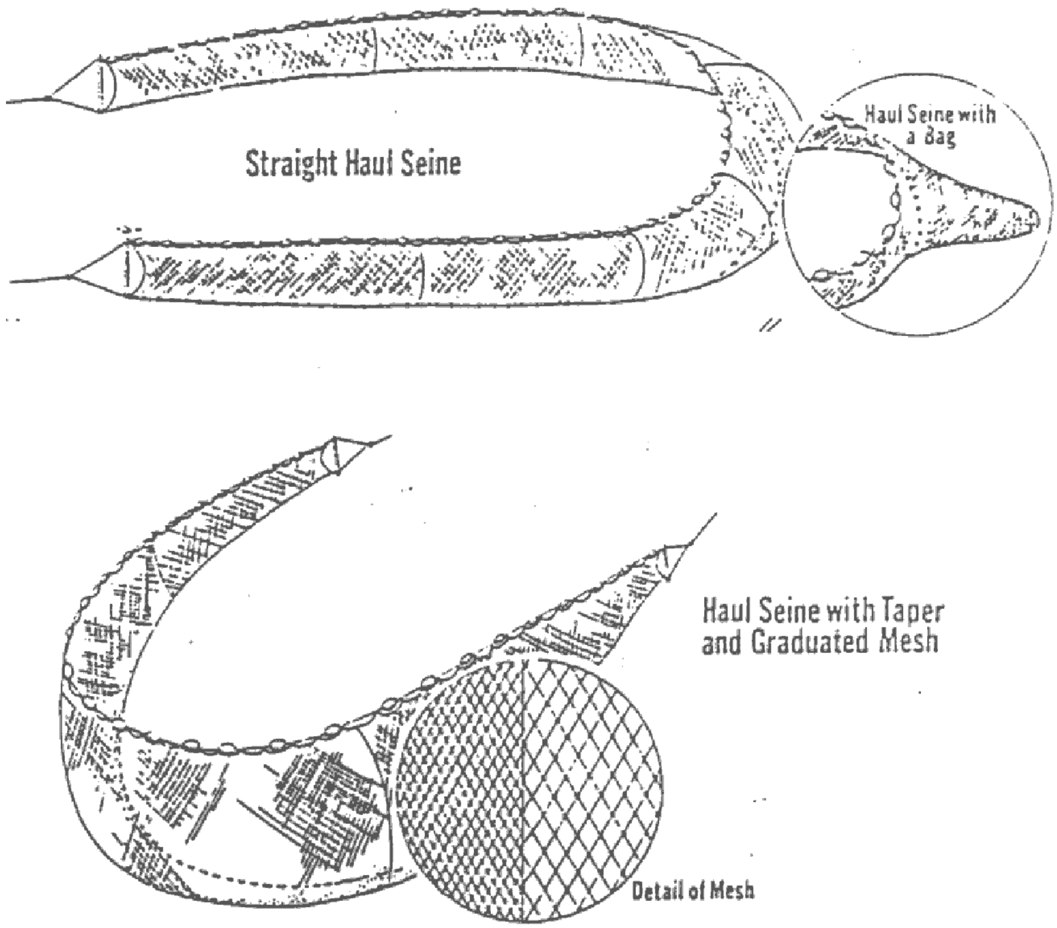


Figure 8-10. Typical seines.

Hoop nets are cylindrical or conical series of hoops covered by netting (Figure 8-9). Funnel-shaped throats of net are directed inward from the mouth. Fish are trapped by swimming through the narrowing funnel from which they are unable or unlikely to pass back. Hoop nets are most often used in flowing channels and are set in alignment with the current. Net dimensions and construction have great influence on fishing bias. Larger diameter nets with larger throat openings have been shown to capture more fish but fewer species than smaller dimension nets. In general, hoop nets are effective at capturing larger species such as buffalo, catfish, and carp. Hoop nets typically capture fish unharmed.

Like passive methods, active fish capture methods are affected by habitat, fish size, and fish behavior (summarized by Hayes 1983). Every gear has limitations, and data interpretation must keep these in mind. In shallow, structurally complex wetlands and adjacent waters, electrofishing and seines are probably the most often chosen active methods of fish capture.

Seines are a rectangular piece of netting attached to a lead line along the bottom and a float line along the top (Figure 8-10). They vary in depth, length, and mesh size. Relatively small seines with relatively small mesh will generally be used in wetland-related sampling. For sampling the entire reach of a stream, a seine should be approximately 20 % longer than the channel width. A seine should be approximately 1.5 times deeper than the water being seined. Shoreline seining involves pulling the net through the water toward the shore. If some current is present, the offshore end of the seine should be kept slightly ahead (downstream) of the nearshore end of the seine. A quadrant seine haul involves positioning one end of the seine at or near shore and extending the other end normal to the shore into the water. The offshore end is then swept along a 90-degree arc toward the shore. When both ends are equal distance from shore, the net is hauled to dry ground. When seining it is important to locate a clear reach of shoreline onto which the seine can be hauled. As for all fishing techniques, careful notes should be recorded on habitat factors, such as presence of snags or other bottom irregularities, that affect the performance of the gear.

Dip nets can be a useful active netting technique in heavily vegetated and shallow water Use of fine mesh (< 2 mm) nets on a frame approximately 1.0 ft. high by 1.5 ft. attached to a long handle (approximately 5 ft long) can be useful in qualitative assessments of small fishes among and at the edge of plant beds and in shallow water along shorelines.

Popnets are enclosure-type nets with the top and bottom attached to a square or rectangular PVC frame (Figure 8-11). The construction and details of their use in submersed aquatic vegetation are detailed elsewhere (Morgan et al. 1988). The upper frame is filled with buoyant foam to act as the float line and the lower frame is loaded with steel rod to act as the lead line. Nets are deployed in a collapsed position (pins are used to hold the float frame to the lead frame) by carefully lowering through plants to the bottom. After sufficient time to overcome the disturbance caused by net deployment the float frame is released by remote triggering using lines that are extended from the pins holding the float frame to the lead frame. Typically nets are set at mid day to dusk and released after dark. The float frame “pops” up to the water surface, enclosing fish in the water column within the area of the frames. A seine is then used from boats on each side of the net to remove all fish from the enclosure. A Zippen depletion method is used in which the enclosure is seined three times, and a count of fish captured is recorded per seine haul.

Trained fisheries biologists can identify and measure (length and weight) in the field fishes caught during most studies. Individuals of those species, such as some cyprinids, that are especially difficult to recognize in the field may need to be fixed in the field and returned to the laboratory for identification. Retention of preserved voucher specimens is a routine aspect of fisheries investigations.

If recreational or commercial fishermen utilize the project area, they can be used as an important source of information (see Malvestuto 1983 and Demory and Golden 1983 for reviews) when direct assessments of fisheries are not possible.

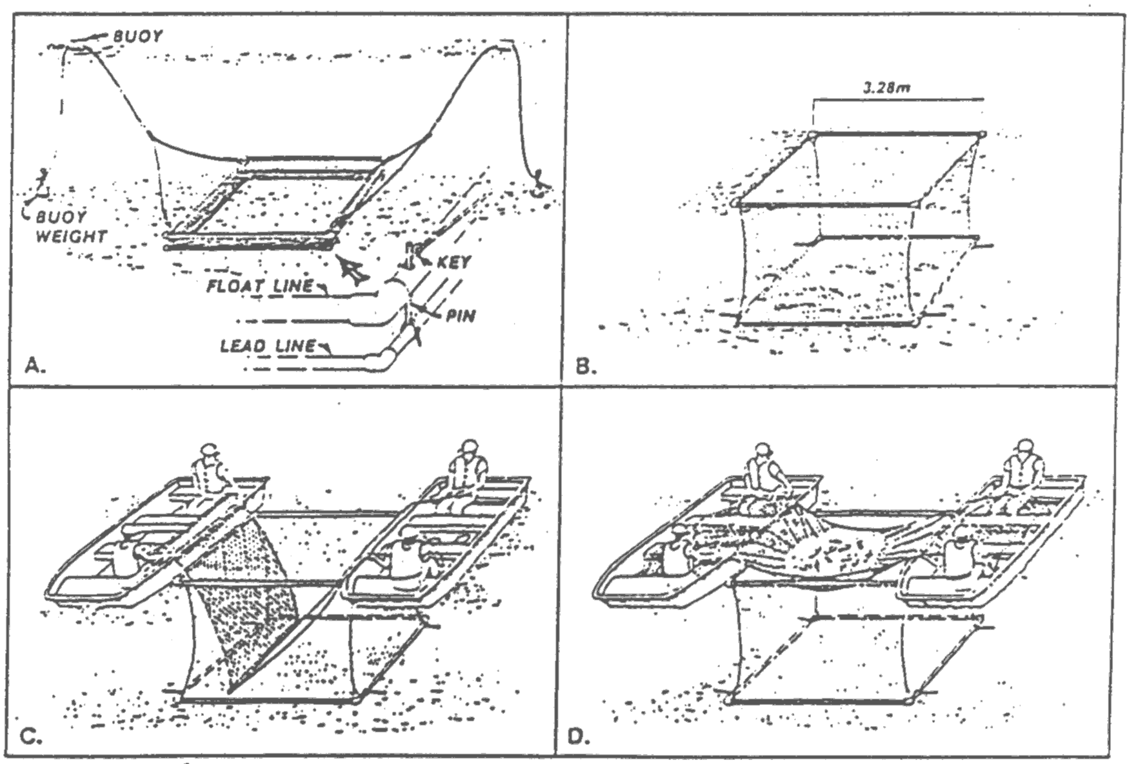


Figure 8-11. Schematic of popnet installation and use.

# Birds

## Background

Birds are often the most visible and appreciated wildlife in both coastal and freshwater wetlands. Wetlands that support rich and diverse avian fauna are usually important habitats for a variety of other wildlife. Evaluating the success of a restored or artificially created wetland in providing avian habitat requires monitoring to characterize avian community composition over time. There are many direct census methods for estimating avian population density and abundance.

A preliminary survey of the project area can provide valuable information for study planning. Using aerial photography, topographic maps, or ground inspection, the wetland should be broken into areas of similar habitat type. For example, a coastal wetland might be divided into the following habitats: beach, dune, unvegetated intertidal zone, vegetated intertidal zone, and salt flats (Pacific Estuarine Research Laboratory 1990). Each habitat type should be sampled separately.

A survey may be designed to focus only on a single key species or group, or to characterize the entire avian community. Any endangered or threatened species known to exist, or formerly exist, in the area should be targeted. Populations of harvestable waterfowl are also monitored in many areas because of their commercial and recreational importance. The importance of observer training is crucial to the success of any avian survey project. If the survey personnel are not already familiar with the species likely to be encountered in a given area, there are several ways to increase their identification skills, and thus the accuracy of the data. The first step might be to study field guides for the region. Once the observer has become familiar with markings and calls of each species, as much time as possible should be spent in the field, preferably in the company of an experienced birder to confirm identifications. Universities and Audubon Society chapters can often be excellent sources of trained personnel who are willing to share information on local avian communities or participate in the collection of survey data.

The importance of audible clues should not be overlooked. This can be particularly important for smaller species in areas where the vegetation cover is substantial and birds might not be easily identified by sight alone. The use of tape recorders to record songs can be a valuable training aid; however, recorded songs should not be used to entice birds to respond during surveys because this can bias the results (Mikol 1980).

Survey techniques also require the accurate estimation and measurement of distances. Observers should practice making quick and accurate judgements of distances. Rangefinders or marked tapes can also be used for more precise measurements, but these require more time.

Depending on the season, breeding, migratory, or wintering populations may be encountered. In order for annual survey data to be comparable from year to year, counts should always be conducted at approximately the same time of year. The exact timing of these activities, however, can significantly differ from year to year due to weather conditions. Amateur birders, university personnel, and local chapters of the National Audubon Society can be valuable sources of information on the arrival of breeding and migratory populations in a particular location.

Weather conditions can affect the accuracy of the data collection. Under ideal conditions, surveys should be conducted at times when the visibility is good, precipitation is minimal, and the wind speed is less than 3.6 m/sec (Mikol 1980). Bird activity levels are reduced in windy or stormy weather, thereby reducing the observer's ability to detect them.

Surveys of breeding birds are usually most effective if conducted in the early morning hours when birds are most active. The survey should begin up to one hour before sunrise and continue for 3 to 4 hours after sunrise (Mikol 1980). Wintering populations of migratory waterfowl are most active in the hours following sunrise after the ground has warmed slightly (Mikol 1980). Coastal and estuarine species, however, are influenced by tidal fluctuations, and are commonly surveyed at low and high tide conditions, beginning about 1 hour before the tidal event (Pacific Estuarine Research Laboratory 1990).

A good study design will include replicate counts conducted over a period of several days until enough individuals of each species have been counted to ensure the statistical accuracy of the data. The number required will vary, but generally forty or more of each species should be counted (Mikol 1980).

Many authors have described methods for estimating avian abundance and density (Burnham et al. 1980, Mikol 1980, Taylor et al. 1985, Verner 1985, Wakeley 1987a, Wakeley 1987b, and Bibby et al. 1992). There are 3 basic types of avian surveys in common use: i) line-transect methods, ii) point or plot surveys, and iii) territory or spot mapping.

Most species of birds can be successfully counted using one or more of these methods. Some birds, however, pose special problems and specific counting procedures have been developed for them. For a complete discussion of avian counting procedures, including descriptions of methods for individual species, see Bibby et al. (1992).

The choice of survey method will be influenced by many factors, including area size, topography, vegetation cover, species of interest, season, available personnel, survey goals, and the degree of accuracy required. Each technique has advantages and disadvantages which should be taken into consideration when planning a survey in a particular area.

Both transect and plot surveys can be conducted at any time of year and are frequently used to estimate avian densities in a variety of habitat types ranging from dense canopy cover to open marsh. These two methods differ in their methods of measurement and data analysis, but share many of the same characteristics. Line transect techniques are best suited to large, open areas with nearly level terrain and uniform vegetation cover in areas where conditions permit the establishment of straight transect lines with a minimum of interference. If the survey area includes many diverse habitat types, separate transects should be set up within each habitat type.

Transect surveys can be conducted on foot or horseback or in small boats and planes. Each mode has advantages and limitations which should be considered when planning a study. Small boats are likely to be the most effective means of transportation in wetland areas with large amounts of open water. Aerial transect surveys permit large, remote, or relatively inaccessible areas to be surveyed in a short period of time and have been successfully used to estimate colonial waterbird densities (Thompson and Landin 1978). However, the use of aerial surveys to estimate avian density is limited to those species which can be visually identified from the air. Large canopy-nesting species such as great blue herons and great egrets, and smaller conspicuously plumaged species such as terns and gulls that prefer a more open habitat are good subjects for this technique (Thompson and Landin 1978). Aerial survey data may tend to underestimate actual density, however, due to limited visibility and the large expanse of territory covered. If possible, aerial survey data should be compared with concurrent ground census data to establish the margin of error.

Plot survey techniques can be used under the same conditions listed for transect surveys above. However, the plot survey may be more appropriate for small, rugged, or diverse areas where it is difficult to set up a series of long, straight transect lines in areas of similar habitat type. Plot methods are preferred in situations where large numbers of birds are disturbed by the movement of the observer on the transect line (Burnham et al. 1980).

Territory mapping is considered one of the best methods for determining populations of territorial breeding birds (Verner 1985). This technique is well-suited to annual monitoring surveys in small, relatively accessible areas that can be repeatedly visited during the breeding season. Although territory mapping may provide a detailed representation of avian habitat usage in a particular area, it does have some serious limitations that should be considered. It is much more labor- and time-intensive than line transect or plot methods, and can only be conducted during the breeding season. Also, since no replicate counts are made, confidence levels for the data cannot be calculated.

## Line-Transect Surveys

There are several variations of this technique but, basically, the line-transect method involves traveling in a straight line of a known length and counting all the birds seen in a certain distance on each side of that line (Wakeley 1987a) (Figure 8-12). Details on the theory and methods of line-transect sampling and data analysis are provided in Burnham et al. (1980).

Basic assumptions of the line-transect surveys are:

i) Every bird located directly on the transect line will be counted.

ii) Transect lines are randomly distributed with respect to the populations being counted.

iii) Each individual bird is not counted more than once.

iv) Distances from the transect line (and angles where required) are measured exactly.

v) If a bird is disturbed and leaves the area, it must be recorded in the position it was in before flushing.

vi) Each sighting is an independent event.

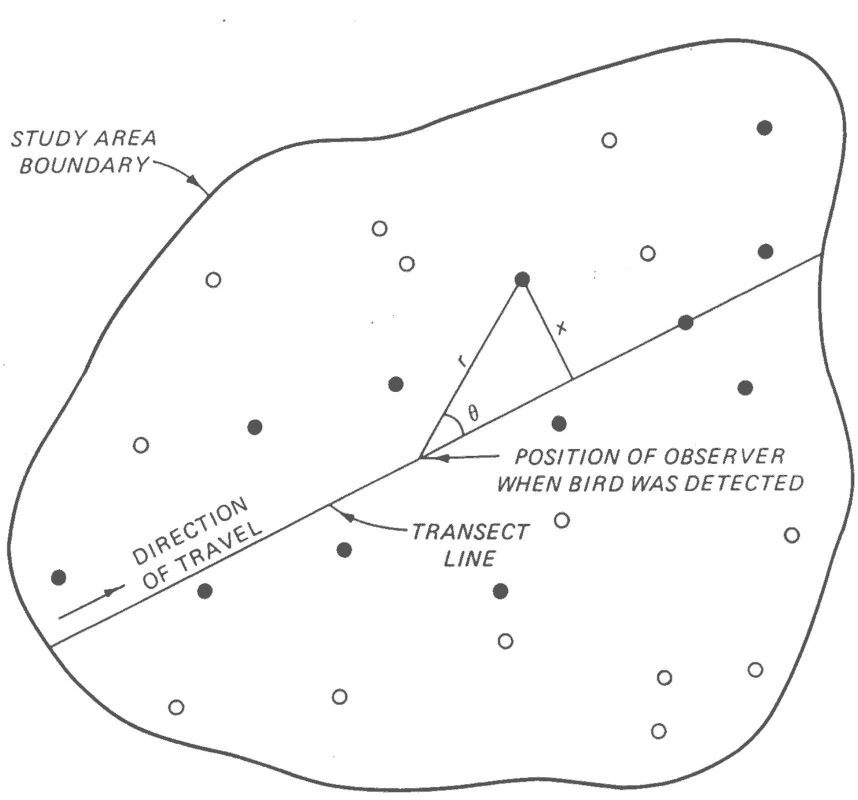


Figure 8-12. Line-transect sampling of a bird community.

If these assumptions are met, line-transect surveys provide accurate density and relative abundance estimates. However, it may be extremely difficult under actual field conditions to ensure that all of these conditions are met. In dense vegetation, even those birds located near the transect line may be overlooked. The precise estimation of right angle distance or sighting distance and angle is also very important and should be carefully recorded.

Transect lines may be evenly or randomly spaced throughout the study area. The minimum distance between transect lines, however, should be at least twice the maximum detection distance for the most obvious species present (Wakeley 1987a). If the study area contains many diverse habitat types, separate transects should be surveyed in each habitat type.

Once the location of the transect lines has been established, they should be mapped, showing the location of any prominent features. The placement of markers at regular intervals along the transect can be useful for determining the position of the observer and estimating distances. Flagging, waterproof paint, or short stakes can be used.

The observer should travel slowly and quietly along the transect line, pausing frequently to note the presence of all birds either observed or heard. Most line transect methods use right angle distances from the transect line to the location of the bird. If it is not possible to measure this distance accurately, then the sighting distance and angle can be used to calculate the right angle distance (Figure 8-13). Distances must be estimated as accurately as possible. If birds are grouped in large flocks, it may be difficult to count each individual present. Emlen (1977) suggests estimating the average flock size for each species and treating each flock as a single unit. This information is recorded on standard data sheets (Figure 8-13), along with other observations such as wind speed, percent cloud cover, and notes on the behavior of the birds observed.

## Belt-Transect Surveys

This variant of the basic line-transect survey method is one of the easiest to conduct from a practical standpoint because it does not require that exact distances from each bird to the transect line be measured; it simply requires that all birds within a specified range be counted (Figure 8-14).

The transect width will differ according to the species being counted, vegetation, and topography. The determination of transect width is extremely important and should be done by preliminary observation in the field prior to the beginning of the survey. The width must be narrow enough to ensure that all birds are counted, but wide enough to permit an adequate sample size. Different transect widths are often used for different species in the same survey.

If the transects have been carefully placed, the population density in the transect area is assumed to be the same as the population density in the entire study area. For a fixed width, or belt transect, the density is calculated using the formula:

$$A = \pi\left(r_D^2 - r_i^2\right) \tag{8-3}$$

## TRANSECT SURVEY FORM

TRANSECT NUMBER:____________________ OBSERVER:___________________

SURVEY NUMBER: ______________________ DATE:________________________

VEGETATION: __________________________ START TIME:_________________

WEATHER: _____________________________ FINISH TIME:_________________

__________________________________________

| SIGHTING NUMBER | SPECIES | NO. OF BIRDS | RIGHT-ANGLE DISTANCE | SIGHTING DISTANCE | SIGHTING ANGLE | COMMENTS |
|---|---|---|---|---|---|---|
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Figure 8-13. Example of a data sheet for line-transect bird surveys.

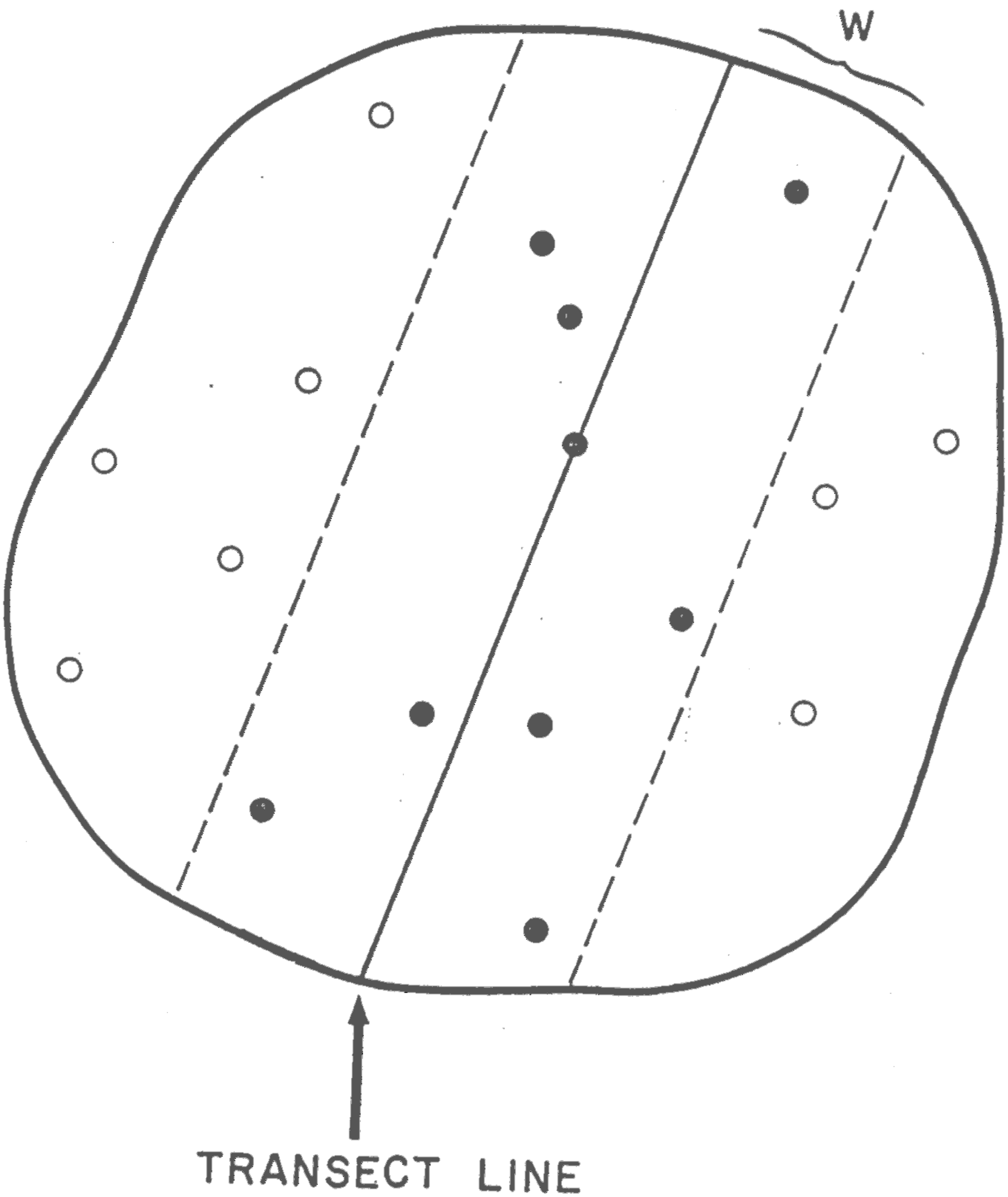


Figure 8-14. Belt-transect survey of a bird community.

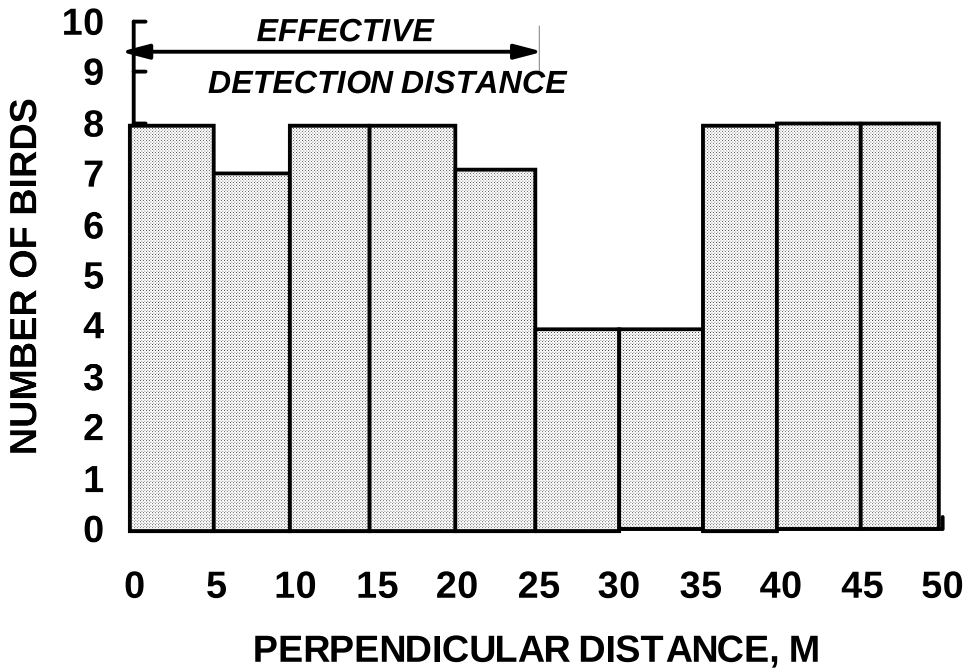


Figure 8-15. Species-specific effective transect width per Emlen's method.

where A = area of the circular zone, $m^2$; $r_D$ = outer zone radius, m; and $r_1$ = inner zone radius, m.

A frequency histogram of densities in each zone by increasing distance from the observer will determine the effective plot radius for each species (Figure 8-15). Assuming a uniform population density and distribution throughout the survey area, the distance at which the observed densities show a marked decline is the effective plot radius for that species.

$$D = \frac{n}{2LW} \tag{8-4}$$

where D = density, birds/$m^2$; n = number of birds counted in the transect area; L = length of the transect line, m; W = half the total width of the transect area, m. At least 8-10 repetitive counts of each transect area should be made over a period of time to allow the calculation of an average density for each species. The 95% confidence interval for each estimate can be determined by adding to and subtracting 1.96 standard errors from the mean.

## Emlen's Method

This variant of the line-transect method is one of the most commonly used methods for avian surveys. Instead of establishing an initial fixed transect width, the effective transect width is calculated from data collected. As in the belt transect method, this distance will be different for each species, habitat type, and observer.

Data should be collected and recorded on standardized data sheets, being careful to estimate the distance from the center transect line as accurately as possible. Once the data are recorded, a frequency histogram can be created for each species at various distances from the transect line. The effective transect width for each species is determined to be that distance at which a significant drop in detection occurs (Figure 8-15). Band widths for the histograms should be narrow for small birds in dense cover (3-10 m) and wider for larger species in open terrain (10-25 m) (Wakeley 1987a). The density for each species can then be calculated using the formula earlier presented, modified such that W equals effective transect width.

Some species may be so rarely encountered that an effective detection distance may be difficult to calculate. One solution to that problem is to identify a more common and equally detectible species present in the same area and use the same distance for the more uncommon species.

One disadvantage of Emlen's technique is that all observations outside the effective detection distance are discarded. A modification of this method, developed by Ramsey and Scott (1981),allows all the data collected to be used. The idea of the effective area surveyed as opposed to the effective detection area is the basis of this modification. The effective area surveyed includes all observations within the area defined by the farthest observation. However, many birds in that area will have been undetected. The effective detection area is defined as the area in which all birds present are observed and recorded. This can be calculated using frequency histograms of the number of observations at various distance intervals as described in Emlen's method above. The effective area surveyed can be calculated using the equation:

$$E = (n/m) \cdot A \qquad (8\text{-}5)$$

where E = effective area, $m^2$; n = total number of birds counted; m = number of birds counted in Area A; A = effective detection area, $m^2$. Density can then be calculated as n divided by A.

## Plot Surveys

The information contained in this section is based on Wakeley's (1987b) description of plot survey techniques. The basic plot survey method involves an observer located at a fixed position for a set length of time. All sightings at a certain distance from the observer during that period of time are recorded on standard data sheets.

Like the line transect method, the validity of plot survey data depends on certain basic assumptions:

i) Plots are randomly placed in respect to the population distribution.

ii) All birds in the immediate vicinity of the observer will be counted.

iii) No bird is counted more than once.

iv) The distance from the observer to the bird is measured accurately.

v) Birds do not move in or out of the area immediately before or during the survey.

vi) Each recorded observation is an independent event.

Sampling points may be either randomly or evenly spaced; however, there should be no possibility of counting the same bird from two different observation points. One method is to place sampling points along parallel transect lines. Another involves the selection of random points from a gridded topographic map overlay. Whichever method is chosen, the minimum distance between plots should be at least twice the maximum distance at which the desired species can be detected (Figure 8-16). Since counts are made for a specific length of time, timing is an important aspect of study design. Some birds are likely to be missed if the duration is too short. If the duration is too long, birds may move in or out of the area or be counted more than once. Recording periods range from 3 to 20 minutes, depending on habitat type (Baillie 1991). A duration of 8 to 10 minutes is commonly used for most species (Wakeley 1987b). A preliminary survey will help to determine the optimum length for each habitat type and geographic area.

The abundance and distribution of the target species, as well as the terrain and vegetation type, will determine the number of plots required to adequately sample an area. As in line transect sampling, at least 40 individuals of each species should be counted in order to achieve an accurate density estimate.

Fixed circular plot surveys are similar to the belt-transect method except the survey area is circular and counts are recorded for a specific period of time. All birds present within the plot area are assumed to be counted. This technique also has the advantage that distances need not be measured; however, the observer must be able to accurately judge the distance to the edge of the plot in order to determine if a bird is within the boundary of the plot. Survey data should be collected using a field data sheet similar to that shown in Figure 8-17.

Replicate counts of each plot should be made over a period of several days and the average count per plot for each species determined. The population density can be calculated for each plot using the simple formula:

$$D = \frac{n}{A} \tag{8-6}$$

where n = average number of birds counted per plot and A = area of the circular plot, $m^2$. The average population density for each species in the study area is simply the sum of each individual plot density divided by the total number of plots.

Circular plots of variable radius can be used in a fashion similar to Emlen's modification of line-transect surveys. Effective plot radius is determined after the data have been collected, using a graph of bird density on increasing plot radius.

The observer takes a position at the center of the plot and records all bird observations during a set period of time, usually 8-10 minutes (Wakeley 1987b). The distance from the observer to the bird must be accurately estimated or measured using a rangefinder. All observations are then

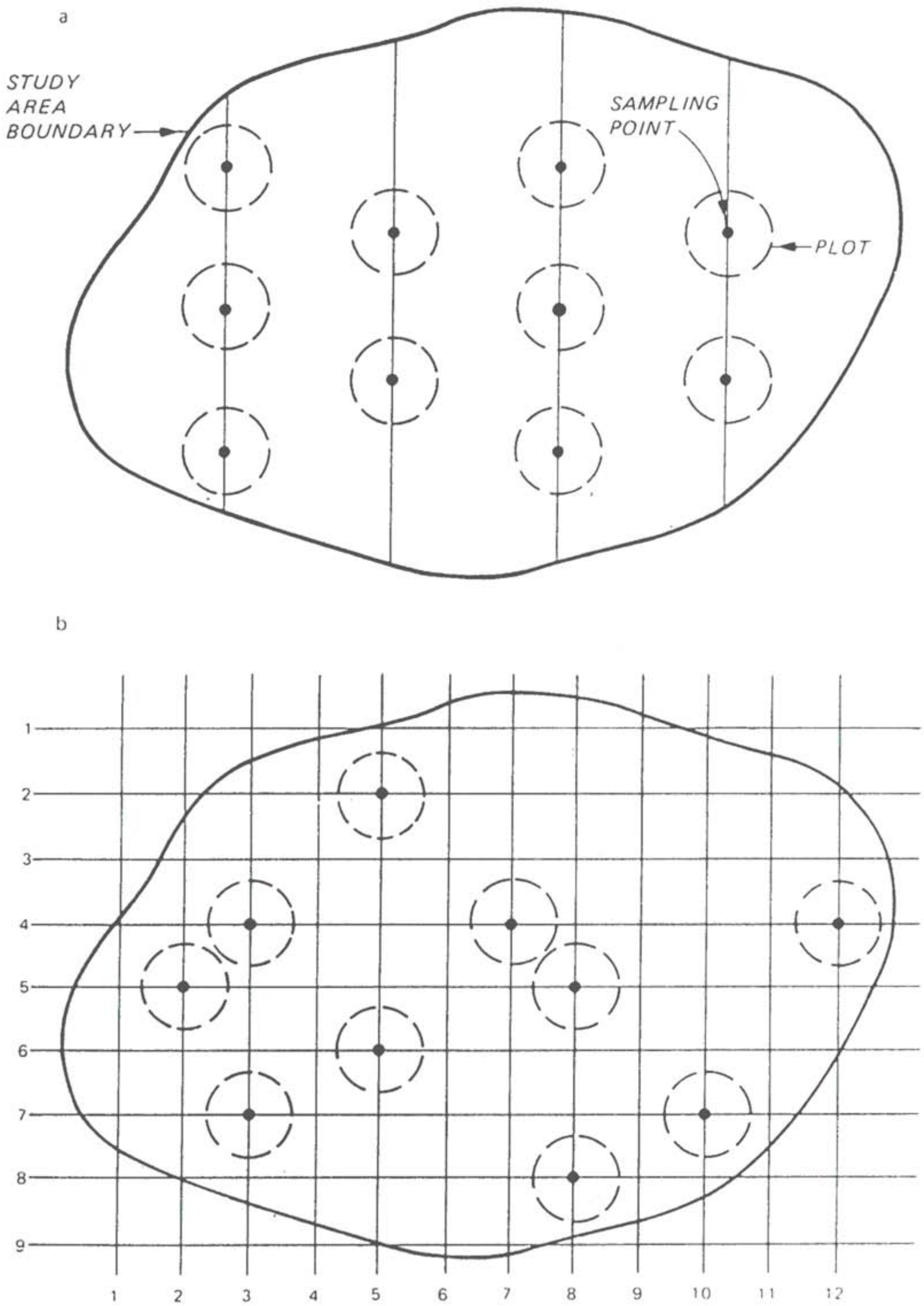


Figure 8-16. Regularly (a) and randomly (b) distributed circular plots for bird surveys.

PLOT SURVEY FORM

PLOT NUMBER:_______________________ OBSERVER:_______________

SURVEY NUMBER: ____________________ DATE:____________________

VEGETATION: _______________________ START TIME:______________

WEATHER: __________________________ FINISH TIME:_____________

______________________________________

| SIGHTING NUMBER | SPECIES | NO. OF BIRDS | DISTANCE | COMMENTS |
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Figure 8-17. Example of field data sheet for circular plot surveys.

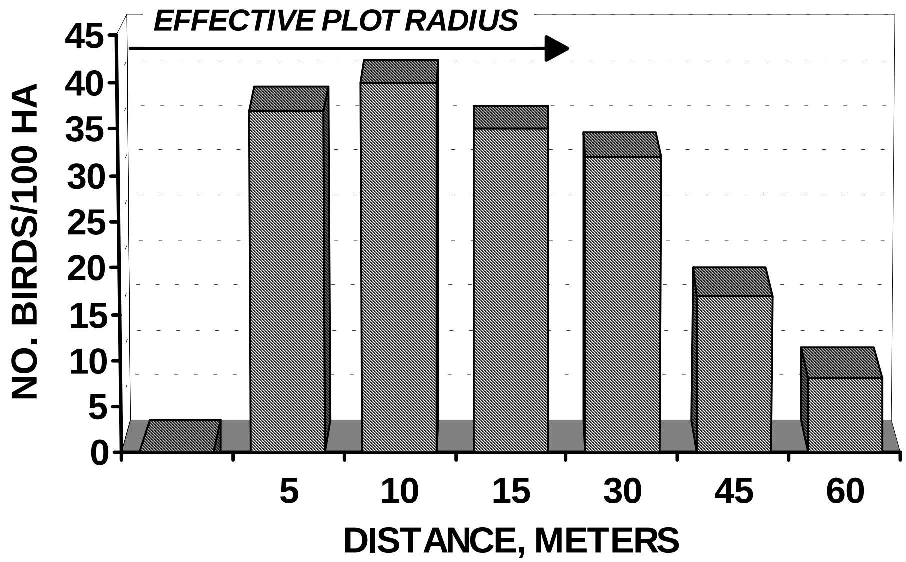


Figure 8-18. Estimation of effective radius of circular plots.

grouped according to detection distance and the density for each group plotted. Observations should be grouped into zones by increasing distance from the plot center. The zone widths do not have to be of equal size. This is a reflection of the observers ability to accurately estimate distances with increasing range.

Population densities for each zone are calculated using the formula:

$$A = \pi\left(r_D^2 - r_i^2\right) \qquad (8\text{-}7)$$

where A = area of the circular zone, $m^2$; $r_D$ = outer zone radius, m; and $r_1$ = inner zone radius, m.

A frequency histogram of densities in each zone by increasing distance from the observer will determine the effective plot radius for each species (Figure 8-18). Assuming a uniform population density and distribution throughout the survey area, the distance at which the observed densities show a marked decline is the effective plot radius for that species.

## Territory Mapping

Territory or spot mapping procedures involve a series of repeated visits to the same area during the breeding season. The locations of all territorial males and their movements during the survey are carefully plotted on detailed maps of the study area. Maps should be made at a scale of about 1:2500 with all prominent features marked, including fencerows and vegetation (Bibby et al. 1992). Symbols and abbreviations should be used to record the number, sex, and behavior of observed birds. Simultaneous observations of different birds are of particular value in defining territory boundaries and should be noted as such. Other information such as weather conditions, wind speed, time, and observer's name, should be recorded on each map.

With continued visits, clusters of observations will begin to develop in specific areas that correspond to the territories of individual birds. Ten visits has been adopted as the standard number for the Common Birds Census (Bibby et al. 1992). If the maps become very complex due to the large numbers of species recorded, separate maps can be made for each species.

One advantage of territory mapping lies in the fact that since the plot is mapped in considerable detail, direct observations concerning habitat preference can be made. Some problems in the procedure and interpretation of the data include:

i) Surveys can only be conducted during the breeding season.

ii) More time and labor is required than with other methods.

iii) Elimination of duplicate counts is difficult.

iv) The minimum number of observations needed to define a single territory is uncertain.

v) Territories often overlap.

vi) There are no replicates of count to establish confidence intervals.

## Methods for Colonial Nesting Sea Birds

It is often difficult to assess populations of colonial nesting seabirds using traditional census methods. Colonies are frequently located in remote, rugged sites that may have limited access. Other problems include estimating the proportion of breeding and non-breeding birds, determining the number of birds which have temporarily left the colony to feed, and evaluating the effects of severe weather on the population (Bibby et al. 1992). As a result, special techniques have been developed for colonial nesting seabirds, described in Bibby et al. (1992).

Detailed maps (1:10,000) should be obtained and the location and extent of all colonies sketched. An observation point from which the entire colony can be observed is desirable; otherwise the colony can be subdivided into sections for counting. Vantage points for cliff-dwelling species should be positioned so that the observer is slightly above or at the same level as the colony. In practice, this will not always be possible; the safety of the observer should always be foremost.

The following information should be recorded on the map or on standard data sheets for each colony: i) colony name, ii) location, iii) description, iv) access, v) counting history, and vi) other notes as appropriate. The description should include detailed notes on substrate, slope, vegetation type, and the locations of the observation points.

The counting method will vary depending on study objectives and the species involved. Aerial surveys may provide adequate data for rough estimates of breeding populations. If more detailed study is needed, other methods may be employed. For medium to small size colonies, a total count may be possible. If the colony is quite large, or cannot be viewed from a single vantage point, randomly chosen quadrants or transects may be sampled. Counting units used for colonial seabirds include: i) individual bird on land, ii) apparently occupied nest site, and iii) apparently occupied breeding territory (Bibby et al. 1992). Photographs can be a valuable means of recording accurate counts in areas of high density.

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# Wetlands Engineering Handbook

## Appendices

# Appendix A
# Soil Classification Systems[1]

Soil classification is a systematic arrangement into groups, according to certain agreed upon rules or criteria, based on identification tests and observations, that provide a *rating* of soils with regard to a certain limited number of qualities and potential behavior characteristics that are considered to be significant and important in a particular field of soil-related work based on criteria established by interpretations of experience. Soil classification is *interpretive* information, whereas soil identification is *factual* information.

There are three soil classification systems frequently encountered in the wetland literature. They are (a) USDA Soil Taxonomy, (b) the Unified Soil Classification System (USCS), and (c) the AASHTO Highway Soil Classification System. Soil Taxonomy was developed for agricultural soil science. Each of the two other systems was developed to serve a special engineering- or construction-related purpose.

## USDA Soil Taxonomy

The U. S. Department of Agriculture Soil Conservation Service (renamed the Natural Resources Conservation Service in 1994) adopted, in 1975, a revised soil classification system entitled: *Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys* (Soil Survey Staff 1975). The basic agronomic soil mapping unit is the *soil series*, whose members have the same genesis and weathering profile. This implies that the soils (a) have the same kind of parent material, climate, and native vegetation, (b) have the same number of horizons of similar depth, (c) have essentially the same slope and landscape position, and (d) are of about the same geologic age. Series having similar but not identical characteristics are grouped into *families*. Similar families are grouped into *subgroups*, then into *great groups*, and then into *suborders*. The highest category of Soil Taxonomy is the *order*, of which ten have been defined.

### Identifying Characteristics of Soils

The identifying characteristics of the soil of each horizon layer consist of (a) color, (b) texture, (c) structure, and (d) consistence. These characteristics correspond, roughly, to the soil's engineering properties. The texture is a measure of material grain (grain size) properties, the structure corresponds to the mass (density) properties, and the consistence compares to the physical behavior (strength) properties.

[1] By S. Joseph Spigolon

## Soil color

The USDA uses the Munsell color chart in its agricultural soil surveys. In this system, all colors are defined with three terms: hue, value, and chroma. The dominant spectral or rainbow color is the *hue*. The relative lightness or darkness of the spectral color is the *value*. *Chroma*, or saturation, is the relative strength or purity of the hue. The Munsell chart system contains colored cards systematically arranged by hue, value, and chroma. In Munsell notation, each of the terms -- hue, value, and chroma -- is measured on a scale of 0 to 10. Value varies from black (0) to pure white (10) with shades of gray in between.

## Soil texture

The basic soil textural class names in present use by the USDA (Soil Survey Staff 1975) are defined in terms of the relative amounts of sand, silt, and clay determined by laboratory mechanical analysis. The gravel and coarser sizes are not included in the definitions. Grain size definitions are contained in Table A-1.

## Soil structure

As defined by the USDA (Soil Survey Staff 1975): "Soil structure refers to the aggregation of primary soil particles into compound particles, or clusters or primary particles, which are separated from adjoining aggregates by surfaces of weakness." A *ped* is an individual natural soil aggregate. Descriptions of soil structure include: (a) the shape and arrangement or *type* , (b) the size or *class*, and (c) the distinctness and durability of the visible aggregates or peds or *grade*.

**Shape and arrangement.** The shape and arrangement of peds is defined by seven *types* of structure in *Soil Taxonomy* (Soil Survey Staff 1975):

*a.* *Platy.* Platelike with the vertical dimension limited and smaller than the other two; arranged around a horizontal plane; faces mostly horizontal.

*b.* *Prismatic.* Prismlike with two horizontal dimensions limited and considerably less than the vertical; particles arranged about a vertical line; vertical faces well defined; vertices angular; no rounded caps.

*c.* *Columnar.* Same as *prismatic,* but with rounded caps.

*d.* *(Angular) Blocky*. Blocklike or polyhedral, with particles arranged around a point and bounded by flat or rounded surfaces that fit the molds formed by the faces of surrounding peds; faces flattened and most vertices sharply angular.

*e.* *Subangular Blocky.* Same as *(angular) blocky,* except faces are mixed rounded and flattened with many rounded vertices.

*f.* *Granular.* Spheroids or polyhedrons having plane or curved surfaces which have very slight or no accommodation to the faces of surrounding peds; relatively nonporous peds.

*g.* *Crumb.* Same as *granular*, except peds are porous.

**Table A-1**
**U. S. Department of Agriculture, Soil Conservation Service,**
**Textural Classification of Soils (Soil Survey Staff 1975)**

| TEXTURAL CLASS | COMPOSITION ( % ) | | | PARTICLE SIZES AND VISUAL APPEARANCE |
|---|---|---|---|---|
| | SAND | SILT | CLAY | |
| SANDY SOILS. -- *Coarse-textured soils.* | | | | |
| Sand | 85 - 100 | 0 - 15 | 0 - 10 | Loose and single grained. Individual grain sizes can be detected. Free-flows when dry. |
| Loamy Sand | 70 - 90 | 0 - 30 | 0 - 15 | Granular soil with sufficient silt and clay to make it somewhat plastic. Sand character predominates. |
| LOAMY SOILS. -- *Moderately coarse-textured soils.* | | | | |
| Sandy Loam | 43 - 85 | 0 - 50 | 0 - 20 | Granular soil with sufficient silt and clay to make it somewhat coherent. Sand character predominates. |
| LOAMY SOILS. -- *Medium-textured soils.* | | | | |
| Loam | 23 - 52 | 28 - 50 | 7 - 27 | Uniform mix of sand, silt, and clay. Uniform sand gradation from coarse to fine. Slightly gritty feel, but smooth and plastic. |
| Silt Loam | 0 - 50 | 50 - 88 | 0 - 27 | Small amount of fine sand and/or clay. Cloddy when dry. Friable; readily broken and pulverized. |
| Silt | 0 - 20 | 80 - 100 | 0 - 12 | Very little fine sand and/or clay. May be cloddy when dry. Friable; readily broken and pulverized. |
| LOAMY SOILS. -- *Moderately fine-textured soils*. | | | | |
| Clay Loam | 20 - 45 | 15 - 53 | 27 - 40 | Fine textured. Makes hard lumps when dry. Resembles clay when in dry condition. |
| Sandy Clay Loam | 45 - 80 | 0 - 28 | 20 - 35 | Granular soil with sufficient clay to make it somewhat plastic and coherent. Sand character is somewhat masked. |
| Silty Clay Loam | 0 - 20 | 40 - 73 | 27 - 40 | Very little fine sand. May be cloddy when dry. Somewhat friable; broken and pulverized with some effort. |
| CLAYEY SOILS. -- *Fine-textured soils.* | | | | |
| Sandy Clay | 45 - 65 | 0 - 20 | 35 - 55 | Clayey soil with sufficient sand to make it somewhat friable. |
| Silty Clay | 0 - 20 | 40 - 60 | 40 - 60 | Clay and silt mixture. Sufficient clay to make it somewhat smooth and plastic. |
| Clay | 0 - 45 | 0 - 40 | 40 - 100 | Clayey soil. Makes hard lumps when dry. Not friable; difficult to crumble into powder when dry. |

**Class sizes**. Five structure *class* sizes are used. The reader is referred to Appendix I, Table 6, of *Soil Taxonomy* (Soil Survey Staff 1975) and Table 1 of the *Glossary of Soil Science Terms* (Soil Science Society of America 1987) for size limits corresponding to each of the structure types. The class sizes are (a) very fine or very thin, (b) fine or thin, (c) medium, (d) coarse or thick, and (e) very coarse or very thick.

**Structure grades**. Four terms for grade of structure, or degree of aggregation, are defined, ranging from 0 to 3.

0. *Structureless.* No observable aggregation or no orderly arrangement of natural lines of weakness.

1. *Weak.* Poorly formed indistinct peds that are barely observable in place.

2. *Moderate.* Well-formed distinct peds that are moderately durable and evident but not distinct in undisturbed soil.

3. *Strong.* Durable peds that are quite evident in undisplaced soil, that adhere weakly to one another, and that withstand displacement and become separated when the soil is disturbed.

## Soil consistence

The USDA (Soil Survey Staff 1975) states: "Soil consistence comprises the attributes of soil material that are expressed by the degree and kind of cohesion and adhesion or by the resistance to deformation or rupture." The terminology for soil consistence includes separate terms for three moisture conditions: wet, moist, and dry, and for cemented soils. All of the degrees of the terms are defined by field expedient, visual-manual evaluation tests. Detailed descriptions of methods for field visual-manual evaluation of the degrees of the various terms are given in Tables A-2 to A-5.

*a.* *Consistence when wet*. The USDA consistence when the soil is *wet* (at or above field capacity) includes terms for degrees of:

   1. *Stickiness* -- the quality of adhesion to other objects, primarily steel.

   2. *Plasticity* -- the ability to change shape continuously under the influence of an applied stress and to retain the impressed shape on removal of the stress.

*b.* *Consistence when moist.* The USDA consistence when the soil is *moist* (midway between air dry and field capacity) includes degrees of resistance of a moist sample to deformation by hand.

*c.* *Consistence when dry*. The USDA consistence when the soil is *dry* (air dry) includes degrees of resistance of an air-dry sample of the material to deformation by hand.

*d.* *Cementation* refers to a brittle hard consistence caused by some cementing substance other than clay minerals, such as calcium carbonate, silica, or oxides of salts of iron and aluminum. Typically, the hardness and brittleness persist in the wet condition, although some cemented soils will soften somewhat with prolonged wetting.

**Table A-2**
**Field Test Methods for Soil Consistence When Wet (Soil Survey Staff 1975)**

| Degree | Observations |
|---|---|
| **Stickiness Test Method:** For field evaluation, the moist soil material is pressed between the thumb and forefinger and its adherence (stickiness) is noted. | |
| Nonsticky | After release of pressure, practically no soil material adheres to thumb or finger. |
| Slightly sticky | After pressure, soil material adheres to both thumb and finger but comes off one or the other rather cleanly. It is not appreciably stretched when the digits are separated. |
| Sticky | After pressure, soil material adheres to both thumb and finger and tends to stretch somewhat and pull apart rather than pulling free from either digit. |
| Very sticky | After pressure, soil material adheres strongly to both thumb and forefinger and is decidedly stretched when they are separated. |
| **Plasticity Test Method:** For field determination, roll the soil material between thumb and finger and observe whether or not a wire or thin rod of soil can be formed. | |
| Nonplastic | No wire is formable. |
| Slightly plastic | Wire formable but soil mass easily deformable. |
| Plastic | Wire formable and moderate pressure required for deformation of soil mass. |
| Very plastic | Wire formable and much pressure required for deformation of soil mass. |

**Table A-3**
**Field Test Methods for Soil Consistence When Moist (Soil Survey Staff 1975)**

| Degree | Observations |
|---|---|
| **Test Method:** For field evaluation, select and attempt to crush in the hand a mass that appears slightly moist. | |
| Loose | Noncoherent (will not stick together). |
| Very friable | Soil material crushes under very gentle pressure but coheres when pressed together. |
| Friable | Soil material crushes easily under gentle to moderate pressure between thumb and forefinger, and coheres when pressed together. |
| Firm | Soil material crushes under moderate pressure between thumb and forefinger but resistance is distinctly noticeable. |
| Very firm | Soil material crushes under strong pressure; barely crushable between thumb and forefinger. |
| Extremely firm | Soil material crushes only under very strong pressure; cannot be crushed between thumb and forefinger and must be broken apart bit by bit. |

**Table A-4**
**Field Test Methods for Soil Consistence When Dry (Soil Survey Staff 1975)**

| Degree | Observations |
|---|---|
| **Test Method:** For field evaluation, select an air-dry mass and break in the hand. | |
| Loose | Noncoherent. |
| Soft | Soil mass is very weakly coherent and fragile; breaks to powder or individual grains under very slight pressure. |
| Slightly hard | Weakly resistant to pressure; easily broken between thumb and forefinger. |
| Hard | Moderately resistant to pressure; can be broken in the hands without difficulty but is barely breakable between thumb and forefinger. |
| Very hard | Very resistant to pressure; can be broken in the hands only with difficulty; not breakable between thumb and forefinger. |
| Extremely hard | Extremely resistant to pressure; cannot be broken in the hands. |

**Table A-5**
**Field Test Methods for Soil Cementation (Soil Survey Staff 1975)**

| Degree | Observations |
|---|---|
| **Test Method:** For field evaluation, select a sample and attempt to break it with the fingers. | |
| Weakly cemented | Cemented mass is brittle and hard but can be broken in the hands. |
| Strongly cemented | Cemented mass is brittle and harder than can be broken in the hand but is easily broken with a hammer. |
| Indurated | Very strongly cemented; brittle, does not soften under prolonged wetting, and is so extremely hard that for breakage a sharp blow with a hammer is required; hammer generally rings as a result of the blow. |

## Unified Soil Classification System

The Unified Soil Classification System (USCS) was derived from the Airfield Classification System developed by Arthur Casagrande, in 1942, to facilitate wartime military airfield construction by the U.S. Army Corps of Engineers. Its purpose was to permit the classification of soils according to their desirability for use in airfield base courses.

Casagrande later proposed his soil classification system for adoption by the civil engineering profession (Casagrande 1948). In the late 1940's, several U.S. government agencies involved in geotechnical engineering agreed on the use of a "unified" soil classification system. In 1953, the USAE Waterways Experiment Station (WES) published the USCS as a technical report. The report was updated in 1960 (USAEWES 1960). The USCS was later adopted as American Society For Testing and Materials (ASTM) Standard D 2487 (ASTM 1994). The information contained in this section of this appendix was obtained from ASTM D 2487.

All soil types in the USCS are divided into soil groups and each group must meet unique criteria. They are described by means of a group name and a two-letter group symbol.

The USCS distinguishes two major categories of soil, based on grain size:

*a.* *Coarse-grained soils*. Mineral soil particles with more than 50 percent by weight coarser than (retained on) the U.S. No. 200 screen (0.074 mm).

*b.* *Fine-grained soils.* Mineral soil particles with 50 percent or more by weight finer than (passing) the U.S. No. 200 screen (0.074 mm).

### Coarse-grained soils

Coarse-grained soils are subdivided into two groups, based on grain size:

*a.* *Gravel.* In a gravel, more than 50 percent by weight of the coarse fraction (+No. 200) is coarser than (retained on) the U.S. No. 4 screen (4.75 mm).

*b.* *Sand.* In a sand, 50 percent or more by weight of the coarse fraction (+No. 200) is finer than (passes) the U.S. No. 4 screen (4.75 mm).

The sieve analysis test is then evaluated to determine the particle-size diameters: $D_{60}$, $D_{30}$, and $D_{10}$, corresponding to 60, 30, and 10 percent respectively passing (finer than) the cumulative particle-size distribution curve. From this are calculated the:

*a.* *Coefficient of Uniformity*, $C_u = D_{60} / D_{10}$

*b.* *Coefficient of Curvature*, $C_c = (D_{30})^2 / (D_{10} \times D_{60})$

Table A-6 contains the criteria for classifying *gravelly soils*. Table A-7 contains the criteria for classifying *sandy soils*.

## Fine-grained soils

Fine-grained soils are grouped according to plasticity: the liquid limit (LL) and plasticity index (PI) as determined in the ASTM D 4318 procedure. The USCS uses a soil plasticity chart, Figure A-1, derived from Casagrande's 1948 chart, to distinguish two fine-grained soil types:

*a.* *High plasticity soils.* LL is equal to or greater than 50 percent.

*b.* *Low plasticity soils.* LL is less than 50 percent.

**Table A-6**
**Group Symbols for Gravelly Soils--Unified Soil Classification System (ASTM D 2487, 1994)**

More than 50 % retained on No. 200 sieve. More than 50 % of coarse fraction retained on No. 4 sieve.

| Group Symbol | Group name * | Criteria | |
|---|---|---|---|
| | | **Percent passing No. 200 sieve** | **Other factors** ** |
| GW | Well-graded gravel | < 5 | $C_u$ greater than or equal to 4; $C_c$ between 1 and 3. |
| GP | Poorly graded gravel | < 5 | Not meeting both criteria for GW. |
| GM | Silty gravel | > 12 | Atterberg limits plot below "A" line or plasticity index less than 4. |
| GC | Clayey gravel | > 12 | Atterberg limits plot on or above "A" line and plasticity index greater than 7. |
| GC-GM | Silty, clayey gravel | > 12 | Atterberg limits plot on or above "A" line and plasticity index is between 4 and 7. |
| GW-GM | Well-graded gravel with silt | 5 - 12 | Meets criteria for GW and GM. |
| GW-GC | Well-graded gravel with clay | 5 - 12 | Meets criteria for GW and GC. |
| GP-GM | Poorly graded gravel with silt | 5 - 12 | Meets criteria for GP and GM. |
| GP-GC | Poorly graded gravel with clay | 5 - 12 | Meets criteria for GP and GC. |

* If sample contains cobbles or boulders, add "with cobbles or boulders or both" to group name.
If sample contains 15 % or more sand, add "with sand" to group name.
If fines are organic, add "with organic fines" to group name.

** $C_u$ = Coefficient of Uniformity = $D_{60} / D_{10}$
$C_c$ = Coefficient of Curvature = $(D_{30})^2 / (D_{10} \times D_{60})$

**Table A-7**
**Group Symbols for Sandy Soils--Unified Soil Classification System (ASTM D 2487, 1994)**

More than 50 % retained on No. 200 sieve. 50 % or more of coarse fraction passes No. 4 sieve.

| Group Symbol | Group name * | Criteria | |
|---|---|---|---|
| | | Percent passing No. 200 sieve | Other factors ** |
| SW | Well-graded sand | < 5 | $C_u$ greater than or equal to 6; $C_c$ between 1 and 3. |
| SP | Poorly graded sand | < 5 | Not meeting both criteria for SW. |
| SM | Silty sand | > 12 | Atterberg limits plot below "A" line or plasticity index less than 4. |
| SC | Clayey sand | > 12 | Atterberg limits plot on or above "A" line and plasticity index greater than 7. |
| SC-SM | Silty, clayey sand | > 12 | Atterberg limits plot on or above "A" line and plasticity index is between 4 and 7. |
| SW-SM | Well-graded sand with silt | 5 - 12 | Meets criteria for SW and SM. |
| SW-SC | Well-graded sand with clay | 5 - 12 | Meets criteria for SW and SC. |
| SP-SM | Poorly graded sand with silt | 5 - 12 | Meets criteria for SP and SM. |
| SP-SC | Poorly graded sand with clay | 5 - 12 | Meets criteria for SP and SC. |

* If sample contains 15 % or more gravel, add "with gravel" to group name.
If fines are organic, add "with organic fines" to group name.

** $C_u$ = Coefficient of Uniformity = $D_{60} / D_{10}$
$C_c$ = Coefficient of Curvature = $(D_{30})^2 / (D_{10} \times D_{60})$

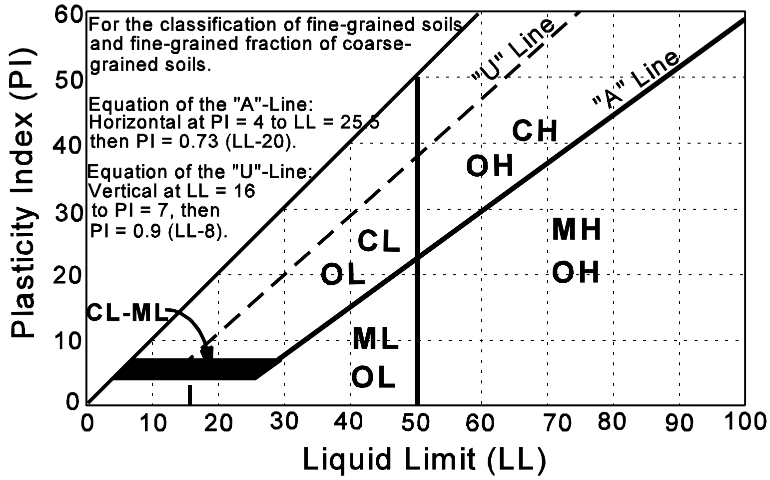


Figure A-1. Soil plasticity chart for classifying fine-grained soils in the USCS.

Two lines are shown on the plasticity chart, Figure A-1, (a) the A-line which is used to distinguish *silt* from *clay*, and (b) the U-line which is an empirical upper limit for natural soils, based on extensive testing at the USAE Waterways Experiment Station, Vicksburg, MS.

*Organic* soils are distinguished from *inorganic* soils by means of the liquid limit test. The liquid limit test is made on a soil sample that has not been dried. The test is repeated on the sample after it has been oven-dried. For organic soils, the ratio of *oven-dried liquid limit* to *undried liquid limit* is generally less than 0.75.

Criteria for establishing the group name and group symbol for fine-grained soils are contained in Table A-8. A comparison of the USDA Soil Taxonomy and the Unified Soil Classification System classes, based on grain size alone, is given in Table A-9.

**Table A-8**
**Group Symbols for Silty and Clayey Soils -- Unified Soil Classification System (ASTM D 2487, 1994)**

50 % or more passes the No. 200 sieve.

| Group Symbol | Group name * | Criteria | |
|---|---|---|---|
| | | **Liquid Limit** | **Other factors** |
| CL | Lean clay | Less than 50 | Plasticity index plots on or above "A" line and PI is greater than 7. |
| CL-ML | Silty clay | | Plasticity index plots on or above "A" line and PI is between 4 and 7. |
| ML | Silt | | Plasticity index plots below "A" line or PI is less than 4. |
| OL ** | Organic clay | | Plasticity index plots on or above "A" line and PI is equal to or greater than 4. |
| | Organic silt | | Plasticity index plots below "A" line or PI is less than 4. |
| CH | Fat clay | Equal to or greater than 50 | Plasticity index plots on or above "A" line. |
| MH | Elastic silt | | Plasticity index plots below "A" line. |
| OH ** | Organic clay | | Plasticity index plots on or above "A" line. |
| | Organic silt | | Plasticity index plots below "A" line. |
| Pt | Peat | Highly organic soils. Primarily organic matter, dark in color, and organic odor. | |

* If sample contains 15 to 29 % plus No. 200, add "with sand" or "with gravel" to group name, whichever is predominant.
If sample contains 30 % or more plus No. 200, add "sandy" or "gravelly" to group name, whichever is predominant.

** For organic soils, (*oven-dried liquid limit)* /(*undried liquid limit)* < 0.75

**Table A-9**
**Probable USCS Equivalent to USDA-SCS Textural Soil Types Based on Sand Content**

| USDA TEXTURAL SOIL TYPE | PROBABLE USCS EQUIVALENT | |
|---|---|---|
| | GROUP NAME | GROUP SYMBOL |
| Sand | Clean sand (less than 15% fines) | SW, SP, SW-SM, SP-SM, SW-SC, SP-SC |
| Sandy loam | Silty sand; Clayey sand | SM; SC |
| Loam | Sandy clay | ML<br>MH |
| Silt loam | Sandy silt | |
| Silt | Clayey silt | |
| Clay loam | Lean clay | CL |
| Clay | Fat clay | CH |
| Organic soil | Organic soil; Peat | OL, OH; Pt |

# AASHTO Highway Soil Classification System

The American Association of State Highway and Transportation Officials (AASHTO 1988) soil classification system is used by highway departments in the United States to classify soils for use as highway embankments, subgrades, subbases, and bases. Like the Unified Soil Classification System, AASHTO uses both gradation and Atterberg limits for its classification criteria.

The classification proceeds as follows:

1. Make a mechanical sieve analysis test and Atterberg limits tests.

2. Using the results of the sieve analysis, enter Table A-10 (first half) and proceed from left to right, i.e., from A-1 to A-2. The first group in which the test data will fit is the correct classification. If no fit is obtained, then proceed to Table A-10 (second half) and again start at the left and proceed to the right.

3. Calculate the Group Index value from the equation:

$$\text{Group Index (GI)} = (F - 35)\,[0.2 + 0.005\,(LL - 40)] + 0.01\,(F - 15)\,(PI - 10)$$

in which
- F = percentage passing the No. 200 sieve (0.074 mm), expressed as a whole number. This is based only on the material passing the 75 mm (3 in.) screen.
- LL = Liquid Limit
- PI = Plasticity Index

When the calculated group index is negative, the GI is reported as zero (0).

4. The results are presented with the group index values in parentheses after the group symbol. For example, A-2-6(3), A-4(5), A-7-5(17).

**Table A-10 (first half of table)**
**AASHTO Classification of Soils**

| Group classification | *A-1* | | *A-3* | *A-2* | | |
|---|---|---|---|---|---|---|
| | *A-1-a* | *A-1-b* | | *A-2-4* | *A-2-5* | *A-2-6* |
| Sieve analysis: percent passing: | | | | | | |
| 2.00 mm (No. 10) | 50 max. | ----- | ----- | ----- | ----- | ----- |
| 0.425 mm (No. 40) | 30 max. | 50 max. | 51 min. | ----- | ----- | ----- |
| 0.074 mm (No. 200) | 15 max. | 25 max. | 10 max. | 35 max. | 35 max. | 35 max. |
| Characteristics of fraction passing 0.425 mm (No. 40): | | | | | | |
| Liquid Limit | ----- | | ----- | 40 max. | 41 min. | 40 max. |
| Plasticity Index | 6 max. | | N.P. | 10 max. | 10 max. | 11 min. |
| Usual types of significant constituent materials. | Stone fragments, gravel, and sand. | | Fine sand | Silty or clayey gravel and sand. | | |

**Table A-10 (second half of table)**
**AASHTO Classification of Soils**

| Group classification | *A-2-7* | *A-4* | *A-5* | *A-6* | *A-7*<br>*A-7-5*<br>*A-7-6* | *A-8* |
|---|---|---|---|---|---|---|
| Sieve analysis: percent passing: | | | | | | |
| 2.00 mm (No. 10) | ----- | ----- | ----- | ----- | ----- | ----- |
| 0.425 mm (No. 40) | ----- | ----- | ----- | ----- | ----- | ----- |
| 0.074 mm (No. 200) | 35 max. | 36 min. | 36 min.. | 36 min. | 36 min. | ----- |
| Characteristics of fraction passing 0.425 mm (No. 40): | | | | | | |
| Liquid Limit | 41 min. | 40 max. | 41 min. | 40 max. | 41 min.* | ----- |
| Plasticity Index | 11 min. | 10 min. | 10 max. | 11 min. | 11 min. | ----- |
| Usual types of significant constituent materials. | Silty or clayey gravel and sand. | Silty soils. | | Clayey soils. | | Highly organic soils (peat or muck). |

* Plasticity index of A-7-5 subgroup is equal to or less than LL minus 30.
Plasticity index of A-7-6 subgroup is greater than LL minus 30.

## References

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# Appendix B
# Tests for Wetland Soil Properties[1]

This appendix contains information intended to serve as a common base of nomenclature and definitions for use by all participants in a wetland restoration or creation project. For more complete discussions of the topics reviewed here, the reader should consult textbooks and other publications on each topic.

All soils are distinguished by their:

*a.* *Material* properties, i.e., the properties of the individual mineral grains or particles, the organic matter, and the pore fluids.

*b.* *Mass* (intact) properties, i.e., the position and arrangement of the soil particles in a soil mass, including density, or unit weight.

*c.* *Physical behavior qualities* , i.e., the erodibility, permeability, and capillarity potential of the soil mass. The physical behavior of a soil is a combined function of its material properties, its mass properties, and the externally applied forces.

## Properties of the Soil Material

The soil material properties are those of the soil components, without reference to their arrangement in a soil mass, i.e., the individual grains, the pore water, or the other materials present. Soil material identification tests are made on a sample whose in situ, mass structure has been completely disturbed by remolding. The main soil material properties that are measured by test or observation are:

*a.* Available water capacity

*b.* Calcium carbonate equivalent

*c.* Cation exchange capacity

*d.* Cementation

[1] By S. Joseph Spigolon

*e.* Color

*f.* Electrical conductivity

*g.* Extractable acidity

*h.* Extractable aluminum

*i* Free iron oxides

*j.* Grain angularity and shape (coarse-grained soils only)

*k.* Gypsum content

*l.* Linear extensibility (volume change)

*m.* Nutrient content

*n.* Organic matter -- amount and type

*o.* Particle density (specific gravity of grains)

*p.* Particle size (grain-size distribution)

*q.* Percent silt and clay

*r.* Plasticity (Atterberg liquid and plastic limits, plasticity index)

*s.* Reactivity (pH)

*t.* Resistivity

*u.* Sodium adsorption ratio

*v.* Water content (moisture content)

## Available water capacity

**Definition.** Available water capacity is the portion of water in a soil that can be absorbed by plant roots. It is commonly estimated as the amount of water held between field capacity and the wilting point (Soil Survey Staff 1993). Field capacity is the amount of water, held by a soil against gravity, after the large pores have *drained* for a short period following a period of saturation. The wilting point is that water content when the water is held so tightly by adhesion that plants cannot suction it away. The amount of water between the field capacity and the wilting point is the amount available to plants.

**Test methods.** Field capacity is determined by sampling soil moisture content just after the soil has drained following a period of rain or humid weather, after a spring thaw, or after heavy irrigation. In the laboratory, an approximation of field capacity is made using the moisture content developed at 33 kPa (1/3 bar) suction in a pressure membrane apparatus. Similarly, the wilting point is determined in the laboratory using 1500 kPa (15 bar) tension (Soil Survey Staff 1992 ).

## Calcium carbonate equivalent

**Definition.** Calcium carbonate equivalent is the quantity of carbonate ($CO_3$) in the soil expressed as $CaCO_3$ and as a weight percentage of the less than 2-mm size fraction (Soil Survey Staff 1993).

**Test method.** Calcium carbonate equivalent is measured in the laboratory by method 6E1 of the Soil Survey Laboratory Methods Manual (Soil Survey Staff 1992). It may also be determined in the field using calcimeters.

## Cation exchange capacity

**Definition.** Cation exchange capacity is the amount of exchangeable cations that a soil can absorb at pH = 7.0 as estimated by the displacement of adsorbed ammonium ions in the ammonium acetate method, if the soils have pH ≥ 5.5, and from the sum of bases plus extractable aluminum, if the soils have pH < 5.5 (Soil Survey Staff 1993).

**Test method.** The ammonium acetate method 5A8 of the Soil Survey Laboratory Methods Manual (Soil Survey Staff 1992) gives the cation exchange value for soils with pH ≥ 5.5. For soils with pH < 5.5, the sum of bases plus extractable aluminum cation exchange capacity method 5A3b (Soil Survey Staff 1992) is used.

## Cementation

**Definition.** Granular and mixed-grain soils may be cemented with various natural cementing agents. These agents are primarily compounds of iron or alumina, or are calcium or magnesium oxides or carbonates. The only cementing agents for which engineering terminology has been developed are those that will react with hydrochloric acid, mostly calcium carbonate (limestone) or calcium oxide (lime).

**Test methods.** Two visual-manual test methods are described in ASTM (1994) Designation D 2488, *Description and Identification of Soils (Visual-Manual Procedure)*:

a. *Reaction with dilute hydrochloric acid.* Drops of dilute hydrochloric acid (HCl) are placed on the soil and the reaction is observed. The reaction is described as shown in Table B-1. This procedure detects the presence of lime.

**Table B-1**
**Criteria for Describing Reaction With HCl (ASTM D 2488, 1994)**

| Description | Criteria |
|---|---|
| None | No visible reaction. |
| Weak | Some reaction, with bubbles forming slowly. |
| Strong | Violent reaction, with bubbles forming immediately. |

**Table B-2**
**Criteria for Describing Cementation (ASTM D 2488, 1994)**

| Description | Criteria |
|---|---|
| Weak | Crumbles or breaks with handling or little finger pressure. |
| Moderate | Crumbles or breaks with considerable finger pressure. |
| Strong | Will not crumble or break with finger pressure. |

*b. Resistance to crumbling.* A sample of the soil is subjected to finger pressure. The reaction is described as shown in Table B-2.

## Color and color standards

Soil color, while not a fundamental property of soil material, is of considerable help in correlating soil samples from location to location in the subsurface investigation. Soil colors are often useful in (a) detecting different strata, (b) defining soil type based on experience in a local area, and (c) possible identification of materials and saturation conditions.

Bright colors, including light grey or white, are associated with inorganic soils. Red colors, caused by iron oxide, are typically found in mature, temperate climate soils. Yellow or yellow brown coloring indicates magnesium and hydrous iron oxides, resulting from wetter soils than red colors. White or pink generally indicate silica, calcium carbonate, or aluminum compounds. White and grey are usually found in sandy parent soils or may indicate leaching of soluble salts or carbonates. Brown and reddish brown result from a combination of organic matter and oxidized iron.

Blue color results when iron is completely isolated from oxygen, as in a saturated soil. Alternating saturation and drying, as occurs in hydric soils, creates small pockets of varying colors called *mottles*. Dark or drab shades of brown or grey, and almost black, soils are typically organic, usually due to humus. However, some soils are black from other minerals, such as magnesium oxide.

A *mottled* soil has spots, streaks, or splotches of one or more distinct colors against a background of another, dominant color. A *marbled* soil contains two or more distinct colors mixed throughout the mass in about equal amounts, without a dominant background color. Other terms indicating color distribution in a soil include *spotted*, *speckled*, *streaked*, and *variegated*.

*Gleyed soil* is soil that formed under poor drainage conditions, resulting in the reduction of iron and other elements in the profile. Dark grey or green or blue hues are indicative of reducing conditions, or gleying, which were the colors at the time of deposition of water-sedimented materials (Spangler and Handy 1982). On exposure to air or oxygen-laden water, gleyed soils will oxidize and the color changes to tan or brown. Gley colors indicate continuous saturation. *Mottled* grey and brown colors suggest occasional saturation from a seasonally high water table or capillary action.

The SCS uses the *Munsell notation* in its pedological soil-survey operations. Soil colors are determined by comparison with the Munsell color chart. The chart consists of 175 colored cards or chips arranged by hue, value, and chroma. Hue is the dominant spectral color. Value is the relative lightness or darkness. Chroma, or saturation, is the relative purity or strength of hue. The Munsell notation is, therefore, a designation of color by degrees of three simple variables -- hue, value, and chroma. For example, a notation of 10YR 6/4 is a color of 10YR hue, value of 6, and chroma of 4.

Geotechnical engineers do not generally require the degree of soil color refinement made possible by the Munsell chart. Ordinarily, about 12 colors, more or less, will suffice in a given area for engineering purposes. However, on wetland projects, it is desirable that the colors used in geotechnical soil identification and description match with selected colors on the Munsell chart so that uniformity of color terminology be maintained between the professional specialties working together on a project.

## Electrical conductivity

**Definition.** Electrical conductivity is the electrolytic conductivity of an extract from saturated soil paste and is a measure of the concentration of water-soluble salts in soils. It is used to indicate *salinity* (Soil Survey Staff 1993).

**Test method.** Free salt may sometimes be seen on structural faces or on the soil surface or from plant growth indicators. In the laboratory, a saturated sample of the soil is placed in an insulated box and a direct current passed through the specimen along a path of known length. The conductivity is measured in millimhos per cm (Soil Survey Staff 1992).

## Extractable acidity

**Definition.** Extractable acidity is a measure of soil exchangeable hydrogen ions that may become active by cation exchange. It is a measure of the pH-dependent charge in soils and is an indicator of soil nutrient availability.

**Test method.** Extractable acidity is determined by method 6H5a of the Soil Survey Laboratory Methods Manual (Soil Survey Staff 1992).

## Extractable aluminum

**Definition.** Extractable aluminum is the amount of aluminum extracted in one normal solution of potassium chloride. It is an indicator of soil nutrient availability and of toxicity.

**Test method.** Extractable aluminum is determined by method 6G9a of the Soil Survey Laboratory Methods Manual (Soil Survey Staff 1992).

## Free iron oxides

**Definition.** Free iron oxides are secondary iron oxides, such as geothite and hematite. This form of iron may exist as discrete particles, as a soil particle coating, or as a soil cementing agent. Free iron oxide plays an important role in the phosphorous fixation ability of soils.

**Test method.** Free iron oxides are measured as the amount extracted by dithonite citrate using method 6C2b of the Soil Survey Laboratory Methods Manual (Soil Survey Staff 1992).

## Grain angularity and shape

**Definitions** and **test methods** for defining the angularity and shape of coarse particles are given in Tables B-3 and B-4, adapted from ASTM (1994) D 2488. The angularity of coarse grains (sand and larger sizes) is a factor in soil erodibility and in shear strength of granular soils. Visual examination with the unaided eye or using a magnifying glass or hand lens is used for comparison with standard shapes.

**Table B-3**
**Criteria for Describing Angularity of Coarse-Grained Particles (after ASTM D 2488)**

| Description | Criteria |
|---|---|
| Angular | Particles have sharp edges and relatively plane sides with unpolished surfaces. |
| Subangular | Particles are similar to angular description but have rounded edges. |
| Subrounded | Particles have nearly plane sides but have well-rounded corners and edges. |
| Rounded | Particles have smoothly curved sides and no edges. |

**Table B-4**
**Criteria for Describing Particle Shape of Coarse-Grained Soils (after ASTM D 2488)**

| DESCRIPTION | CRITERIA |
|---|---|
| Flat | Particles with width to thickness ratio greater than 3 |
| Elongated | Particles with length to width ratio greater than 3 |
| Flat and Elongated | Particles meeting criteria for both flat and elongated. |
| Spherical (typically not stated in description) | Particles having width to thickness ratio and length to width ratio less than 3. |

### Gypsum content

**Definition.** Gypsum is the percent, by weight, of hydrated calcium sulfates ($CaSO_4 \cdot xH_2O$) in the < 20-mm fraction of soil. If the gypsum content is greater than about one percent, the soil can be corrosive to concrete structures. The water in gypsum will be removed by the normal oven-drying procedures used to measure soil water content and can, therefore, affect those measurements.

**Test method.** The gypsum content is determined by method 6F1a of the Soil Survey Laboratory Methods Manual (Soil Survey Staff 1992).

### Linear extensibility (volume change)

**Definition.** Linear extensibility is the linear expression of the change in volume of a natural soil fabric as the water content changes from field capacity (see discussion above for *available water capacity*) to oven dryness. In engineering practice, the volume change is often measured on completely remolded soil samples. The capacity of a soil to undergo volume changes on wetting and drying can also be estimated by the plasticity index (see *plasticity* below). The higher the plasticity index of a clay, above about 15 percent, the greater is the expected relative volume change.

**Test method.** Two direct methods are described in the National Soil Survey Handbook (Soil Survey Staff 1993):

*a.* *Core method.* An undisturbed sample core, taken in accordance with methods described in Appendix B, is extruded, measured, and set upright in a dry place (and finished drying in an oven). The change in height of the core is the linear extension.

*b.* *Clod method.* A relatively undisturbed clod may be obtained and coated with paraffin wax as described in the test method for *bulk density*. The wax coated clod is then measured and dried as described above for the core method.

## Moisture content (see water content below)

## Nutrient content

**Definition.** Plant nutrients, such as nitrogen, phosphorus, and sulfur, exist mostly as negatively charged ions in the soil. Micronutrients, or trace elements, include such elements as iron, manganese, and copper.

**Test methods.** There are numerous standard chemical test methods for elemental analysis. Many are contained in the Soil Survey Laboratory Methods Manual (Soil Survey Staff 1992).

## Organic matter

**Definition.** Odor is an immediate and evident indicator of the presence of organics or chemical pollutants. The organic content of a soil is established in the laboratory by loss on ignition. The *ash content* is the uncombusted residue, mostly rock and clay minerals, after the sample has been dried at a sufficiently high temperature to burn all the organics.

**Test methods.** The primary test method for moisture, ash, and organic matter of organic soils uses the ASTM (1994) D 2974 procedure. As an expedient, the probable presence of organics may be determined by using the Atterberg limits procedure of ASTM (1994) Method D 2487. In the latter procedure, the Atterberg liquid limit is determined on a sample that has not been previously dried and again on the sample after it has been oven dried. If the liquid limit, oven dried, is less than 75% of the liquid limit, never dried, the soil is defined as organic. Definitions of organic content are given in Appendix A.

## Particle density (specific gravity of grains)

**Definition.** The specific gravity of the solid constituents of a soil is the ratio of the unit weight of the solids to the unit weight of water. Knowledge of the specific gravity is essential for the calculation of void ratio and porosity. The other properties needed are the in situ density and water content. Those calculations involve determination of the density and volume of the soil solids as part of the total in situ volume.

**Test method.** A test procedure for the specific gravity of soils is given in ASTM (1994) Method D 854. The test includes measurement of (a) the oven dry weight of a mass of soil particles, (b) the determination of the volume of the particles by displacement of water, and (c) calculation of the specific gravity as weight divided by volume.

## Particle sizes (grain-size distribution)

**Definitions.** The distribution of particle sizes is determined by screening the dried soil through a set of sieves. The results are expressed in the form of a cumulative semilog plot of

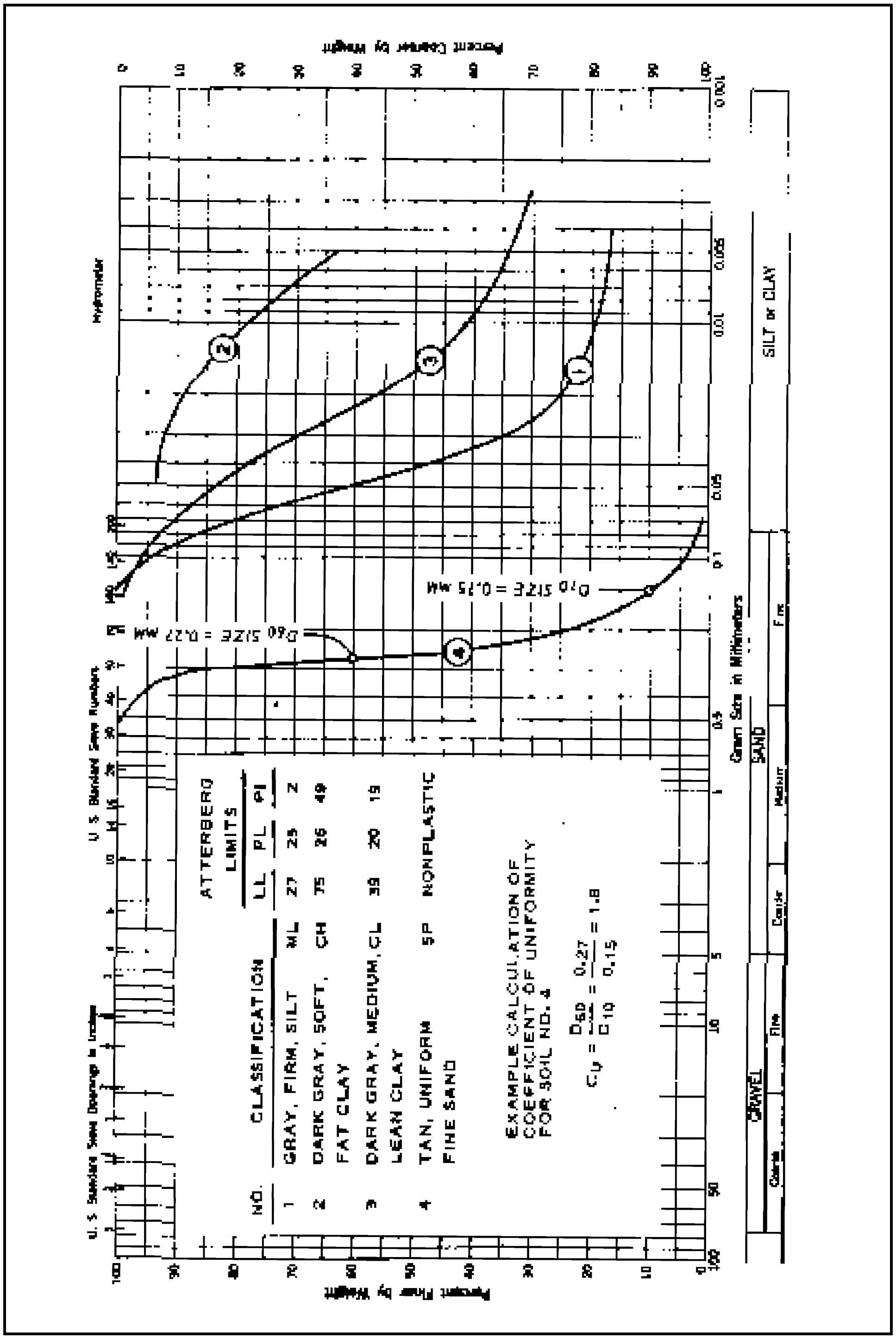



Figure B-1. Grain-size distribution graph.

percent finer versus grain diameter, as shown in Figure B-1. The use of screens to fractionate silt- and clay-sized particles, smaller than about 0.075 mm (No. 200) to 0.063 mm (No. 230), is impractical because of the fineness of screens and their tendency to become clogged with particles. For that fraction of the soil the sedimentation rate in water is used to establish quantities of various sizes.

Useful values determined from the grain-size distribution curve are:

*a.* *Maximum grain size*: Smallest screen size through which all particles will pass.

*b.* *Median grain size*: Grain diameter ($d_{50}$) corresponding to the 50% finer ordinate on the particle-size distribution curve.

*c.* *Effective size*: Grain diameter ($d_{10}$) corresponding to the 10% finer ordinate on the particle-size distribution curve.

*d.* *Coefficient of uniformity*: Ratio of the $d_{60}$ size to the $d_{10}$ size.

*e.* *Coefficient of curvature*: Ratio of the square of the $d_{30}$ size to the product of the $d_{60}$ and the $d_{10}$ sizes.

**Test methods.** The mechanical analysis of soils is made using the ASTM (1994) Method D 422 procedure. The finest practicable screen size is the range of the No. 200 (0.074 mm), the No. 230 (0.063 mm), or the No. 270 (0.050 mm), depending on the classification system used. The distribution of grain sizes finer than these screens is normally done by using the sedimentation rate in water, as described below. If only the amount of material passing the No. 200 screen is needed, the soil can simply be washed through that screen using the ASTM Method D 1140 procedure.

## Percent silt and clay

Material finer than 0.074 mm (No. 200 sieve), 0.063 mm (No. 230 sieve), or 0.050 mm (No. 270 sieve), depending on the classification system used, contains silt and clay sizes. There is general agreement between the various soil classification systems that all particles with a spherical equivalent diameter of 0.002 mm and smaller constitute clay sizes. Because clay-sized particles cannot be separated from the coarser silt particles by sieving, a test using the sedimentation rate of soil particles in water is commonly used.

The rate at which individual or flocculated soil particles will settle in still water is based on Stokes' Law, which indicates that the settlement rate of spherical particles is a function of (a) grain diameter, (b) viscosity and specific gravity of the fluid, (c) grain specific gravity, (d) distance the particle settles, and (e) time. Clay-silt floc are deflocculated by the addition of a water softener, sodium hexametaphosphate (Calgon).

The settlement rate of deflocculated soils in distilled water may be determined by the standard laboratory test for grain-size distribution ASTM (1994) Method D 422, i.e., the hydrometer test. Using this test, a continuation of the grain-size distribution curve of Figure B-1 can be extended into the silt and clay range. Individual clay particles exist as platelets. The settlement rate and amount of clay sizes present are predicated on spherical particles. This difference, while it exists, is not significant as long as all tests are made using the same standard method.

If only the percent silt and percent clay sizes is required rather than a continuous curve, the pipette or decantation method can be used. At a specific time, calculated from Stokes' Law, all of the soil-water slurry above a specific level in the sedimentation column is removed with a pipette or by decantation through a hole in the side of the column. This is continued for repeated trials until only clear water is removed. According to Stokes' Law, all particles larger than the specified size will have settled and all smaller sizes will have been removed.

The laboratory test procedure for silt and clay sizes (hydrometer, pipette, or decantation test) usually requires dispersal of the individual particles using a chemical deflocculating agent. Because of the electrical charges of attraction and repulsion acting on clay particles, the presence of salt in seawater will cause clay particles to flocculate, or combine, to form apparently larger particles. The larger particles, or flocs, will then settle at a rate dependent on their floc size rather than individual grain sizes. A special sedimentation test (USACE 1987) using seawater as the suspending medium may be more instructive in that situation.

### Plasticity (Atterberg limits) of the fine fraction

**Definitions.** A distinction exists between the terms clay *sizes* and clay *minerals*. The clay *size* fraction is determined by an appropriate gradation (sedimentation) test and includes all particles smaller than a given size, usually taken as 0.002 mm. However, the physical behavior characteristics of the fine fraction depend also on the mineralogical composition of the fine-grained soil fraction, i.e., the type of clay *minerals*.

The plasticity of the fine-grained soil fraction (No. 40 sieve) reflects the combined influence of the mineralogy of the clay and the physico-chemical interactions of the fine fraction of soils (Terzaghi and Peck 1967). The Atterberg limits indicate the range of water content over which the soil behaves in a plastic manner. The range is affected by the type and amount of -0.002 mm clay mineral present. The upper limit of the range is defined as the *liquid limit* (LL) and the lower limit is defined as the *plastic limit* (PL). The LL is the water content at which the soil will just begin to flow when jarred in the prescribed manner. The PL is the water content at which the soil will just begin to crumble when rolled into threads 3 mm (1/8-inch) in diameter. The *plasticity index* (PI) is calculated as the difference between the liquid limit (LL) and plastic limit (PL) water contents, i.e., PI = LL - PL. Based on a chart developed by Casagrande (1948), the identification of the fine-grained fraction of soils in the Unified Soil Classification System (USAEWES 1960, ASTM 1994) is based solely on the Atterberg limits, as shown in Figure B-2. When paired with a determination of the percent clay (-0.002 mm) size fraction, they provide a simple method of estimating the clay mineral type.

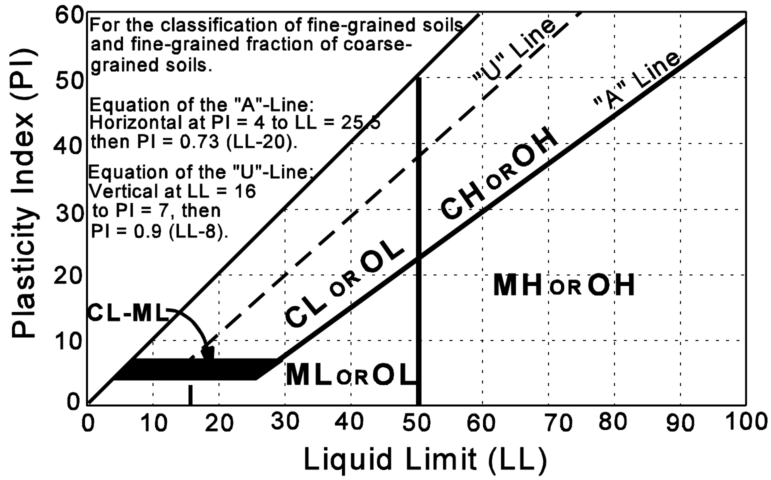



Figure B-2. Soil plasticity chart.

The *liquidity index* (LI) is a numerical expression of the water content (w) of cohesive soils *relative* to the limits of the plastic range of water contents for a disturbed clay soil and therefore an indicator of the relative consistency of the clay. It is defined as LI = (w-PL)/(LL-PL). Since the range of water content from the liquid limit (LL) to the plastic limit (PL) is the plasticity index (the range of plastic soil behavior for the specific clay soil), the existing water content may be related to the plasticity index (PI) as LI = (w-PL)/PI. A liquidity index of zero indicates that the remolded soil is at the plastic limit water content and is stiff, whereas at LI = 1.00 (or 100%) the soil is at the liquid limit water content and is extremely soft. A liquidity index of greater than 1.00 indicates a liquid-like soil, i.e., a soil slurry.

Skempton (1953) defined the *activity* of a clay as the ratio of the plasticity index to the percent -0.002 mm clay, a direct linear relationship. He identified a large group of marine and estuarine clays, with illite as the main clay mineral, having activities ranging from 0.75 to 1.25, i.e., A = PI / (% -0.002 mm) = 0.75 to 1.25. Sowers (1979) stated: "The activity expresses the plasticity of the . . . clay minerals. This . . . suggests whether the clay is a kaolinite (low activity, <1), a montmorillonite (high activity, >4), or illite (intermediate activity, 1-2)." The higher the liquid limit and plasticity index, and therefore the higher the clay content, the greater the cohesiveness, stickiness, and dry strength and the lesser the friability of the clay.

**Test method.** The Atterberg limits tests are expedient and inexpensive, making them a valuable tool in fine-grained soil identification. The laboratory tests are made in accordance with ASTM (1994) Method D 4318. The liquid limit test is based on finding the water content at which a pat of wet soil, placed in a cup as shown in Figure B-3, with a standard groove, will sustain a groove closing of 1.25 cm (½ inch) under 25 standard impacts of the cup. The plastic limit test is done manually, without a testing device.

## Reactivity (pH)

**Definition.** Soil reaction is a numerical expression of relative acidity or alkalinity. pH is the hydrogen ion concentration. A pH of 7 is neutral; pH < 7 is acid; pH > 7 is alkaline.

**Test method.** A soil-water slurry, usually an even mixture of soil and water, is tested in the laboratory with a pH meter. There are several field test methods available, including litmus paper, water soluble dye sensitive to pH, and portable pH meters.

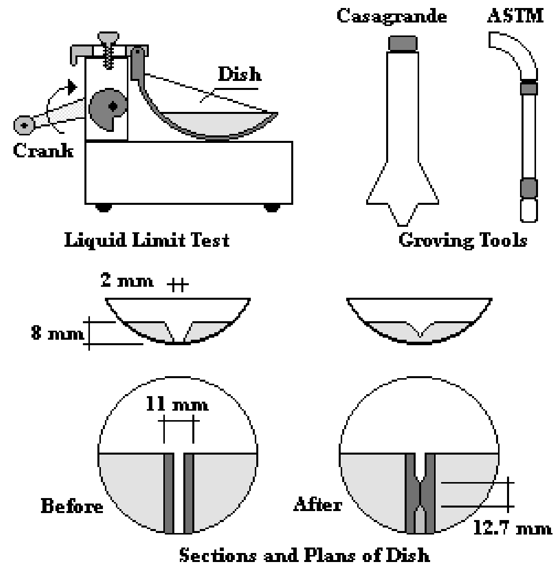


Figure B-3. Liquid limit test device and appearance

## Resistivity

**Definition.** Resistivity is the impedance of a saturated soil paste to alternating current as measured in a Bureau of Standards electrode cup. Resistivity is used to estimate the salt content of a soil.

**Test method.** The soil is made into a saturated paste by addition of deionized water. The paste is placed in a standard electrode cup. The soil-filled cup then becomes one leg of a Wheatstone Bridge circuit, in which the resistance of the soil is measured against a known, standard resistance.

## Sodium adsorption ratio

**Definition.** The sodium adsorption ratio (SAR) is a measure of the amount of sodium (Na) relative to calcium (Ca) and magnesium (Mg) in the water extracted from a saturated soil paste. It is used to indicate the potential for dispersion of organic matter and clay particles and is a measure of soil degradation (Soil Survey Staff 1993).

**Test method.** The sodium adsorption ratio is determined by standard chemical analysis. It is determined by method 5 of the Soil Survey Laboratory Methods Manual (Soil Survey Staff 1992).

## Specific gravity of grains (See particle density)

### Water content

**Definitions.** The water content is defined as the weight of water in the soil expressed as a percentage of either:

a. The dry weight of the solid matter present in the soil (used by civil-geotechnical engineers), or

b. The total mass, including soil and water (used by most scientists and some engineers).

**Test methods.** There are two basic methods for determining the water content, direct measurement and indirect measurement, using procedures given in the various test methods of ASTM (1994). In a marine environment, a correction for salinity of the pore water is generally made (Eckert and Callender 1987).

The *direct measurement* methods all rely on drying the test specimen, weighing the material before and after drying, and assuming the loss equals the weight of water. In the laboratory standard oven method, ASTM D 2216, the water content is based on the loss of water at the constant drying temperature of $105^{o}$ to $110^{o}$ C.

Another drying method uses a microwave oven, ASTM D 4643. In this method a conventional microwave oven is fitted with a piston extending through the bottom. The piston supports and weighs the soil sample being tested. The oven is activated and the weight loss is continuously monitored by a computer that calculates when the sample has reached constant weight. At that time the test is terminated. This is a rapid, accurate test method. However, it must be done in a laboratory or office environment that has electric power available.

The *indirect measurement* methods involve either chemical reaction or radioactive energy absorption. The calcium carbide device, ASTM D 4944, combines the free water in the soil with calcium carbide to form acetylene gas in a closed container. The resulting gas pressure is correlated with the water content. The nuclear moisture-density gage uses the thermalization (slowing down) of neutrons as a measure of the amount of hydrogen atoms present in the soil. This effect is calibrated against a standard whose hydrogen ion content is known.

## Properties of the Soil Mass

The soil mass properties are those relating to the arrangement of the material components. They include the relative positions of the soil grains, their structure, and mass density. The soil material and soil mass properties are independent of each other. The same soil material can exist in a number of different arrangement states, and different soils can have the same water content, density, and other soil mass characteristics. The mass properties of interest are:

*a.* Bulk density (mass density, unit weight)

*b.* Relative density of clean granular soils *c.* Structure (macro) of cohesive soils

## Bulk density (mass density, unit weight)

**Density definitions.** The mass density is the total weight per unit of volume. It is a dynamic soil property, because the volume of the soil varies with degree of saturation, particularly in cohesive soils. *Wet density* (wet unit weight) is defined as the total weight of gas, water, and soil solids per unit of volume of the soil. *Dry density* (dry unit weight) is the dry weight of solids per unit volume of the soil, with the voids completely occupied by air. *Saturated density* (saturated unit weight) is the total weight of water and soil solids per unit of soil volume when the void space contains only water (no gas).

As defined by the USDA (Soil Survey Staff 1993), the *moist bulk density* is the *dry density* of a soil mass whose original volume had a moisture content at or near field capacity (see available water capacity definition above). Density is sometimes referred to by scientists as the *specific gravity*, the ratio of the mass of a body to the mass of an equal volume of water. For clarity, engineers reserve the term "specific gravity" to mean the specific gravity of grains.

*Porosity* is calculated as the ratio of the volume of voids in a soil mass to the total volume of soil, which includes gas, water, and solids. *Void ratio* is calculated as the ratio of the volume of the void space, including water and gas, in a soil mass to the volume of the solid constituents. Void ratio is used in geotechnical engineering because of its benefit in further calculations involving weight-volume relations.

*Degree of saturation* is calculated as the volume of water as a percentage of the total volume of voids. Thus, at 100 % saturation, all of the void space is occupied by water and at 0 % saturation, all of the void space is occupied by gas (air or other gas).

**Laboratory test methods.** Two laboratory methods are in common use: (a) the core method, and (b) the clod method. Several designs of undisturbed core sampling devices are commercially available for surface or borehole sampling. ASTM Method D 2937 describes a drive cylinder. All of the cautions described above for undisturbed sampling apply to sampling for density measurements.

*a.* *Core method.* An undisturbed sample of the soil can be obtained in a thin wall tube sampler. The sample is carefully extruded from the tube and a suitable length cut with a knife or wire. The sample is weighed, the dimensions are measured and the volume calculated, and a moisture content sample is taken and tested. Sample tubes are described in Chapter 2-3.

*b. Clod method.* If a reasonably undisturbed clod of cohesive soil can be obtained by excavation, the weight and volume of the clod can be used to calculate density. Clod volume is usually measured by immersion and displacement of a liquid. The liquid may be mercury or heavy oil. If water is to be used, the clod must be covered with a coating of known weight and volume. Paraffin wax has been used, weighing the clod before and after application of the wax determines the weight of paraffin. By using the specific gravity of the wax, the volume can be calculated and used to correct the measured volume.

**Field test methods.** There are two basic procedures for determining the in situ unit weight of a soil mass: (a) direct measurement and (b) indirect measurement, described in the various test methods of ASTM (1994). Each of the field density methods must be done on the surface of the soil, whether at the ground surface or at the bottom of a pit.

The *direct field excavation* methods have been used by engineers for measuring the density of mechanically compacted soils. All are based on the procedure of digging a hole, measuring its volume, and weighing the excavated material.

The hole digging and volume measurement methods differ only in the manner of measuring the volume of the dug hole. There are ASTM standards for the most popular methods. The *sand cone method*, ASTM Method D 1556, uses calibrated sand, whose loose unit weight is known, and which is carefully poured into the hole. The unit weight of the sand used is converted to volume. The *water balloon method*, ASTM Method D 2167, uses a rubber balloon-type membrane to line the hole. The membrane is then filled with water, whose volume is measured. A *viscous oil*, whose volume can be directly measured in the container before and after use, may be used to fill the hole.

The *indirect measurement* methods involve energy absorption, either seismic refraction or radioactive energy transmission. Seismic refraction was discussed in Chapter 2-3 on geophysical survey methods. The determination of the average density of a soil deposit is inherent in that method.

The nuclear moisture-density gage uses the procedures given in ASTM Method D 2922 for shallow depths, Figure B-4, or Method D 5195 for below surface tests. In both cases, a radioactive source in close contact with the soil emits gamma rays. A nearby Geiger Counter measures the intensity of gamma rays transmitted through the soil. The intensity is inversely proportional to the bulk density. A calibration with materials of known density is used to calculate the density. Similarly, the thermalization (slowing down) of neutrons by impact with hydrogen atoms is used to measure the water content.

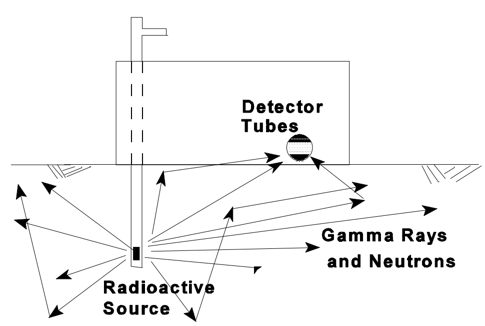



Figure B-4. Nuclear moisture-density gauge.

## Relative density

**Definitions.** The terms loose and dense are, implicitly, terms that define relative density. Relative density is the dry unit weight of a clean granular soil relative to its minimum and maximum densities:

$$D_r = \frac{\gamma_d - \gamma_{dmin}}{\gamma_{dmax} - \gamma_{dmin}} \; x \; \frac{\gamma_{dmax}}{\gamma_d} \; x \; 100 \qquad \text{(B-1)}$$

where: *$D_r$ = relative density, percent; $\gamma_d$ = in situ dry density; $\gamma_{dmax}$ = maximum dry density (densest state); and $\gamma_{dmin}$ = minimum dry density (loosest state).*

This terminology applies only to those soils that will densify, or loosen, readily as a result of vibration, i.e., gravels, sands, silty sands, and inorganic cohesionless silts. This implies a low fines content, with little or no plasticity (stickiness) in the fines. The percentage of fines that will allow a soil to be successfully densified by vibration is a function of the plasticity of the fines and the gradation of the granular component.

**Test methods.** The maximum and minimum densities of a soil sample are determined by laboratory tests using ASTM (1994) Methods D 4253 and D 4254, respectively. A relative density of 100 % means the soil is at its maximum achievable density and zero percent meaning it is at the minimum density state. It is possible to have in situ densities greater than the maximum or less than the minimum since these values are defined by standardized laboratory tests.

## Structure (macro) of cohesive soils

The visual-manual procedures of ASTM (1994) D 2488 include engineering definitions for various forms of macrostructure of cohesive soils. The descriptive terms are defined in Table B-5.

## Weight-volume relationships

The several soil mass properties defined above are interrelated. Calculations for weight-volume relationships are illustrated in Figure B-5.

Typical values for porosity, void ratio, saturated water content, and unit weight for natural soils in situ are given in Table B-6, using the engineering definition of water content. The tabulated values were taken from various published engineering sources and are shown here for illustration only; actual measured values may differ slightly from those shown.

**Table B-5**
**Criteria for Describing Structure of Cohesive Soils (ASTM D 2488, 1994)**

| Description | Criteria |
|---|---|
| Stratified | Alternating layers of varying material or color with layers greater than 6 mm (1/4 in.) thick; note thickness. |
| Laminated | Alternating layers of varying material or color with layers less than 6 mm (1/4 in.) thick; note thickness. |
| Fissured | Breaks along definite planes of fracture with little resistance to fracturing. |
| Slickensided | Fracture planes appear polished or glossy, sometimes striated. |
| Blocky | Cohesive soil that can be broken down into smaller angular lumps which resist further breakdown. |
| Lensed | Inclusion of small pockets of different soils, such as small lenses of sand scattered through a mass of clay. |
| Homogeneous | Same color and appearance throughout. |

## Physical Behavior Properties

The soil physical behavior (structural and hydraulic) properties of interest for plant growth in a wetland and during soil handling operations are:

*a.* Compressibility

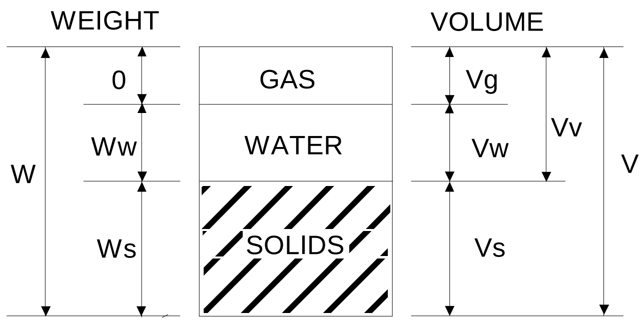
*b.* Erodability

*c.* Permeability

*d.* Shear strength

*e.* Suction potential (capillarity)

A specific soil's physical behavior properties are highly sensitive to minor changes in its mass properties. Therefore, tests of the soil's physical behavior properties must be made on *undisturbed* soil, either in situ or on relatively undisturbed samples, carefully taken and tested to preserve the important in situ structure. Summaries of test methods and estimation procedures are given below. These properties are subject to considerable professional interpretation. Details for tests for these properties are contained in the professional literature and in textbooks on the subjects.




WATER CONTENT
(Geotechnical definition)
$$w = \frac{Ww}{Ws}$$

SPECIFIC GRAVITY
$$Gs = \frac{Ws}{Vs\,\gamma w}$$

VOLUME OF SOLIDS
$$Vs = \frac{Ws}{Gs\,\gamma w}$$

VOLUME OF VOIDS
$$Vv = V - Vs$$

VOID RATIO
$$e = \frac{Vv}{Vs} = \frac{n}{1 - n}$$

POROSITY
$$n = \frac{Vv}{V} = \frac{e}{1 + e}$$

DEGREE OF SATURATION
$$S = \frac{Vw}{Vv} = \frac{w\,Gs}{e}$$

UNIT WEIGHT OF WATER
(Fresh water)
$$\gamma w = \frac{Ww}{Vw} = 62.4 \text{ PCF}$$

DRY UNIT WEIGHT
(Dry density)
$$\gamma d = \frac{Ws}{V} = \frac{\gamma m}{1 + w}$$

WET UNIT WEIGHT
(Wet density)
$$\gamma m = \frac{W}{V}$$

SUBMERGED UNIT WEIGHT
(Buoyant density)
$$\gamma ' = \gamma m - \gamma w$$

$$\gamma ' = \frac{Gs - 1}{1 + e}\,\gamma w$$

Figure B-5. Weight-volume relationships.

**Table B-6**
**Typical Weight-Volume Properties of Soils**

| Soil Description | State | n[1] % | e[1] | w[1] % | Unit Weight: Dry PCF | Unit Weight: Dry Kg/m³ | Unit Weight: Saturated PCF | Unit Weight: Saturated Kg/m³ | Reference[2] |
|---|---|---|---|---|---|---|---|---|---|
| Uniform spheres (theoretical) | Loose | 48 | 0.92 | | | | | | HOU |
| | Dense | 26 | 0.35 | | | | | | |
| Well graded silty, sandy gravel | Loose | 39 | 0.65 | 25 | 100 | 1600 | 125 | 2000 | SOW |
| | Dense | 20 | 0.25 | 10 | 132 | 2120 | 145 | 2320 | |
| Glacial till, mixed grained | Firm | 20 | 0.25 | 10 | 132 | 2120 | 145 | 2320 | PHT |
| Sand, mixed-grained | Loose | 40 | 0.67 | 25 | 99 | 1590 | 124 | 1990 | PHT |
| | Dense | 30 | 0.43 | 16 | 116 | 1860 | 135 | 2160 | |
| Well graded sand, sub-angular | Loose | 41 | 0.70 | 27 | 97 | 1560 | 123 | 1970 | SOW |
| | Dense | 30 | 0.35 | 14 | 122 | 1960 | 139 | 2230 | |
| Well graded sand, fine to coarse, clean | Loose | 49 | 0.95 | 35 | 85 | 1360 | 115 | 1840 | HOU |
| | Dense | 17 | 0.20 | 7 | 132 | 2210 | 148 | 2370 | |
| Uniform sand | Loose | 46 | 0.85 | 31 | 90 | 1440 | 118 | 1890 | PHT |
| | Dense | 34 | 0.51 | 19 | 109 | 1750 | 130 | 2080 | |
| Uniform sand, fine to medium, clean | Loose | 50 | 1.00 | 37 | 83 | 1330 | 114 | 1830 | HOU |
| | Dense | 29 | 0.40 | 15 | 118 | 1890 | 136 | 2180 | |
| Silty sand, well graded | Loose | 47 | 0.90 | 33 | 87 | 1390 | 116 | 1860 | HOU |
| | Dense | 23 | 0.30 | 12 | 127 | 2040 | 142 | 2280 | |
| Sand and silt, micaceous | Loose | 56 | 1.25 | 47 | 75 | 1200 | 110 | 1760 | SOW |
| | Dense | 44 | 0.80 | 30 | 94 | 1510 | 122 | 1960 | |
| Windblown silt (loess) | Firm | 50 | 0.99 | 36 | 85 | 1360 | 116 | 1860 | PHT |

**(Continued)**

[1] n = total porosity; e = void ratio; w = water content (percent of dry weight); PCF = pound per cu. ft.

[2] HOU = Hough (1957); PHT = Peck, Hanson, and Thornburn (1974); SOW = Sowers (1979)

**Table B-6 (Concluded)**

| Soil Description | State | n[1] % | e[1] | w[1] % | Unit Weight Dry PCF | Unit Weight Dry Kg/m$^3$ | Unit Weight Saturated PCF | Unit Weight Saturated Kg/m$^3$ | Reference[2] |
|---|---|---|---|---|---|---|---|---|---|
| Uniform inorganic silt | Loose | 52 | 1.10 | 41 | 80 | 1286 | 113 | 1810 | HOU |
| | Dense | 29 | 0.40 | 15 | 118 | 1890 | 136 | 2180 | |
| Organic silt | Loose | 75 | 3.00 | 118 | 40 | 640 | 87 | 1390 | HOU |
| | Dense | 35 | 0.55 | 19 | 110 | 1760 | 131 | 2100 | |
| Sandy or silty clay | Soft | 64 | 1.80 | 67 | 60 | 960 | 100 | 1600 | HOU |
| | Stiff | 20 | 0.25 | 9 | 130 | 2160 | 147 | 2360 | |
| Glacial clay | Soft | 55 | 1.20 | 45 | 76 | 1220 | 110 | 1760 | PHT |
| | Stiff | 37 | 0.60 | 22 | 106 | 1700 | 129 | 2070 | |
| Clay (30 - 50 % clay sizes) | Soft | 71 | 2.40 | 88 | 50 | 800 | 90 | 1510 | HOU |
| | Stiff | 33 | 0.50 | 19 | 112 | 1800 | 133 | 2130 | |
| Slightly organic clay | Soft | 66 | 1.90 | 69 | 58 | 930 | 98 | 1570 | PHT |
| Very organic clay | Soft | 75 | 3.00 | 107 | 43 | 690 | 89 | 1430 | PHT |
| Organic clay (30 - 50 % clay sizes) | Soft | 81 | 4.40 | 170 | 30 | 480 | 81 | 1300 | HOU |
| | Stiff | 41 | 0.70 | 25 | 100 | 1600 | 125 | 2000 | |
| Montmorillonitic (high P.I.) clay | Soft | 84 | 5.20 | 196 | 27 | 430 | 80 | 1280 | PHT |

[1] n = total porosity; e = void ratio; w = water content (percent of dry weight); PCF = pounds per cu. ft.
[2] HOU = Hough (1957); PHT = Peck, Hanson, and Thornburn (1974); SOW = Sowers (1979)

## Compressibility

Compressibility is the property that permits a soil to remain compressed after the application and removal of a load, i.e., the soil acts in a manner similar to a lead sponge. Following the application of a load to a confined soil mass, the excess pressure in the pore fluid (water and air) tends to cause an expulsion of the pore fluid, leading to a permanent volume change, or consolidation, of the soil mass. The rate at which the pore fluid is expelled and consolidation occurs is a function of the magnitude of the load, compared to the maximum previously applied load, and the permeability, or hydraulic conductivity.

Loads smaller than the pre-consolidation load (maximum previously applied load) tend to cause only minor volume changes, whereas larger loads cause significantly larger volume changes. Open, porous soils such as clean sand will consolidate very quickly because of their high permeability. Clays, on the other hand, having a low permeability, will take extended periods of time to reach full consolidation in equilibrium with the applied load.

## Erodibility

**Definition.** Erodibility is defined as the ease with which particles, or aggregations of particles, can be excavated, or removed, from their in situ position and condition with a fluid such as water, flowing across the surface as sheets or rills, or air blowing across the surface. The physical forces causing movement of the soil particles consist of a combination of *cavitation* (traction) and *impingement.*

The minimum water or air velocity for erosion occurs in fine sand and silt sizes, about 0.2 to 0.4 mm. If the grains are coarser, the energy needed to erode the soil and suspend the grains increases because of the body weight of the particles. In finer soils, the required shear force (erosion energy) is higher because of the cohesive forces between the clay particles. Shells, because of their flat shape, require a much higher tractive force than spherical grains.

**Test method.** The surface erosion of a soil deposit depends on a number of interrelated factors whose properties are used in empirical methods for estimating the potential for water or wind erosion. These factors include: texture, clay content (indicated by the Atterberg limits), organic matter content, stability and strength of the soil aggregate, calcium carbonate reaction, rock fragments content, subsoil permeability, and depth to a pan.

Direct measurement of water or wind erodibility would require full-scale field tests in which all of the contributory factors are present. This would, in most wetland investigations, be prohibitively expensive. There are several methods for using the index properties to estimate erodibility. For example, a nomograph for estimating soil erodibility is contained in the *National Soil Survey Handbook* (Soil Survey Staff 1993).

## Permeability (hydraulic conductivity)

**Definition.** Permeability is that property of a soil that allows it to transmit water or other fluids. The in situ permeability of a soil affects its shear strength and rate of volume change under a consolidating pressure. The permeability depends on the size and number of continuous soil pores. It varies with such factors as void ratio, grain size distribution, structure, degree of saturation, and degree of cementation.

Permeability is usually expressed in terms of the *coefficient of permeability*, which is defined as the apparent velocity of fluid (water) flow through a *saturated* soil under a unit hydraulic gradient. The hydraulic gradient is the pressure head, or height of water, divided by the distance through which the fluid flows. Therefore, the quantity of water that will flow through a given cross section of soil in a given time and distance under a known head of water is:

$$Q = k \left(\frac{H}{L}\right) A \ t \qquad \text{(B-2)}$$

where (in metric units): *Q = quantity of water, cubic centimeters; k = coefficient of permeability, centimeters per second; H = hydrostatic head (pressure head), centimeters; L = thickness of soil, centimeters, through which the water flow is determined under hydrostatic head, H; A= cross-sectional area of soil, in square centimeters; and t = time, seconds*

**Test methods.** The permeability of a soil is greatly affected by minor changes in its mass properties, i.e., the density and structure of its component particles and its water content. Therefore, it is imperative that measurement of the coefficient of permeability is done (a) in the laboratory on undisturbed samples, having as close to the in situ density and structure as possible, or (b) directly on the soil in the field. Because direct measurement of permeability is difficult and time-consuming, it is often useful and satisfactory to use correlations with index properties tests as an estimate.

Undisturbed samples may be used in the laboratory to determine the permeability coefficient using carefully controlled tests. These include the falling head test used for cohesive soils, ASTM Method D 5084, and the constant head test for granular soils, ASTM Method D 2434. The previously made admonitions about undisturbed sampling apply to permeability samples as well.

The field measurement of permeability is difficult and time-consuming, although this is usually preferable to the use of laboratory samples of dubious quality. Several accounts have been published of field inflow and outflow test methods for measuring the permeability of a soil below the water table. Among the many geotechnical engineering, hydro-geological, and soil-science sources are (a) ASTM Methods D 3385 and D 5093 using double-ring infiltrometers for permeability tests at the ground surface, and (b) bore hole test methods described in the Water and Power Resources Service (formerly the U.S. Bureau of Reclamation) Earth Manual and by M. J. Hvorslev, USAE Waterways Experiment Station, Bulletin No. 36 (Hvorslev 1951). The rate of flow into partially saturated soils can be estimated by methods described by C. H. Zangar, U.S. Bureau of Reclamation, Engineering Monograph No. 8 (Zangar 1953). Field tests of saturated and unsaturated soils are also described in *Soil Sampling and Methods of Analysis* (Canadian Society of Soil Science 1993). These publications should be referred to for specifics of the test procedures and methods of analysis.

## Shear strength

**Definition.** Methods for determining the strength, or load-supporting capacity, of a soil for a given loading involve the use of complex formulas that contain its shear strength developed under the applied force system. The shear strength of a soil mass is an engineering behavior property that is characterized by its cohesion and coefficient of internal friction. In the generally used model, the maximum shear stress is related to the normal stress on the shear surface as:

$$s = c + (\sigma - u) \tan \phi \qquad \text{(B-3)}$$

where *$s$ = shear stress parallel to the shear plane; $c$ = cohesion intercept; $\sigma$ = normal stress on shear plane; $u$ = pore water pressure; and $\phi$ = soil angle of internal friction.*

**Test methods.** Estimates of in situ shear strength are based on (a) laboratory shear strength tests made on undisturbed samples of the soil, (b) direct or indirect measurements from field tests of the in situ soil, or (c) correlations with the index properties tests, i.e., soil material and mass properties tests such as grain-size distribution, plasticity, density, and water content. The *unconfined compression* test is a special case of the triaxial Q-test in which the confining pressure is zero (ambient). This test is applicable only to *saturated cohesive soils* in which it is assumed that $\phi = 0^{o}$ and all strength derives from the cohesion component. (See Appendix C)

### Soil suction (capillarity)

**Definition.** Plants rooted in the soil profile's solum will suction water from the surrounding soil, if possible, by capillarity. This can only occur if the capillary potential of the plant roots is greater than the capillary potential (also called matric potential or soil suction) of the soil. The number and size of continuous channels in a soil determine its capillarity. The matric potential or *soil suction* is defined as the work required to pull a unit mass of water away from a unit mass of soil, exclusive of osmotic and other influences.

The phenomenon of soil suction exists only in partially saturated soils, above the water table. In a partially saturated soil, the water coexists in the void spaces with air, with the water forming a meniscus attached to the soil particles. This creates a surface tension, or negative pore water pressure, which then increases the apparent normal force on a shear plane, increasing the soil's strength. If the negative pressure, or negative head, is expressed in terms of the unit weight of water times negative height (above the free water surface), then the height is the height of capillary rise in a moist soil. The height of capillary rise can be a few centimeters (few inches) in sand to almost 9 meters (30 ft) in clays.

**Test methods.** The soil suction, or matric potential, of a soil can be measured either in the laboratory, on an undisturbed sample of the soil, or in the field using some form of an equilibrium or a no-flow device. This is the equivalent of measuring the negative pore water pressure in the soil. Soil suction, or negative pore water pressure, results from the very small radius menisci formed in the soil pores as a result of partial saturation.

Various tensiometer designs are used to measure the direct suction force of a soil in the field either using a vacuum or using mercury in a U-tube as the resisting force. Similar principles are used in laboratory test devices. In no-flow devices, the soil is placed in contact with a porous plate or membrane with pores finer than those of the soil. Air pressure is applied to both sides of the plate or membrane to balance the capillary forces in the soil.

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# Appendix C
# Strength Tests of Soil[1]

Estimates of in situ shear strength of a soil are based on either (a) laboratory shear strength tests made on undisturbed samples of the soil, (b) direct or indirect measurements from field tests of the in situ soil, or (c) correlations with the index properties tests, i.e., soil material and mass properties tests such as grain-size distribution, plasticity, density, and water content.

## Laboratory Strength Tests

Laboratory tests for measuring the in situ shear strength use some form of compression or shear testing on a sample of the soil. They include (a) the unconfined compression test of an undisturbed cohesive tube sample, (b) the hand-operated shear test of a cohesive sample, and (c) the shear tests of a re-densified sand sample.

### Unconfined compression test of clay

The simplest undrained shear strength test of cohesive soils is the unconfined compressive strength test. This is a special case of the triaxial Q-test in which the confining pressure is zero (ambient). This test is applicable only to *saturated cohesive soils* in which it is assumed that $\phi = 0^o$ and all strength derives from the cohesion component. Because of test geometry, the unconfined compressive strength is twice the cohesion.

The unconfined compression test is applicable only to saturated cohesive soils which will stand unsupported and have a low permeability so that undrained conditions exist during the test. This applies only to very soft to hard clays. The unconfined compression test is not suitable for characterizing (a) the extremely soft slurries (often referred to as fluid mud) encountered at lake or river bottoms, (b) partially saturated soils, or (c) soils with a very low clay content.

The relative consistency of a cohesive soil is defined in terms of the unconfined compressive strength as shown in Table C-1. Any test method, field or laboratory, that will indicate, or correlate well with, the unconfined compressive strength may be used as an estimator of consistency.

[1] By S. Joseph Spigolon

**Table C-1**
**Descriptors for Relative Consistency of Cohesive Soils**

| Consistency Term | Unconfined Compressive Strength | |
|---|---|---|
| | kPa | Tons/sq. ft. |
| Very Soft | 0 - 25 | 0 - 0.25 |
| Soft | 25 - 50 | 0.25 - 0.50 |
| Medium (Firm) | 50 - 100 | 0.50 - 1.00 |
| Stiff | 100 - 200 | 1.00 - 2.00 |
| Very Stiff | 200 - 400 | 2.00 - 4.00 |
| Hard | > 400 | > 4.00 |

## Hand-held shear test devices for cohesive samples

Hand-held mechanical shear testing devices are used to provide a rapid, but rough estimate of the unconfined compressive strength of clays. These include the hand, or pocket, penetrometer and the hand vane device. The hand penetrometer, Figure C-1, operates as a hand-held footing test of cohesive soil. The spring-actuated load indicator is calibrated to correspond to the shear strength of a cohesive soil based on the relationship between the strength and maximum load a shallow footing can sustain. The Torvane device, Figure C-1, is a hand-held miniature vane shear tester that makes a test on the exposed surface of an intact sample.

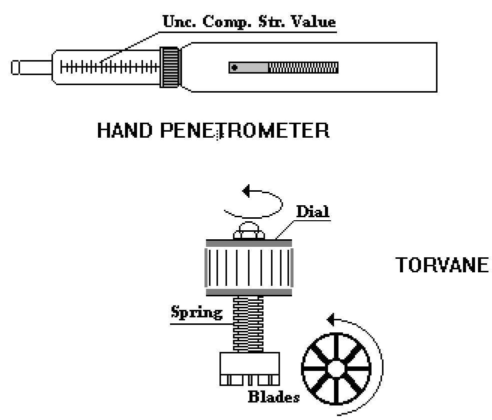


Figure C-1. Hand-held shear testing devices.

It should be recognized that these methods provide only a rough estimate of consistency. However, this may be sufficient for the purpose of checking the validity of the primary test or as an aid in interpreting that test. For example, the hand penetrometer or the hand vane may be used on an intact, clayey SPT sample as a rough check on the visual field identification of soil type. For a given SPT N-value (blow count), a low plasticity, silty soil will give a lower hand penetrometer reading than expected from the usual correlation of N-value and compressive strength. For the same blow count, a medium to high plasticity clay will give a reading more nearly consistent with the correlation. Also, the agreement between hand penetrometer and hand vane readings is affected by the clay content of the soil. The less the agreement, the less the cohesiveness of the soil. Therefore, it may be concluded that the validity of a hand penetrometer value varies directly with the clay content, or plasticity, in the same manner that the unconfined compression test does.

### Shear test of sand sample

The shear strength of a clean granular soil is rarely of concern in a wetland except where earthquake-induced liquefaction is possible. Laboratory shear tests, made at several different void ratios, can establish the critical void ratio, i.e., the limiting void ratio above which the soil will attempt to contract during shear, or the corresponding bulk density below which the soil will contract rather than dilate. This value is then compared to the in situ density to determine the liquefaction potential. The laboratory shear tests normally used are the drained direct shear test or the triaxial compression test.

## Field Tests for Shear Strength

Field tests for shear strength are either direct or indirect. The Field Vane Shear Test (VST) of a cohesive soil measures shear strength *directly*, by making the equivalent of a field direct shear test. *Indirect estimates* of in situ shear strength of soil generally involve measuring the soil's resistance to penetration by a static or dynamic device. Then, a correlation between the penetration resistance and the shear strength is used. These devices include (a) the Standard Penetration Test, (b) the Static Cone Penetration Test, and (c) various forms of the hand-held sounding rod test.

### Field vane shear test (VST)

The Field Vane Shear Test conditions are equivalent to an unconsolidated undrained (Quick) direct shear test, made on undisturbed soil in the vertical plane, with the normal force provided by the lateral pressure of the soil. Therefore, the undrained cohesion of a clay stratum can be measured. *The test is applicable only to clays.*

All of the requirements for a valid undrained test must be met, i.e., the soil must be a saturated cohesive soil with very low permeability (a clay) and the soil must be homogeneous and not stratified in the test zone. Furthermore, the soil must be soft enough that the thin blades will not deform during the test. The upper limit of shear strength for the VST is on the order of 200 kPa (2 tsf), i.e., a stiff clay.

**Equipment.** The design of a multi-blade shear vane and the method of field test are given in ASTM (1994) D 2573. A typical hand-operated VST setup is shown in Figure C-2. This system uses a torque wrench to apply and to indicate rotational resistance. The equipment for shallow testing (less than 3 meters, 10 feet) is lightweight and highly portable. The Field Vane Shear Test requires a stable platform for the operator, but does not require a heavy reaction weight.

**Analysis of data.** Interpretation of VST data is simple and straightforward: a direct shear test has been made in situ and the measured shear strength is the undisturbed in situ strength. The Bjerrum correction factor to account for soil plasticity is applied to the indicated shear strength:

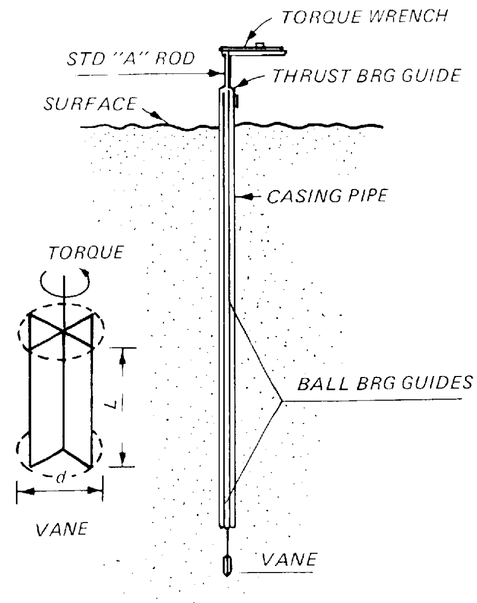


Figure C-2. Hand operated Field Vane Shear Test device.

$$C = 1.7 - 0.54\ (P.I.) \qquad \text{(C-1)}$$

where: *C = correction factor ; and P.I. = plasticity index of the soil*

## Standard penetration test (SPT)

The recognized standard for estimating compactness or consistency is the Standard Penetration Test (SPT) as defined in ASTM (1994) Method D 1586. A thick-walled, split barrel sampler, 5.1 cm OD x 3.8 cm ID (2.0 in. OD x 1.5 in. ID) is attached to the end of a drill rod string and placed at the cleaned out bottom of a drill hole. A 63.5 kg (140 lb) drop hammer is allowed to drop freely a distance of 76 cm (30 in.) onto the top of the drill rod, forcing the sampler into the soil. The sampler is first driven 15 cm (6 in.) and the number of blows to drive the sampler another 30 cm (12 in.) is recorded as the SPT N-value or blow-count.

**Equipment.** The test can be performed in most soil types with the aid of a common, relatively lightweight truck- or skid-mounted soil exploration drill rig. The test can also be made using a portable tripod and either a small engine or hand-pulling to lift the 63.5 kg (140 lb) drop weight. The equipment required to perform the SPT is simple and durable. The Standard Penetration Test procedures are relatively easy to follow, thus permitting rapid training of personnel and frequent, inexpensive testing. A representative but remolded sample of soil is obtained simultaneously with performance of the test. The SPT can be performed during adverse weather conditions without significant effect on the test results.

**Relative compactness of cohesionless soils.** The Standard Penetration Test (SPT) has been empirically correlated with the relative density of sands. The results of recent investigations (Skempton 1986) have shown that the factors that affect the SPT are (a) energy of the hammer and hammer release system, (b) rod length, (c) presence of liner in the sampler, (d) bore hole diameter, (e) effective overburden pressure, (f) overconsolidation, and (g) aging of the deposit. Based on consideration of all of these factors, the current recommendations for the compactness of sands using relative density in terms of the SPT, including the effects of aging of the sand deposit, are shown in Table C-2. Given the relative density of the granular soil, the shear strength (angle of internal friction), may then be estimated.

**Relative consistency of cohesive soils.** An empirical relationship exists between the SPT N-value and unconfined compressive strength of cohesive soils. The relationship has been modified to correct for plasticity of the cohesive soil, based on extensive field and laboratory correlations. The relationships for fine-grained soils contain a considerable amount of test scatter and are, therefore, only marginally precise. Table C-3 may be used to estimate the unconfined compressive strength and the relative consistency of clayey soils from the SPT.

## Static cone penetration test (CPT)

The slow penetration of a soil by a sounding rod with an enlarged cone-shaped tip has been standardized as the Static Cone Penetration Test (CPT) in ASTM (1994) Method D 3441. The tip resistance has been related to the angle of internal friction and the relative density of granular soils and to the compressive strength of cohesive soils.

**Equipment.** The CPT is made by slowly pushing a rod with an enlarged cone tip, as shown in Figure C-3, into the soil and measuring the force required for penetration. The cone tip is 36 mm (1.4 in.) in diameter with a 60 degree point, giving an end area of 10 sq cm (1.54 sq. in.). To reduce friction between the push rod and the surrounding soil, the solid rod is encased in a

**Table C-2**
**Relative Compactness of Sands Based on SPT (Skempton 1986)**

| Relative Compactness | Relative Density, percent | Normalized* SPT N-values | | |
|---|---|---|---|---|
| | | Natural Deposits** | Recent Fills** | Laboratory Test Fills** |
| Very Loose | 0 - 15 | 0 - 3 | 0 - 2 | 0 - 2 |
| Loose | 15 - 35 | 3 - 8 | 2 - 6 | 2 - 5 |
| Medium (firm) | 35 - 65 | 8 - 25 | 6 - 18 | 5 - 16 |
| Dense | 65 - 85 | 25 - 42 | 18 - 31 | 16 - 27 |
| Very Dense | 85 - 100 | 42 - 58 | 31 - 42 | 27 - 37 |

* Corrected to 60% of free-fall energy of standard hammer weight and drop and normalized to unit effective overburden pressure of 100 kPa (1 Tsf).

** Natural deposits have been in place (undisturbed) for over 100 years. Recent fills have been in place for about 10 years. Laboratory test fills have been in place for less than one month.

**Table C-3**
**Relative Consistency of Cohesive Soils Based on SPT**

| Relative Consistency | Unconfined Compressive Strength, kPa | SPT (blows/30 cm; blows/ft) | | |
|---|---|---|---|---|
| | | High Plasticity * | Medium Plasticity * | Low Plasticity * |
| Very Soft | < 25 | < 1 | < 2 | < 3 |
| Soft | 25 - 50 | 1 - 2 | 2 - 3 | 3 - 7 |
| Medium | 50 - 100 | 2 - 4 | 3 - 7 | 7 -13 |
| Stiff | 100 - 200 | 4 - 8 | 7 - 16 | 13 - 27 |
| Very Stiff | 200 - 400 | 8 - 16 | 16 - 27 | 27 - 53 |
| Hard | > 400 | > 16 | > 27 | > 53 |

* Low Plasticity -- liquid limit is less than 30;
Medium Plasticity -- liquid limit is between 30 and 50;
High Plasticity -- liquid limit is greater than 50.

hollow rod. The hollow rod terminates in an enlarged sleeve just above the cone point. The sleeve is 13.26 cm (5.22 in.) long by 3.57 cm (1.4 in.) in diameter, with a surface area of 150 sq cm (23.25 sq. in.), although sleeves with 200 sq cm area have been used. The sleeve rod, in turn, is encased in a hollow shaft of 36 mm (1.4 in.) diameter.

The three rods are pushed simultaneously at the rate of 2 cm. per min. (0.8 in. per min) and the forces to push the cone and sleeve rods are separately measured. A typical force reaction is a 20-ton weight (truck or other) and force measurement may be mechanical, hydraulic, or by use of electric strain gages. The soundings and recordings for push forces are continuous.

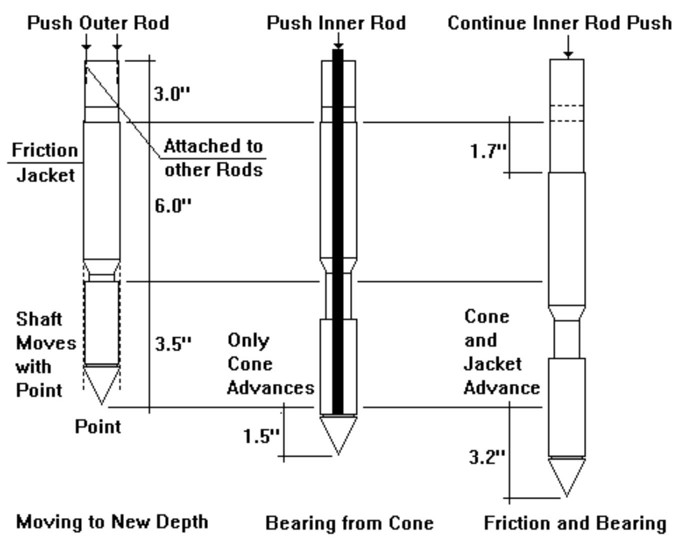


Figure C-3. Static Cone Penetration Test sequence.

**Analysis of data.** The interpretation of the tip resistance data requires knowledge of the soil type. By also measuring the sleeve frictional resistance, a ratio of the sleeve friction to the cone bearing, called the *friction ratio*, is calculated and used in estimating soil type. The relationship of cone bearing capacity to sleeve friction ratio, corrected for effective overburden pressure, has been empirically related to soil type.

*Granular soils.* The CPT friction ratio, corrected for effective overburden pressure, has been empirically related to Standard Penetration Test (SPT) N-values, which have also been corrected for the effect of overburden pressure. One correlation is shown in Figure C-4. There are also a number of correlations in the geotechnical engineering literature of cone resistance and angle of internal friction for sands.

*Cohesive soils.* The unconsolidated, undrained shear strength, which is one-half of the unconfined compressive strength, is determined from:

$$S_u = \frac{q_c - \overline{\sigma_v}}{N_c} \qquad \text{(C-2)}$$

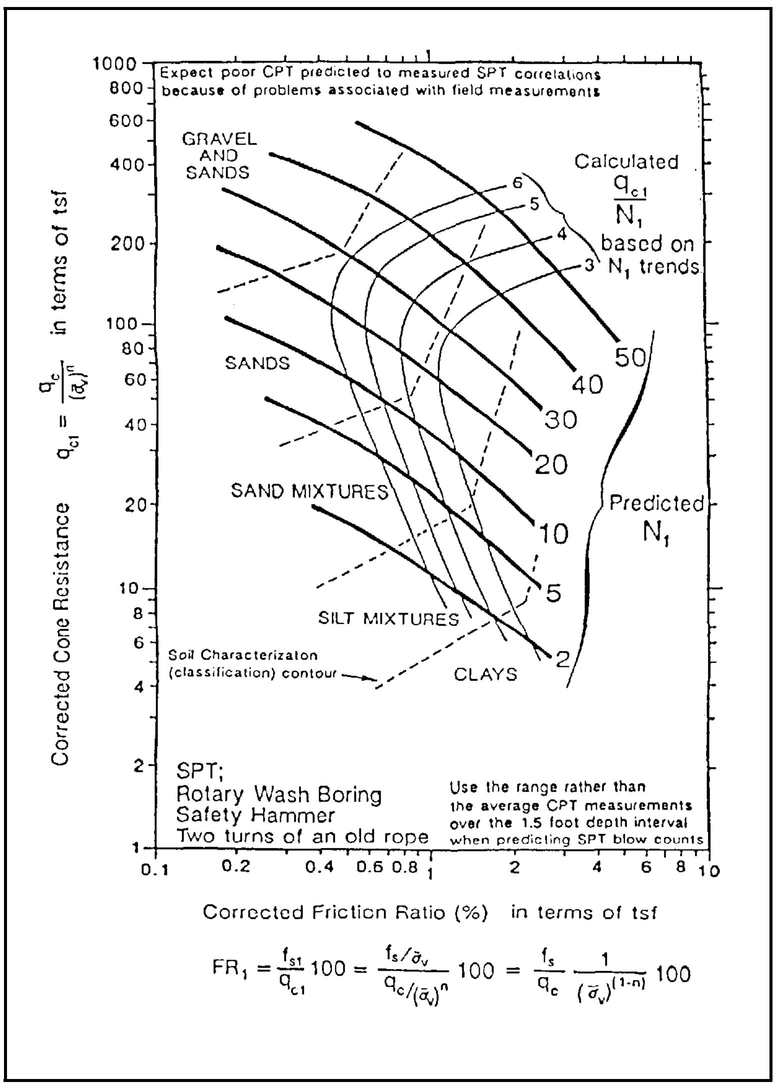


Figure C-4. Correlation chart of CPT with SPT (Olsen and Malone 1988).

where $S_u$ = *undrained shear strength (½ of unconfined compressive strength);* $q_c$ = *cone penetration resistance;* $\bar{\sigma}_v$ = *effective overburden pressure; and* $N_c$ = *bearing capacity factor.*

The value of bearing capacity factor, $N_c$ , usually ranges from 12 to 20, with a typical value of $N_c = 16$ recommended for general use with the admonition that, where possible, an empirical correlation should be developed for local clays and CPT designs.

The CPT requires a heavy reaction frame and is, therefore, usually truck mounted and the force is derived from the engine. However, for shallow bucket auger borings, where the soil type is known from the cuttings, only the center rod is needed. The equipment for this arrangement can be very lightweight and portable, consisting only of the cone point, sufficient rod to reach to the bottom of the hole, and a force indicator, either a Bourdon tube gauge or a proving ring. Because the cone is only inserted a few centimeters (few inches) at a time, the force is not great and can be applied by a single person. Hand-held static cone penetrometers have been extensively used in roadway trafficability studies.

The CPT tests are less expensive to make than SPT tests. About three times the test boring footage can be obtained with CPT than with SPT in the same time. However, when only a shallow depth is involved, the actual testing time is a very small part of the total time at a site and in moving from site to site. Total on-hole time is more of a concern than the time to make the boring and tests.

In spite of claims to the contrary, it is still necessary to obtain representative samples of the soils to validate the CPT data and to determine the other laboratory tests such as organic content, specific gravity, and grain shape and hardness. This means that another device must be used to obtain representative samples of the soils tested by the CPT. The samplers that could be used to obtain a full profile companion sample to the CPT include the vibrating tube sampler or a bucket auger (machine or hand operated).

## Sounding rod test

Virtually all soil probing is done to evaluate or estimate the relative in situ strength of a soil. Where successive layers vary widely in strength or hardness, the pushing, driving, or jetting of a simple probing device, such as a metal rod or steel reinforcing bar, can be used to define the stratum changes with relatively good accuracy. This test method is particularly effective for low-cost, rapid investigation of the depth to the surface of a hard layer or rock. No sample is obtained.

Hand-held probing, or sounding, devices fall into several categories, including (a) hand-pushed rods, (b) rods driven by a hand-operated drop weight, and (c) water- jetted rods.

**Hand-pushed sounding rods**. Steel rods, reinforcing bars, or similar devices, can be continuously pushed by hand into a soft or loose sediment. There is no need for a heavy reaction weight or the need to withdraw the rods after each test. In most circumstances, the operator can feel a sufficient change in pushing resistance to register a change in stratum hardness or type.

If the sounding rod has an enlarged tip, is cased to reduce or eliminate sidewall friction on the rod, and the casing is pushed or driven concurrently with the rod so that very little of the rod extends beyond it, then the penetration resistance can be used to estimate the compactness or consistency of a sediment.

Resistance to penetration can be measured by a force indicating device such as a proving ring, a calibrated spring, a Bourdon gage, or other suitable device. Accurate measurement of in situ strength will require (a) a consistent testing procedure and consistent equipment, and (b) correlation of sounding rod penetration resistance with a standard, recognized test method.

**Weight-driven sounding rods**. Cone-tipped rods (penetrometers), or similar devices, can be continuously impact driven using a hand-operated drop weight rather than pushed, as shown in Figure C-5. This eliminates the need for a heavy reaction weight and the need to withdraw the rods after each increment of test.

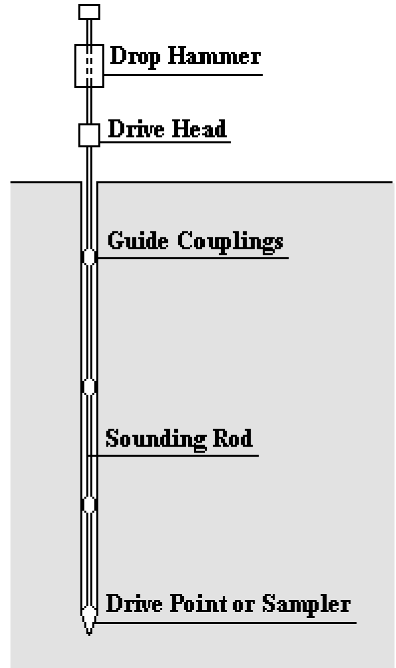


Figure C-5. Weight-driven sounding rod.

If the sounding rod is cased to reduce or eliminate sidewall friction on the rod, and the casing is driven concurrently with the rod so that very little of the rod extends beyond it, then the penetration resistance can be used to estimate the compactness or consistency of a sediment.

Resistance to penetration can be measured by (a) the number of drops of the drive weight required to drive the rod a given distance, or (b) the distance the rod is driven for a specified number of drops of the drive weight. Accurate measurement of in situ strength will require (a) a consistent testing procedure and consistent equipment, and (b) correlation of sounding rod penetration resistance with a recognized standard method.

**Water jetted sounding rods.** A hollow metal rod, such as a pipe or drill rod, can be used to penetrate an easily eroded soil using a high pressure water stream. The jetting action will scour the soil, returning soil particles to the surface as in wash boring, permitting the probe-rod to easily be pushed into the soil until a hard layer or rock is reached. Penetration resistance is difficult if not impossible to measure; therefore, this method is not used to indicate strength except in terms of gross change in strength--such as going from loose sand to rock.

This test method is particularly useful in locating the surface of a hard layer or rock in a fairly shallow waterway. Either fresh or seawater may be used in the pump. The pump size can be fairly small, permitting it to be operated from a small boat or other platform.

## Correlations With Index Properties Tests

The formal shear strength tests, both laboratory and field, tend to be expensive in time and cost and are, therefore, often augmented by estimates using correlations with the much less expensive index properties tests. For that reason, simple indicator, or index properties, tests of soils have been used extensively to indicate the results of the more costly, time consuming, and complex tests. Many of the standard textbooks of geotechnical engineering contain some correlation test relationships. The reader is referred to the textbooks and other pertinent publications for specifics of the correlations. Two excellent engineering reference sources are (a) U. S. Army Technical Manual TM 5-818-1, *Soils and Geology*, (USACE 1983), and (b) *Design Manual DM 7.1* (Department of the Navy 1982).

Correlations for granular soil physical behavior properties have been published between (a) angle of shearing resistance and SPT blow count, (b) angle of shearing resistance and relative density, and (c) coefficient of earth pressure and angle of shearing resistance. Other useful correlations have been established for local soils that may exist only in local files.

Correlations for cohesive soil physical behavior properties have also been published in textbooks and other literature. These include correlations between (a) sensitivity and liquidity index, (b) shear strength of remolded clays and liquidity index, (c) the ratio of undrained shear strength to effective overburden pressure as a function of plasticity index or of liquidity index, and (d) angle of shearing resistance with plasticity index.

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# Appendix D
# Case Studies[1]

## Bodkin Island, Chesapeake Bay, Maryland

The Chester River flows through the central part of Maryland's Eastern Shore, between Kent and Queen Annes counties and is about 50 miles Southeast of Baltimore, MD. The Federal navigation channel at Chester River is maintained by the US Army Engineer District, Baltimore, approximately every three to five years. Bodkin Island is located in Eastern Bay, about 6.8 miles south of the navigation channel at Chester River. Bodkin Island is a small privately owned island, just under one acre in size, and provides refuge for various species of migratory birds, including the native black duck.

The black duck population has declined throughout its range since the 1950s despite the implementation of strict harvest regulations. In the Eastern Bay area, most black ducks nest on uninhabited islands, presumably because of the species' aversion to human disturbance. Throughout the primary zone of nesting in Chesapeake Bay, islands and remote marshlands are preferred nesting areas. For Eastern Bay, a major deficiency in production capability is a lack of suitable brood areas (intertidal wetlands) close to premium island nesting areas. The majority of historic brood habitats are now rimmed with residential development, minimizing or eliminating black duck use. Females have been forced to move their broods immediately after hatching over much longer distances to reach suitable brood habitat, exposing ducklings to higher mortality rates. Additionally, the Eastern Bay region has lost 7 of 19 islands to erosion in the last 20 years. The remaining islands are much reduced in size and continue to erode.

The purpose of the project is to expand the existing island and create additional nesting and brood habitat for the black duck. The expansion will be accomplished by placing dredged material from the Chester River adjacent to the existing island. Another objective was to stabilize the island using shoreline armor and use innovative habitat design to appropriately shape and vegetate the island to be a combination of upland nesting, intertidal marsh, and shallow tidal pond habitat.

The initial thought was to place the dredged material adjacent to the existing island to an effective height of 6 to 7 feet above mean high water (MHW) and stabilize by using riprap or some equivalent. Geotechnical concerns that the dredged material would not mound to the required bank slope for the armor stone nor support the weight of the armor stone called for a stone dike containment structure to be created and dredged material placed inside the dike. After

[1] By Jack E. Davis, Steven T. Maynord, and John McCormick

placement, the island could be formed to meet all habitat requirements of upland, wetland, and intertidal areas. Storm surge and wave analysis were conducted to determine the required size and elevation of armor stone to prevent scour and undercutting of the restored island. Tidal fluctuation was determined to conduct topographic design of the intertidal areas.

The enlarged island was designed in the shape of a horseshoe with the existing one-acre island at the base of the horseshoe. The open part of the horseshoe provided an opening for tidal flushing of the island's interior. The armor size surrounding the island was designed to remain stable for wave heights corresponding to a 73-year return period. Water levels associated with a 5-year return period were selected for determining the top elevation of the armor stone. This resulted in a top of revetment of 5.5 to 6.5 ft above mean low water (MLW). Across the opening of the horseshoe, a low sill of armor rock was placed to dissipate wave energy while allowing tidal flushing of the island's interior. The enlarged island provided about 5 acres of additional habitat. Appropriate species of vegetation were proposed for planting in the upland, high marsh, low marsh, and tidal pool areas.

The $2.8 million price of the original design was too costly and a different design was needed. A major portion of the total cost was in the stone containment dike and the armor stone. The rock design was replaced with a timber bulkhead having the same height and length. Vegetation and habitat shaping was kept the same as the original design. However the $1.8 million cost of the timber bulkhead design was also prohibitive.

The Bodkin Island project was delayed and the Chester River dredged material was used at the Eastern Neck Wildlife Refuge in a wetland creation project. Geotextile tubes were used at Eastern Neck to serve as a protective barrier. These large diameter geotextile tubes are proposed for protection at Bodkin Island in lieu of the armor stone or timber bulkhead. The anticipated cost using the tubes is $650,000 which may result in the project becoming a reality.

## Gulf Intracoastal Waterway (GIWW), West Bay, Texas

### Problem

Halls Lake is located (Figure D-1) north of West Bay separated from the bay by a narrow isthmus. The barrier islands to the south of the GIWW have been eroding steadily for the past several years, exposing the isthmus to waves generated from the predominant southerly summer winds. Resulting wave erosion threatens to breach the isthmus and reduce the lake's value as habitat for wintering birds and developing juvenile fish. Additionally, the dredged material containment dikes east of the lake have been undergoing erosion along the GIWW bankline, threatening the integrity of the dikes. A dike breach could cause massive shoaling in the channel and create additional disposal and navigation problems.

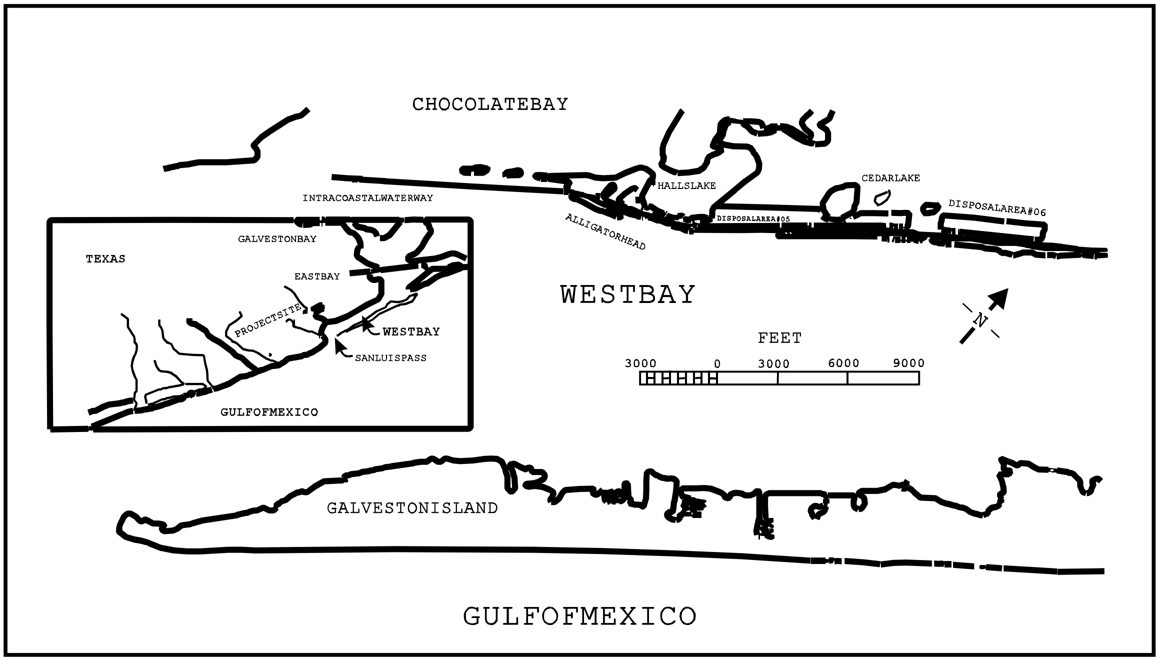


Figure D-1. Location map for West Bay Project.

## Approach

An existing island on the south side of the GIWW was extended approximately 1500 m to the east, sheltering the exposed shoreline (Figure D-2). The width of the island averaged 70 m. The island extension was experimental in that it was composed of dredged material from the GIWW placed behind a confining levee structure. The dredged material and levees were planted with *Spartina alterniflora* and *Spartina patens* to establish tidal marsh habitat. Several experimental erosion protection alternatives were tested along sections of the exterior of the levees. The locations of the sections are shown in Figure D-2.

## Construction

The general construction process consisted of 1) building up levees, 2) installing specified slope protection, 3) placing dredged fill within the confines of the levees to desired elevations, and 4) reshaping and vegetating the dredged material when sufficient soil strength develops.

All levee sections noted as A, B, C, D, G, H, and I in Figure D-2 were constructed in the same manner except the hydraulically placed clay levee. In situ material inside the proposed containment area was removed using an amphibious dragline and placed according to specified crest elevation, crest width, and exterior slope for each section. Crest elevations range between +0.76 m and + 1.22 m Mean Low Tide (MLT) with crest widths of 3.0 m to 4.57 m. Exterior slopes ranged between 1:5 to 1:15. Section E on Figure D-2 consists of a hydraulically placed clay levee made from clay taken from beneath the maintenance material in the channel. The

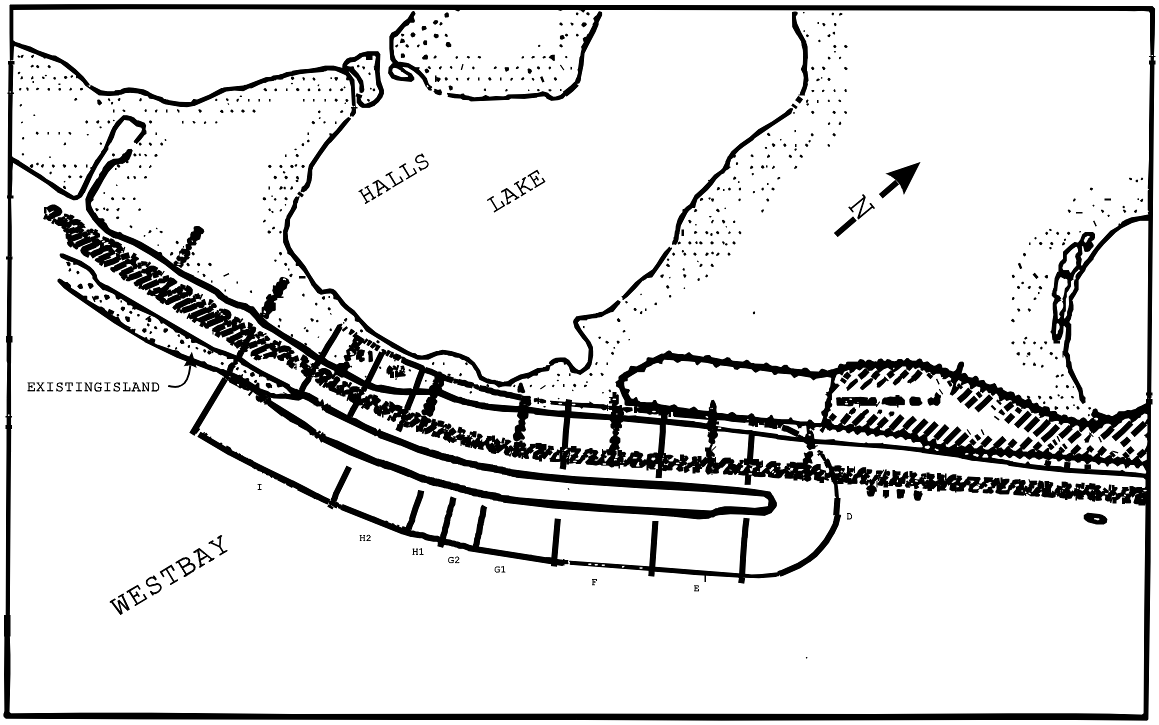


Figure D-2. Plan view of proposed project showing centerline of structures.

crest elevation for this section is +1.22 m MLT and the crest width is 3.0 m. The side slopes depended on the mounding characteristics of the clay but were expected to fall between 1:7 and 1:25. Section F consisted of about 300 m of geotextile tube which was placed adjacent to a low lying sill and also functioned as a low-lying sill, allowing regular inundation of the marsh. The crest elevation of the geotextile tube is +0.76 m MLT.

The exterior slopes of the levees were predominantly protected by vegetation, coconut-fiber mats, or coconut-fiber mats sprigged with vegetation. Each varying slope has sections with and without coconut-fiber mats to determine if vegetation itself provides the desired protection. Where coconut-fiber mats were used they are placed from MLT to the crest of the levee. The mats will be anchored with U-shaped rebar driven about 1 m below the surface. All of the fiber mats were destroyed soon after installation. The fiber seems to have separated from its backing material and drifted away. All that remains is a field of rebar staples spaced one meter or so apart.

On the east end of the island, a dynamic revetment was constructed which allows wave action to rearrange the stones to an equilibrium profile. The 2-lb armor stones were placed on a filter fabric on the steep slope from the toe to the crest. The armor stone was extended across the crest of the levee which was at elevation +0.76 m MLT. The appropriate volume of stone was dumped evenly around the levee without shaping. The stone was allowed to find its own angle of repose. After two years, inspection of the stone indicated that much of the stone had moved off the east point of the island and around to the north and south sides. The north and south sections of the revetment were still protecting the levee and marsh. The point of the island was still protected by some of the stone but would sooner or later begin to erode. The revetment was considered successful, but design modifications are necessary. The main modification would be to provide retaining elements that would prevent the revetment from moving laterally. This modification might be accomplished with a structure or with a few substantially larger stones that could not be moved by the waves.

## Conclusions

The mild slopes fared better than the steeper slopes on the north side of the island which were primarily exposed to boat waves. On the bay side the levees have been eroded to where they are often near or just below the water line. However, in this condition they continue to cause waves to shoal and break before the waves enter the marsh area. The geotextile tube is still in place and functions much like the eroded levees by causing waves to break before they enter the marsh areas that have developed leeward of the tube. Vegetation by itself has not withstood the wave assaults and the fiber mats were unsuccessful. The interior region of the marsh is a blend of stands of cordgrass and open water.

Shell that has apparently been winnowed out of the levee material during the erosion process has formed berms along the submerged levee crests that also inhibit wave penetration into the marsh.

The island extension though changing slowly from its as-built condition is expected to continue to act as a shield against wave attack on the north bank of the Gulf Intracoastal Waterway (GIWW). The waves will first have to completely destroy the levees (even the submerged sections) on the bay side of the island; remove the marsh vegetation on some of the material on the interior of the island; and then completely destroy the levees on the channel side of the island. The intent of the Galveston District was to have the island function for the three years or so between dredging cycles on the waterway. The island will clearly function for that long, if not longer.

## Costs

The approximate costs for construction of the different protection alternatives are listed in Table D-1. The values are based on an average of five bid estimates for their construction.

**Table D-1**
**Approximate Construction Costs for Protection Alternatives**

| Protection Alternative | Average Cost, $1991 |
|---|---|
| Hydraulically Placed Levee (50,000 cu. yd.) | $ 4.10/cu.yd. |
| Geotextile Tube (1000 linear ft.) | $ 100/lin. ft. |
| Dynamic Revetment (100 tons) | $ 60.00/ton |
| Coconut Fiber Mats (282 rolls) | $ 635.00/roll |

# Appendix E Engineering Specifications for Wetland Establishment[1]

This appendix provides example engineering specifications for wetland establishment projects that can be modified by the funding agency or consultant to develop a full engineering package suitable for advertisement and public bid. Example engineering specifications are provided for vegetation establishment and substrate placement. Explanations for the specifications are provided along with discussions of potential pitfalls and concerns.

The appendix is published as a separate document because of its size and potential use. It is available as:

Dunne, Kenneth P., Rodrigo, A. Mahendra, and Samanns, Edward (1998). "Engineering Specification Guidelines for Wetland Establishment and Subgrade Preparation," *Technical Report WRP-RE-19*, USAE Waterways Experiment Station, Vicksburg, MS.

[1] By Kenneth P. Dunne, A. Mahendra Rodrigo, and Edward Samanns

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This handbook discusses engineering procedures for establishing necessary hyrologic conditions, geotechnical design, and soils handling for site modification, selecting appropriate vegetation and planting schemes, and establishing substrate conditions conducive to the desired functions. It also discusses baseline assessments of existing site conditions, monitoring strategies to determine long-term success, and contracting considerations.

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