Research Report 119

The New Chicago Model: A Reassessment of the Impacts of Lake Michigan Allocations on the Cambrian-Ordovician Aquifer System in Northeastern Illinois

by
Stephen L. Burch

ILLINOIS STATE WATER SURVEY
DEPARTMENT OF ENERGY AND NATURAL RESOURCES

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The New Chicago Model: A Reassessment of the Impacts of Lake Michigan Allocations on the Cambrian-Ordovician Aquifer System in Northeastern Illinois

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ABSTRACT

This study reports the effects of substituting water from Lake Michigan for ground-water withdrawals in northeastern Illinois. It describes the use of a digital computer model to predict future ground-water levels based on anticipated pumping schedules. The model focuses primarily on the "Chicago region," which consists of Cook, DuPage, Kane, Kendall, Lake, McHenry, and a portion of Will and Grundy Counties.

The effort made during this project departed so far from the original Chicago model, that the code used in this report is referred to as the "New Chicago Model." The source code for the new model was translated from Fortran to QuickC, although most of the variable names used by Prickett and Lonnquist (1971) were preserved, particularly in calculations of head, storage, and recharge at each node. The new version was developed and tested in the era of the Intel 80286 processor, and several runs were made on the faster 80386-based machines.

Six geologic surfaces were used in the New Chicago Model to define the five-layer Cambrian-Ordovician aquifer system. Each layer varies in hydraulic conductivity and thickness, and therefore in its ability to transmit water. The transmissivities of each layer, when summed at each node, describe the aquifer system in greater detail than has been done previously. Distinctive stratigraphic controls exerted by the Prairie du Chien Group in Illinois and the Mt. Simon in Wisconsin have been included to help incorporate regional differences into the New Chicago Model.

The pumpage data set contains information on 1,150 individual wells. A distance-weighting program was developed to distribute a proportional amount of an individual well's historical pumpage to each of the surrounding four comers of the model grid. Demand forecasts were developed on the basis of trends at each facility utilizing the Cambrian-Ordovician aquifer. Future well locations were determined simply by averaging the Lambert coordinates for each well at each of the 289 Illinois facilities.

The model predicts that Chicago's regional pumping cone will first become shallower without becoming significantly smaller in areal extent. Ground-water levels will rise throughout much of northeastern Illinois between 1985 and 1990, particularly in Cook County, since it was the first to switch to Lake Michigan water. The model predicts that by 2010, water levels will rise in some places by 350 feet or more throughout DuPage and much of western Cook Counties, and by almost 650 feet around Elmhurst. Water levels will rise by 50 feet or more as far away as Belvidere, DeKalb, Morris, and Kankakee. The actions taken in Illinois will even cause water levels to rise in southeastern Wisconsin and northwestern Indiana.

1. INTRODUCTION

Schicht et al. (1976) estimated that the practical sustained yield of the deep ground-water system in northeastern Illinois was 65 million gallons per day (mgd). However, pumpage has exceeded this amount every year since 1959. The inevitable consequence is that critical water levels will be reached. When this occurs, well yields will decline significantly and water users will have to look elsewhere for supplies.

In 1966, the U.S. Supreme Court issued a decree concerning diversions of water from Lake Michigan. As a result of an amendment to that decree, the state of Illinois planners had to formally recognize the need to reduce pumpage from the Cambrian-Ordovician aquifer system (Fetter, 1981). Accordingly, the 81st General Assembly directed the Illinois Department of Transportation/Division of Water Resources (IDOT/DWR) to implement a long-term program for allocating Lake Michigan water. The program regulates the use of Lake Michigan water by Illinois and has funded impact studies of pumpage from the deep sandstone underlying northeastern Illinois.

This study is also a result of the allocation program and reports the effects of substituting Lake Michigan water for ground-water withdrawals. It describes the use of a digital computer model used to predict the effect of anticipated pumping schedules on ground-water levels. The model, originally developed by the Illinois State Water Survey (Prickett and Lonnquist, 1971), is a predictive or "deterministic" one. It solves equations numerically and is useful in describing certain cause-and-effect relationships. With its simplifying assumptions about ground-water flow equations, aquifer boundaries, and initial starting conditions, the model can be used to predict water levels. Conclusions about ground-water drawdowns or recoveries can be made by comparing the results of different simulations.

Visocky (1982) used the traditional Chicago model developed by Prickett and Lonnquist to predict the impact that Lake Michigan substitutions would have on ground-water levels in northeastern Illinois. But since the conclusion of that study, several changes have been made in the Lake Michigan allocation program. The original pumpage schedules used by Visocky are no longer in effect, and the model has become outdated because of improvements in computer technology. Therefore, revised simulations have become necessary and possible.

An enhanced version of the traditional Chicago model was developed for this project. The new model incorporates updated pumping schedules and other information refinements over earlier models. The study area, however, is the same as that of the traditional model: 148 miles wide and 148 miles long, spanning northeastern Illinois and southeastern Wisconsin. The model focuses primarily on the "Chicago region." As defined by Suter et al. (1959), the focus area consists of Cook, DuPage, Kane, Kendall, Lake, McHenry, and a portion of Will and Grundy Counties, all in northeastern Illinois. Figure 1 illustrates the overall study area and highlights the focus area.

Purpose and Scope

The objective of this report is to outline the goals that guided the redevelopment of the traditional model, to describe the methodology used to prepare pumpage and head data for input to the new model, and to review the lessons learned from model calibration and the prediction of future ground-water levels. The new version of the Chicago model observes the previously used framework (Prickett and Lonnquist, 1971; Schicht et al., 1976; Visocky, 1982): it still is represented by a grid of 100 horizontal rows and 100 vertical columns, which forms a variably spaced, finite-difference grid.

The new Chicago model seeks to determine the impact of substituting Lake Michigan water for ground water in northeastern Illinois. This investigation makes use of detailed pumpage and hydrogeologic data by merging classical methods with new mapping techniques.

Previous Reports

The numerical representation of the ground-water flow system supplying northeastern Illinois is commonly referred to as the "Chicago model." The modeled area was initially described by Walton (1962), although Suter et al. (1959) actually provided the baseline study for the Chicago region. Prickett and Lonnquist created the first computer simulation of the area as an example of one of many such models for their 1971 publication. Although they referred to their example as a "digital model of the Cambrian-Ordovician aquifer in the Chicago region," the two key words that have come to be remembered are "Chicago" and "model." The size and solution technique associated with that modeling effort (alternating direction implicit) has become traditional, at least in Illinois. Others (Young, 1976; Steinhilber and Young, 1979; Butler, 1982; Young et al., 1986) have modeled the area somewhat differently and used other numerical techniques, but they all refer back to the Prickett and Lonnquist example.

Because the model has become so widely accepted and because the effort made during this project departed so far from the original, the code used in this report is referred to

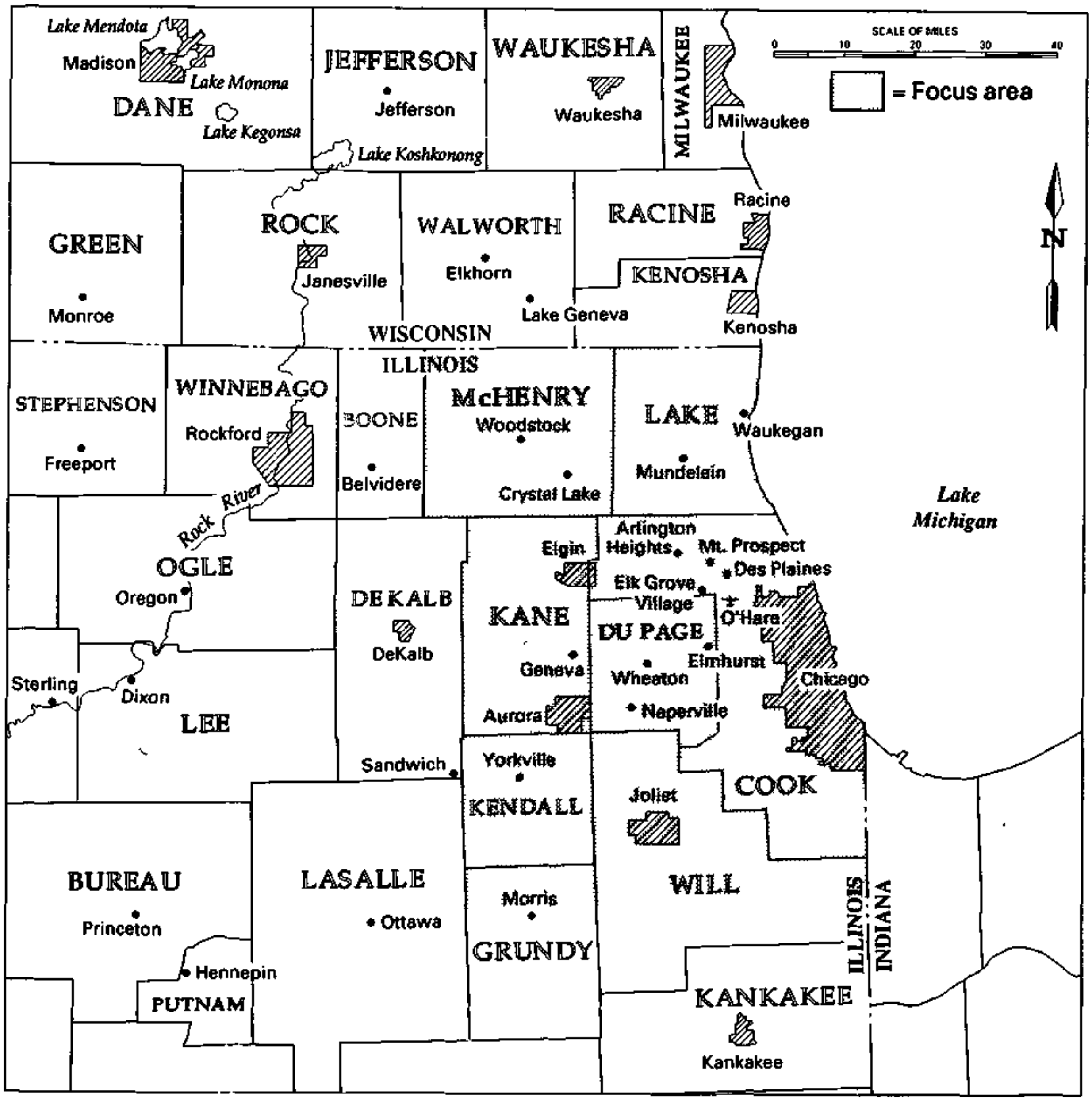


Figure 1. The study area

as the "New Chicago Model." Additional impetus for the name change came from the author's intention to significantly change the model rather than to add more refinements (Schicht et al., 1976; Visocky, 1982).

Motivation for the Redevelopment of the Chicago Model

This effort was specifically geared to the redevelopment of the model. Redevelopment was partly necessary because computer hardware is no longer limited to the mainframes and punch cards that Prickett and Lonnquist described. The redevelopment goal also grew out of the desire to use the model in a microcomputer/personal computer (PC) environment, which allows low-cost preprocessing of input data and postprocessing of model calculations.

Hardware standards in the PC environment are, of course, volatile. Over the course of this investigation, computing has changed drastically. The new version of the model was developed and tested in the era of the Intel • 80286 processor. However, by the end of the study, several runs were made on the faster 80386-based machines.

Computer languages have changed too. The source code for the new model was translated from Fortran to QuickC (Microsoft, 1988), although most of the variable names used by Prickett and Lonnquist were preserved, particularly in calculations of head, storage, and recharge at each node. A new supportive postprocessing program was also written using QuickBasic 4.0 to convert model output to a form acceptable to contouring software (SURFER). Maps were drawn using plotters driven by either SURFER or AutoCad software.

Today ground-water models and computer facilities are more commonplace than they were in 1971. The trend is to blend the predictive abilities with the emerging ability to produce computer-driven maps. This approach contrasts with that employed in the original digital model of the Chicago region. In those days, the investigator would manually transfer calculated drawdowns from computer printouts to a paper overlay on the model grid. The drawdown values were contoured by hand and then sent on to a draftsman for publication-quality drawings. But because coordinates for pumpage locations and geological controls can now be described digitally, today's final drawings are based on computer-generated maps.

Acknowledgments

This study was financed under contract through the University of Illinois at Urbana-Champaign by the Division of Water Resources of the Illinois Department of Transportation. The initial idea for the project was developed by Mark A. Collins, formerly with the Illinois State Water Survey, and Daniel Injerd, Chief of the Lake Michigan Management Section of the DWR.

Special acknowledgment is extended to Evan P. Mills of the Illinois State Water Survey for his computing expertise. He translated the old Fortran code into QuickC (Microsoft, 1988), porting it from a mainframe environment to a PC environment, and wrote the postprocessing program, called "CHI2SURF" (appendix A). The source code for the model and supporting programs are available on diskette from the Hydrology Division of the Illinois State Water Survey, telephone (217) 333-2210.

This report was prepared under the general administrative guidance of Richard G. Semonin, Chief, and Ellis W. Sanderson, Head of the former Ground-Water Section, both of the Illinois State Water Survey. Technical review of the final report was completed by Water Survey researchers Richard J. Schicht and Adrian P. Visocky.

Other Water Survey personnel also assisted with the project. Significant computer programming support was provided by Douglas J. Kelly. Julie Rose keypunched stacks of handwritten pumpage data sheets collected by Robert J. Sasman during the 1960s and 1970s, transforming them into machine-readable format James R. Kirk provided computerized pumpage data for the years 1980 through 1987 from the Illinois Water Inventory Program database. Dorothy M. Woller and Rachael (Hammen) Contorer provided invaluable assistance in determining which wells in the Chicago region actually utilize the Cambrian-Ordovician aquifer.

Graphics were computer-generated by the author and enhanced for publication by John W. Brother, Jr., and David L. Cox. The readability of this report was greatly enhanced by the editorial comments of Laurie Talkington.

2. MODELING THE HYDROGEOLOGIC SYSTEM

The procedure for developing a deterministic (predictive) ground-water model is fourfold. The first step is to understand the physical behavior of the ground-water system and to form a conceptual model of how it works. The modeler must abstract the real system into an operational computer code that will preserve the essential elements of the hydrogeologic system.

Next the model user must assemble a large body of data, such as boundary definitions, water levels, and pumping patterns (Bachmatt et al., 1980). These data serve as a starting point for preliminary computer simulations.

The third step involves calibrating the model to ensure that it can reproduce a set of historical data with some acceptable degree of accuracy (Konikow, 1978). Calibration frequently involves adjustment of input parameters, particularly those that are poorly known. A quantitative evaluation of the response to an adjustment should be made to see whether the degree of changed response is directly proportional to the adjustment. Once the model has been calibrated to reproduce historical data effectively, the next step is to verify whether or not its accuracy and predictive capabilities are within acceptable limits. These tests should not be dependent on the calibration data.

Having been established as a reliable tool, the model is finally ready to make ground-water level predictions. Future scenarios can be developed for periods as long or short as the user cares to specify with situation data.

Hydrogeologic Setting

The ground-water resources of northeastern Illinois have been described in numerous reports of the Illinois State Water Survey and the Illinois State Geological Survey. The resources comprise four major aquifer systems, best described by the comprehensive, early work of Suter et al. (1959): the unconsolidated sand-and-gravel deposits of glacial age; 2) the shallow dolomite formations, mainly of Silurian age; 3) the Cambrian-Ordovician aquifer system, which provides the most ground water to the region; and 4) the often saline Mt. Simon aquifer of lower Cambrian age.

A stratigraphic column (figure 2) depicts the stratigraphy of the region and provides brief lithologic descriptions of the formations encountered in the subsurface. Although ground water is available from shallower units, high-capacity wells drilled in the Chicago region frequently reach depths of 1,500 feet, withdrawing water from the Cambrian-Ordovician Sandstones of the Ironton-Galesville and St. Peter Formations. Buschbach (1964) and Willman et al. (1975) have published excellent references on these sandstones in northeastern Illinois, while Foley et al. (1953) did similar work for southeastern Wisconsin.

Stratigraphic Controls on the Model

The Cambrian-Ordovician aquifer system in northeastern Illinois and southeastern Wisconsin represents a classic artesian situation (Fetter, 1981). The aquifer is bounded below by the relatively impermeable beds of the Eau Claire Formation (shale), and above by Maquoketa Shale and Galena-Platteville dolomite. Suter et al. (1959) first noted that on a regional basis, the entire sequence of strata between the confining beds behaves hydraulically as one aquifer. Any differences in artesian pressure that may have existed among the units has been equalized by the great number of wells open to all the units. In the western part of the study area, the aquifer comes nearer the land surface and is more readily recharged, in large part because the Maquoketa Shale is absent. The ground water entering the aquifer is transmitted eastward toward pumping centers in the Chicago and Milwaukee areas.

Six geologic surfaces were used in the New Chicago Model to define a five-layer aquifer system. Figure 3 illustrates the stratigraphic relationships. Each layer varies in hydraulic conductivity (K) and thickness (b), and therefore in its ability to transmit water. The transmissivities of each layer, when summed at each node in the model, describe the aquifer system in greater detail than does Prickett's uniform transmissivity assumption of 17,000 gallons per day per foot (gpd/ft).

The Mt. Simon layer is an important producer in Wisconsin and in the northernmost tier of Illinois counties. South of these counties, however, it quickly becomes saline, and for all practical purposes it is not desirable in much of the model area. This condition is represented numerically in the model by setting the bottom elevation of the Mt. Simon layer equal to the bottom of the overlying Ironton-Galesville layer. The effective thickness of the Mt. Simon layer in most of the model area is equal to zero.

To achieve a pattern of transmissivities in Wisconsin similar to that described by Young (1976), the thickness of the Mt. Simon Sandstone was arbitrarily increased. However, model calibration was not reached until a hydraulic conductivity of 60 gpd/sq ft was used to describe the Mt. Simon layer. This value, which is four times greater than that used by Young, results in unusually high transmissivity values in the Milwaukee-Waukesha portion of the New Chicago Model. This discrepancy is likely the result of the fact that the northern boundary of the model does not coincide with an actual physical boundary.

SYSTEM	FORMATION OR GROUP	LOG	DESCRIPTION
Quaternary			Unconsolidated glacial deposits. Commonly pebbly clay, but with silt, sand, and gravel. Some glacial deposits consist of very permeable bodies of sand and gravel.
Silurian			Dolomite, very pure to very silty. Upper part frequently creviced and broken. Lower part contains thin shale layers and tends to be silty.
Ordovician	Maquoketa		Shale, gray or brown.
	Galena-Platteville		Dolomite, commonly creviced when not underlying the Maquoketa Shale. Some limestone layers and thin shale partings.
	Glenwood		Sandstone and dolomite, shale at the top.
	St. Peter		Sandstone, fine to medium texture, well sorted and poorly cemented. Exceptionally pure quartz sand.
	Prairie du Chien		Interbedded dolomites and sandstones.
Cambrian	Eminence-Potosi		Dolomite, white, fine-grained, but typically sandy at its base. (Lower unit known as St. Lawrence in Wisconsin.)
	Franconia		Sandstone, dolomitic with thin shale partings.
	Ironton-Galesville		Sandstone, coarse to fine-grained, well sorted. May be dolomitic in the upper part.
	Eau Claire		Shale and siltstone. Contains a sandy dolomite member in northeastern Illinois. Entire formation becomes essentially a fine-grained sandstone in Milwaukee.
	Mt. Simon		Sandstone, coarse-grained. Thickness estimated at 2,000 feet in Illinois.
Precambrian			Crystalline rock, probably granite.

Figure 2. Stratigraphic column showing nomenclature and classification in the study area

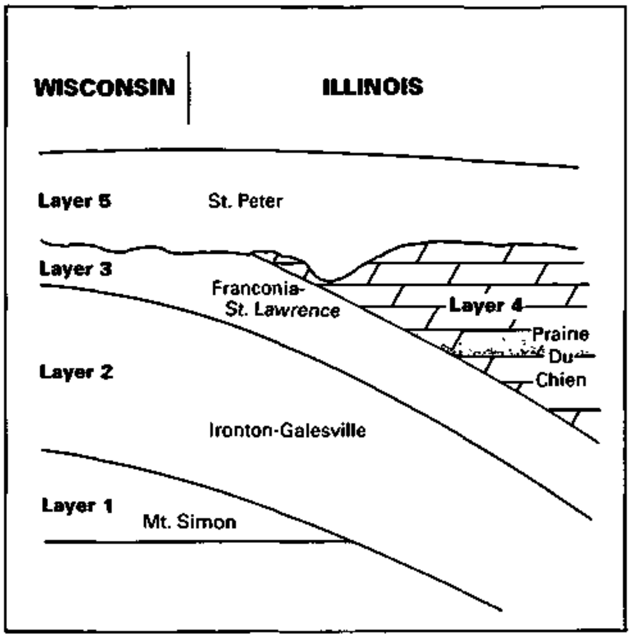


Figure 3. Stratigraphic relationships in the New Chicago Model

Above the Mt. Simon is the Ironton-Galesville Formation. This geologic unit is the principal water-yielding unit of the entire system, according to Suter et al. (1959). It has excellent hydraulic properties and is perhaps the most uniformly distributed of all the layers. It ranges in thickness from about 100 to 200 feet A hydraulic conductivity value of 100 gpd/sq ft was used successfully during calibration and subsequent model runs. Prickett and Lonnquist used a K-value of 48.57 gpd/sq ft in their model (1971, fig. 73). Young (1976) chose to agree with Prickett and Lonnquist, so the value used here is double the traditional value for the Ironton-Galesville.

The Franconia-SL Lawrence layer (as it is known in Wisconsin) constitutes the third layer of the model. In Illinois it consists of upper Cambrian-age rocks belonging to the Franconia Formation and the overlying Potosi Dolomite and Eminence Formation. This sequence of lithologies ranges from argillaceous sandstone to pure dolomite. For this reason its hydraulic conductivity was considered to be one order of magnitude less than that of the Ironton-Galesville Sandstone. A value of 10 gpd/sq ft was used in this model. Unlike its treatment in other models, this layer is limited to these rocks alone and is modeled as from 0 to 738 feet thick.

Layer four contains rocks of the Prairie du Chien Group, which are intentionally distinguished from those in the underlying Franconia-SL Lawrence layer and the overlying Ordovician-age units. Although this group is present throughout much of Illinois, it is almost entirely absent from the northern two tiers of Illinois counties and from the Milwaukee area of Wisconsin (Foley et al., 1953; Willman et al., 1975). Furthermore, Prairie du Chien strata are frequently missing locally throughout the northern third of Illinois, having been removed by erosion before the St. Peter Sandstone was deposited.

The Prairie du Chien Group (layer four) is important to modeling efforts because it thickens rapidly to more than 900 feet in the southern part of the study area and because it has very low hydraulic conductivity. To minimize the ground-water contributions from this layer, particularly in the Joliet area of the model, the hydraulic conductivity was defined as 3 gpd/sq ft as the result of a trial-and-error calibration process.

The fifth and uppermost layer refers to the St. Peter Sandstone of the Ancell Group. It is an unusually extensive, very pure, uniformly fine-grained, and well sorted quartz sandstone (Willman et al., 1975). Its thickness varies greatly from less than 100 feet to more than 600 feet, owing to the irregular surface of the underlying Prairie du Chien rocks (Visocky et al., 1985). Included in layer five, although regarded as insignificant to the modeling effort, is another part of the Ancell Group, the Glenwood Sandstone.

The initial hydraulic conductivity estimated for the St. Peter Sandstone was greater than those used previously by Prickett and Lonnquist or Young. This difference occurred because the Galena-Platteville unit, at 300 feet thick, was never considered to be part of the Cambrian-Ordovician aquifer. Instead of a hydraulic conductivity of 5.1 gpd/sq ft, as inferred from Prickett and Lonnquist's figure 73 (the result of dividing a transmissivity of 2,550 gpd/ft by a thickness of 500 feet), the transmissivity was divided by the thickness of the St. Peter in the new model, thereby inferring a hydraulic conductivity of at least 12.75 gpd/sq ft.

The hydraulic conductivity of the St. Peter is probably greater than that of the sandstones of the Franconia-St. Lawrence sequence because of decreased clay content A value of 30 gpd/sq ft was assigned to the St. Peter based on calibration testing. Like the Ironton-Galesville, this value is twice that used by Prickett and Lonnquist. Nevertheless, 30 gpd/sq ft seems consistent with the generally higher values used in this study because as Walton and Csallany (1962) observed, the hydraulic conductivity of the St. Peter is about one-third that of the Ironton-Galesville.

The key to understanding the stratigraphic controls on the model is that the Cambrian-Ordovician aquifer system is bounded above by the Galena-Platteville Formation. This directly contradicts earlier Illinois studies (Walton, 1962; Prickett and Lonnquist, 1971; Schicht et al., 1976; Fetter, 1981), although Young (1976) in Wisconsin did recognize this difference during calibration of his model.

Stratigraphic controls are also exerted by the Prairie du Chien Group in Illinois and the Mt. Simon in Wisconsin. These two layers help incorporate regional differences into the New Chicago Model that have not been appreciated in previous models. As figure 4 illustrates, the result is a transmissivity map that reflects the real world more accurately. It also refutes the simplistic assumption of uniform transmissivity (17,000 gpd/ft) that had been used in the earlier models.

Structure Contour Maps

Digitized map data for the various geologic surfaces were provided by the U.S. Geological Survey (USGS) district office in Madison, Wisconsin. For purposes of this project, four geologic surfaces were chosen (at 1:500,000 scale), representing elevations on top of the St. Peter, the Franconia-St. Lawrence (Wisconsin term referring to the Potosi Dolomite), the Ironton-Galesville, and the Eau Claire Formations.

The structure contour data were developed by the various state agencies within the Midwest and submitted as input to the Northern Midwest Regional Aquifer-System Study (RASA). Using a new custom-designed program (DIG2ARC.BAS) written in QuickBASIC (Microsoft, 1987), the Water Survey was able to convert the USGS digitizer output (in digitizer inches) to corresponding locations in real-world system coordinates. Because the real world is not rectangular, the USGS-mapped data were necessarily distorted by means of a mathematical process known as bilateral transformation.

Once the digitized (map) data were transformed, they were associated with the Lambert feet coordinate system. Data files containing x-y-z information about the four geologic surfaces were discretized into a regularly spaced grid (149 columns x 149 rows), using a commercially available software package (SURFER, Ver. 3). The Kriging option was used to interpolate the elevations of points lying between the 100-foot contour intervals for all points on the grid. This output was parsed by the QuickBASIC program, which reduced the data set to a 100 x 100 grid that contained information about those points coinciding with nodes in the ground-water flow model.

Recharge

Previous modeling efforts (Walton, 1962; Prickett and Lonnquist, 1971; Young, 1976) have shown the northwest comer of the traditional study area to be a recharge area because the Maquoketa Formation is absent there. While this simplistic observation is true, more detail can be deduced, particularly if the geologic maps and two other previous investigations (Weidman and Schultz, 1915; Anderson, 1919) are reviewed.

Weidman and Schultz used cross sections to show that several of the lakes at Madison, Wisconsin, were hydrogeologically connected with the "Upper Cambrian" (Ironton-Galesville) Sandstone. In fact, they commented that the pressure in the sandstone in 1882 was sufficient to raise water levels 4.5 feet above the surface of Lake Mendota, which was at 849 feet above mean sea level (feet msl). This observation is interpreted to mean that today's lower artesian pressures have resulted in a gradient reversal. Consequently, recharge from that and presumably other nearby lakes has a stabilizing effect on ground-water levels.

Weidman and Schultz's accompanying plate (number 1) indicates that the preglacial Rock River valley eroded deeply enough in Wisconsin to expose the "Upper Cambrian" Sandstone in Dane, Jefferson, and Rock Counties. In modem times, the sandstone subcrops glacial deposits of varying thickness. Recharge to the sandstone is determined by the hydraulic conductivities of the overlying materials. Because these values can be high, recharge can also be significant The cross-sectional drawings by Weidman and Schultz (1915, figures 29 and 64) clearly illustrate the connection between the permeable alluvial sand-and-gravel deposits associated with the Rock River and the St. Peter Sandstone.

Anderson (1919) observed a similar geologic situation at Rockford, Illinois. He reported that the St. Peter Sandstone either directly underlies the Pleistocene sand and gravels, or it is found just below a thin Galena-Platteville Formation. The Ironton-Galesville does not, however, subcrop glacial deposits in Illinois. Consequently, its recharge is more likely to be restricted than in Wisconsin.

Earlier studies (Walton, 1964; Schicht et al., 1976; Visocky et al., 1985) have estimated recharge rates in this area of the model at 20,400 to 42,000 gpd/square mile (gpd/sq mi). Elsewhere, the Maquoketa Shale Group or the Galena-Platteville Formation limit recharge. This is particularly true in Illinois, where the Maquoketa is 150 to 200 feet thick (Visocky et al., 1985).

In northeastern Illinois the Maquoketa Shale is the stratigraphic unit that effectively controls leakage to the Cambrian-Ordovician aquifer. Earlier reports frequently discussed maximum hydraulic gradients and flow through the Maquoketa. Walton's (1965) estimate of 2,100 gpd/sq mi has been firmly established and was used in the New Chicago Model.

Storage Coefficients

Artesian Conditions. The coefficient of storage for the Cambrian-Ordovician aquifer is fairly uniform throughout the model area. Earlier reports in Illinois (Suter et al., 1959; Walton, 1964; Prickett and Lonnquist, 1971) determined the artesian coefficient of storage to average about 0.0005. Subsequent investigators, however, have not been quite so sure. Visocky et al. (1985) pointed out that since the effective radius is not accurately known for most pumped wells, storage coefficients cannot be calculated with sufficient accuracy. They reported results from five tests averaging 0.00039, suggesting that the values reported in earlier studies might have been too high.

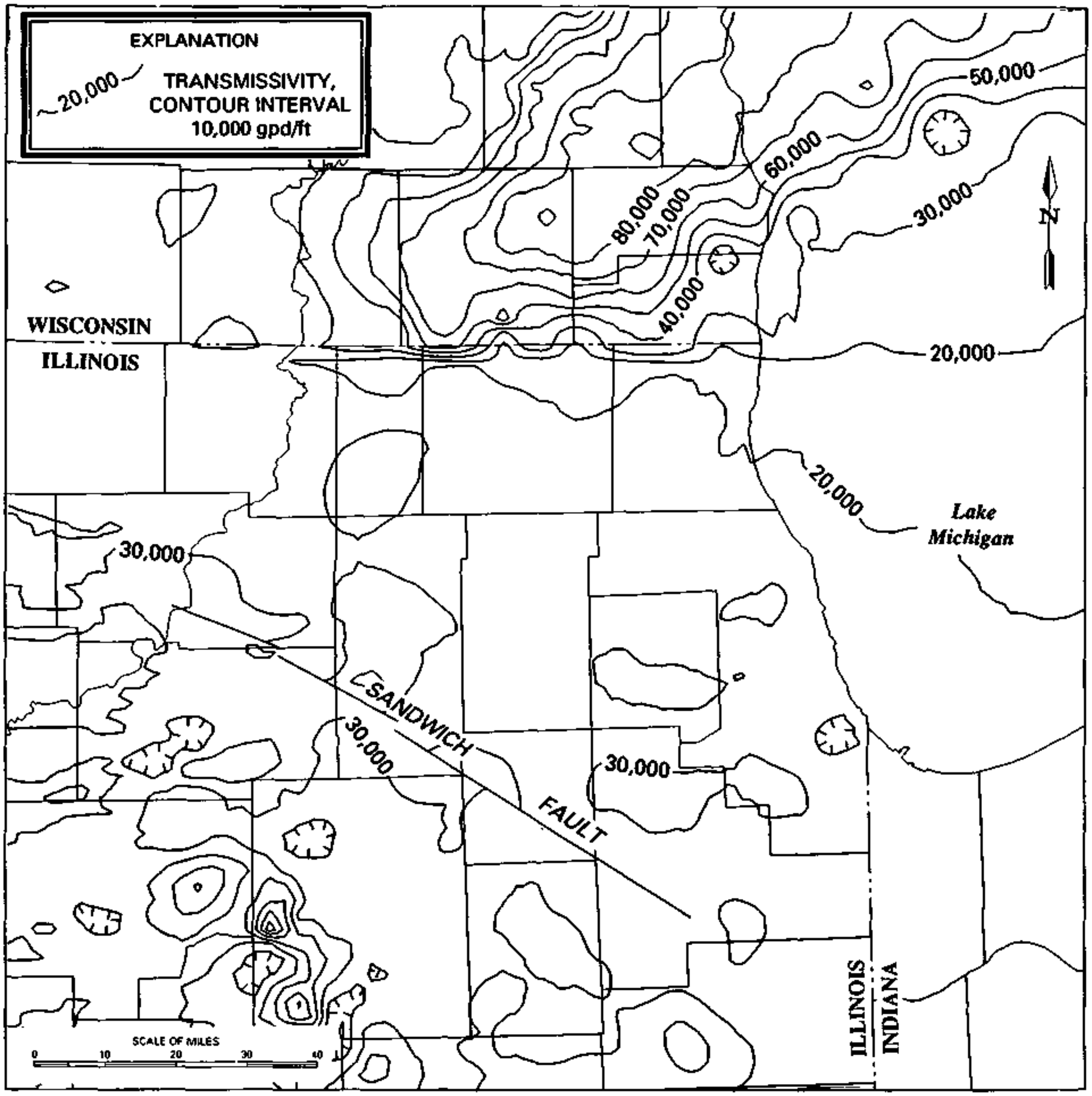


Figure 4. Transmissivity map used with the New Chicago Model

In Wisconsin, values reported for artesian storage coefficients seem to confirm this observation. Foley et al. (1953) reported an average value of 0.00039 in the Milwaukee-Waukesha area. Young (1976) modeled the Chicago and Milwaukee region, and although he relied on Prickett and Lonnquist for many numbers, he reduced the artesian storage coefficient to 0.0004 in his model.

Consequently there is precedent for adjusting the artesian storage coefficient But the choice of values employed could either deepen or broaden a cone of depression. It follows then that the better the choice, the better the representation of the pumping surface. Freeze and Cherry (1979) point out, by way of illustration, that for a given transmissivity, a larger value of storage coefficient will result in a shallower and less extensive cone.

Water-Table Conditions. In Prickett and Lonnquist's traditional Chicago model, the water-table storage coefficient was defined at a constant 100 times the artesian value. The new code allows the user to define the value and employ it in the New Chicago Model when the water level at a grid node drops below the top of the St. Peter Sandstone. In practice, this condition occurs in three areas: in the dewatered area of Dupage County, Illinois, in the areas of high recharge, and where the St. Peter has become exposed along the Sandwich Fault

Goals of Model Redevelopment

The Fortran code was redeveloped between 1985 and 1986 as an initial step in the investigation. Four goals were identified as being important to this new version. Consequently the original code was carefully studied to elicit changes that would:

1. Eliminate the need to have specifically formatted data structures.
2. Use a more meaningful error criterion in determining when convergence had been reached.
3. Model the aquifer in "two and a half dimensions. That is, transmissivity values would depend on the thickness of the aquifer layers beneath every point on the model's grid.
4. Incorporate a preprocessing step that would distance-weight the pumpage data to grid corners.

As a result, the user now has more freedom in specifying model parameters. Pumpage rates for each well, for example, can change at equally spaced times, rather than being fixed for the whole simulation. The elevations of the various formations can be specified at each node. Thus, transmissivity represents the summation of each layer's thickness times its hydraulic conductivity, as shown by the following equation:

$$T = \Sigma K_i b_i$$

where:

T = transmissivity in gpd/ft of "i" layers
K_i = hydraulic conductivity in gpd/sq ft per foot of saturation in the ith aquifer layer
b_1 = saturated thickness of the ith layer in feet

The error criterion procedure used by the old model was also modified. Instead of terminating calculations when the sum of all nodal errors exceeded some criterion (50 feet in Prickett and Lonnquist's Chicago model), the revised model checks head changes between two successive iterations *at each node*. Convergence continues iteratively within the time step until the maximum head change at any node is less than the specified criterion. The algorithm used by the model was modified significantly in an attempt to lower the convergence error inherent in the old model. The new model has been designed to predict the head at each node to within 0.5 foot. The new error-checking code, combined with increased accuracy of the pumpage data and digitized geologic data, should improve water-level projections by an order of magnitude. This increased precision in assembling hydrogeologic data greatly extended the duration of the modeling process.

Data Assembly

Ground-Water Withdrawals

Meinzer (1928) was one of the first geologists to consider the relative significance of pumping on regional flow systems. He noted that local pumping affects only a small area in a regional aquifer. But when the stresses caused by ground-water withdrawals grow, the dynamic equilibrium of the natural flow system is disturbed. Individual cones of depression spread out. Water levels are lowered in larger and larger areas as water is removed from storage. And eventually, large cones form at major pumping centers.

The long-term pumpage from the Cambrian-Ordovician aquifer in northeastern Illinois has had a widespread effect on water levels. By 1960, the drawdowns at major pumping centers had overlapped into two separate cones of regional proportions. The larger of the two represented the Chicago area, and the other represented Milwaukee. Withdrawals had grown so large that after 1957, they exceeded the capacity of the natural system. This event was of such major significance that it was used as the starting point of the numerical simulations reported in this study.

More than 30,000 pumpage records in northeastern Illinois were examined and computerized. Thousands of well logs in Illinois and Wisconsin were reviewed and classified according to the aquifers the wells were utilizing. In the eight Illinois counties, 806 Cambrian-Ordovician wells were identified and their pumping records compiled for use with the new model.

Since 1980 the Illinois State Water Survey has maintained computer records of ground-water pumpage. Prior to that time, however, only penciled notations on paper were kept for most communities, industries, and golf courses in northeastern Illinois. From time to time the Water Survey published summaries of these notes, which generally represented annual compilations for each county and usage type. These early records, which were diligently maintained between 1964 and 1980, were combined with the computer data to form the best available record of ground-water pumpage in northeastern Illinois.

Although this project was primarily concerned with modeling the drawdown effects of sandstone wells, every Water Survey well record in the eight-county northeastern Illinois area was keyed into computer-readable format regardless of well depth. Later, after aquifer codes had been determined and assigned to these records, the sandstone records were selected for use in this project.

Similar well and usage data for Wisconsin were provided by the USGS office in Madison. Many of those data were developed as part of the Northern Midwest Regional Aquifer-System Analysis program. The Wisconsin pumpage data set was reduced to 6,953 records for 344 sandstone wells that were used between 1964 and 1985 and located within the boundaries used in the model.

The accuracy of the Illinois withdrawals can be validated by comparing the published pumpage estimates with tabulations made specially for this project. Generally, the greatest disparity occurs with the oldest records. The difference decreases from about 22 percent in 1964 to only 2 percent in 1980.

The Illinois and Wisconsin pumpage data for the period 1964 to 1985 were then combined. This data set contains information on 1,150 individual wells. The locations of these wells were converted to Lambert feet coordinates. Because the locations of the grid nodes were also known in terms of Lambert feet (appendix B), the distance between each well and its surrounding nodal locations could then be calculated. A distance-weighting program written in QuickBASIC (appendix C) was developed to solve these calculations. [The distance-weighting program is included with the CHI2SURF program on diskette from the Hydrology Division of the Illinois State Water Survey, telephone (217) 333-2210.]

Figure 5 illustrates how the program distributed a proportional amount of an individual well's pumpage to each of the surrounding four grid corners. As a consequence, the pumpage pattern was applied to a total of 1,846 nodes, instead of the 112 used by Visocky (1982), the 83 used by Schicht et al. (1976), or the 7 that were used by Prickett and Lonnquist (1971). Therefore, the New Chicago Model offers a much better geographic representation of pumpage than all previous models.

Water Levels

Water levels measured in wells are conveniently studied by means of maps. Most frequently used are water-level maps or, more precisely, potentiometric contour maps. Depths to water are subtracted from points of known elevation, usually the top of the well. The resulting values represent the water-level elevations above mean sea level. The differences in water-level elevations between wells are interpolated to produce contour lines. The interval between contour lines is a matter of choice and is usually based on a judgment of what makes the most effective illustration.

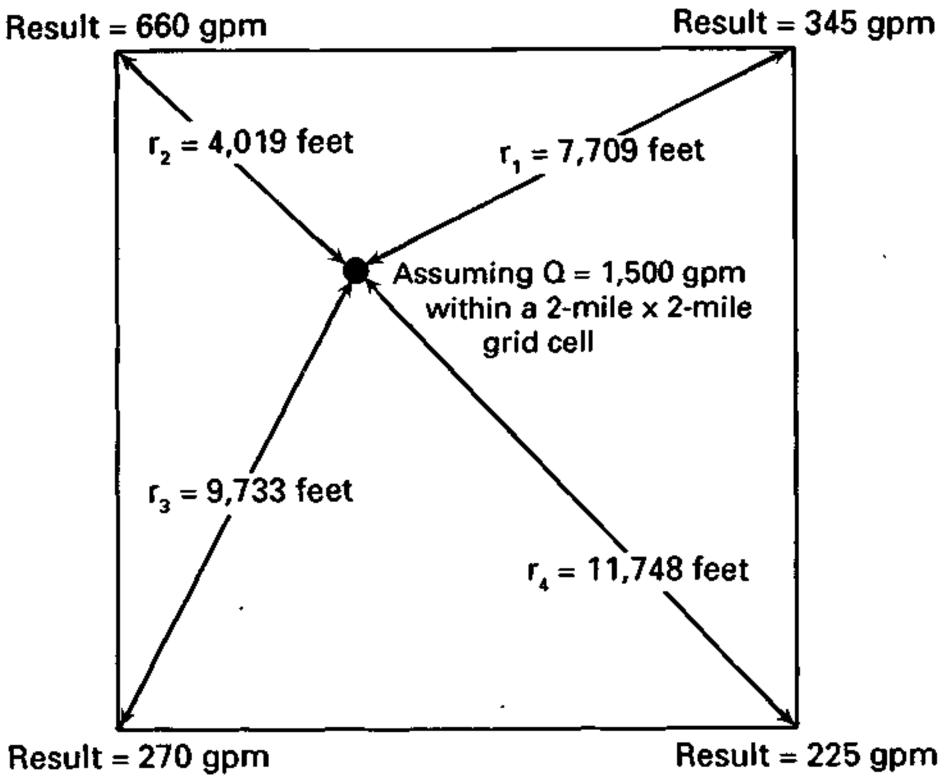
Water-level maps reflect hydraulic pressure (head) within an aquifer. A map can be used to depict the distribution of pressure and to infer flow directions. In Illinois the Water Survey has been collecting and reporting deep-well water levels since 1958. These data are obtained by a variety of methods and under a wide range of operating conditions and reliability (Sasman et al., 1986).

Collection of water-level information in Wisconsin, however, has been less frequent. The best known regional potentiometric map of southeastern Wisconsin was prepared in 1961 (Green and Hutchinson, 1965). The USGS prepared a second map for 1985 (Young and MacKenzie, unpublished) as part of its RASA project. Neither of these maps represents predevelopment conditions normally referred to as "starting head."

Starting Head

The exact configuration of the natural flow system in the Chicago-Milwaukee region is not known. However, Weidman and Schultz constructed a head map for Wisconsin (1915, plate 1) that described conditions in both the St. Peter and the lower Cambrian sandstones. The blue contour lines on the Wisconsin map are regarded as indicative of the Ironton-Galesville aquifer. Those lines are probably the best approximation of steady-state conditions and should be used as a starting head map. Visocky et al. (1985) revised an interpretation by Anderson (1919) and Suter et al. (1959) on the same aquifer in Illinois. It is assumed to represent predevelopment Illinois water levels.

For the New Chicago Model, 158 arbitrarily selected points were digitized from the contours illustrated on both maps. These data points (relative to mean sea level) were interpolated over the entire model area, using an unbiased estimation procedure called "kriging." Kriging has the distinct advantage of taking into account the distance between points and their values. In this case, a quadrant search was used for the nearest five neighboring points. As a result, a starting head value could be calculated at one-mile intervals over the entire study area (148 by 148 miles). Values for locations coinciding with nodes on the variably spaced model grid (100 by 100) were selected. The result was the starting head map (figure 6) used in this numerical simulation.



	Weighting factor	Distributed Q (gpm)
$\% wt_1 = {}^1/r_1 \div \Sigma ({}^1/r) = 1/7{,}709 \div (5.666 \times 10^{-4}) =$	0.23	345
$\% wt_2 = {}^1/r_2 \div \Sigma ({}^1/r) = 1/4{,}019 \div (5.666 \times 10^{-4}) =$	0.44	660
$\% wt_3 = {}^1/r_3 \div \Sigma ({}^1/r) = 1/9{,}733 \div (5.666 \times 10^{-4}) =$	0.18	270
$\% wt_4 = {}^1/r_4 \div \Sigma ({}^1/r) = 1/11{,}748 \div (5.666 \times 10^{-4}) =$	0.15	225
	1.00	1,500

Figure 5. Example of the distance-weighting technique used to distribute pumpage to finite-difference grid nodes

An examination of the starting head map reveals a significant and previously unrecognized fact: the Rock River is of great hydrologic importance in any model of the Chicago area because it controls the location of the ground-water divide in DeKalb County. The divide has been shown on maps for more than 30 years and is regarded as the western edge of the Chicago flow regime. However, while calibrating the New Chicago Model, the position of this divide was found to be maintained by ground-water discharges to the Rock River. Consequently its importance has been underestimated.

In this model, the Rock River has been simulated as a series of constant head nodes. Singh and Stall (1973) determined that baseflow figures for the Rock River range from about 900 to 1,200 cubic feet per second (cfs) at these nodes on the model grid. Most of this contribution from the ground-water system probably comes from the Pleistocene sand-and-gravel deposits in the river valley, but some contribution also comes from the discharge of the Cambrian-Ordovician Sandstones. While the exact amount is unknown, it almost certainly should be simulated in regional models, as the next chapter will show.

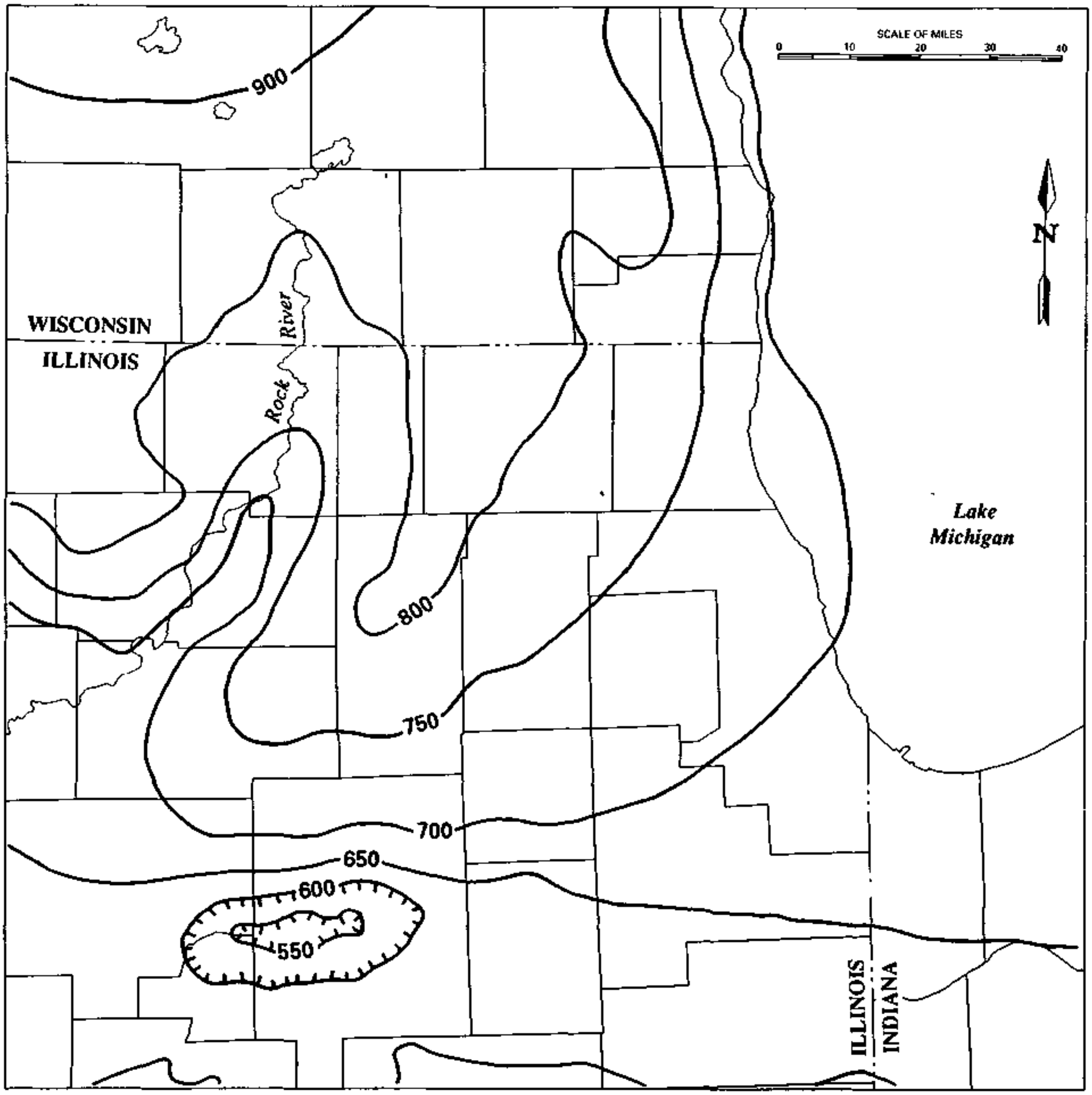


Figure 6. Starting head map showing potentiometric surface (feet msl) in the study area, c. 1865 (after Weidman and Schultz, 1915; Visocky et al., 1985)

3. FLOW SIMULATION AND MODEL CALIBRATION

Traditionally, the eight counties that constitute the focus area of this study have been used to illustrate water-level declines in northeastern Illinois. But to calibrate the parameters used by the model, pumpage simulations were made for the period 1957 through 1985 for the entire study area. Approximately 80 computer runs were made with the model. Various aquifer parameters and boundary conditions were tried until a satisfactory match was made with historic water-level maps. Final calibration of the model was assumed when computed water levels in the Chicago cone of depression closely approximated the values measured by Sasman et al. in 1985 (1986).

The New Chicago Model was successfully used to simulate the 1985 potentiometric surface. The calculated surface for the Chicago region is presented as figure 7. This map was compared to an interpreted map of observed water levels (figure 8) collected by Sasman et al. (1986, figure 11). Particular attention was given to the eight-county Chicago region because the purpose of this investigation was to gauge the impacts of Lake Michigan water deliveries to DuPage and Lake Counties.

Well hydrographs were used to judge the model's ability to predict water levels, particularly within the Chicago cone of influence. Measured levels were compared to calculated values for the node nearest each observation well. This examination indicated that the model converged to a correct solution by 1980, and at that point it was predicting water levels accurately. A regression analysis compiled from eight sites (figure 9) shows that calibration seems to have been achieved because the slope of the regression line is near 1, and the y-intercept for each is near 0.

As a further test, a difference map was prepared to compare the calculated change between 1980 and 1985. Sasman et al. (1986, fig. 12) observed that initial recoveries occurred in southeastern Cook County due to the transition of public supplies from ground water to lake water. At the same time, his map of observed data suggests ground-water declines of more than 100 feet in DuPage County. The model indicated similar results in both areas during calibration runs. Because it can calculate current water levels that agree with observed changes, the model is considered to be capable of producing accurate predictions of future water levels as well.

Model Grid

Finite-difference modeling is based upon solving equations at nodes on a predefined grid. The grid used in the New Chicago Model is shown as figure 10. Aquifer properties and initial conditions must then be provided for each grid block.

In their model, Prickett and Lonnquist oriented the finite-difference grid over the area to be modeled so that the last column and the bottom row coincided with the eastern and southern barrier boundaries described by Suter et al. The finite-difference grid used in the new model is oriented toward grid north. And in a manner similar to that of Prickett and Lonnquist, it is also referenced to the northwestern corner of Cook County where it adjoins McHenry County. Although Suter et al. did not mention this location, it coincides with their grid location i=(column)47, j=(row)41. In the New Chicago Model, this location also can be described as Lambert coodinates x=3,333,857.5 feet and y=3,290,490.5 feet. The four finite-difference grid corners, expressed in Lambert feet coordinates, are:

xmin = 2,911,457.5
xmax = 3,692,897.5
ymin = 2,899,770.5
ymax = 3,681,210.5

In terms of legal location, the Cook County reference point can be expressed as the Center, West 1/4, Section 6, Township 41 North, Range 9 East. It corresponds to 42.067 degrees north latitude and 88.263 degrees west longitude.

Recharge Rates

The approximate edges of the recharge boundaries in this report are at different locations than in previous Water Survey models. Prickett and Lonnquist used column 29 and row 82 as the lines of demarcation. In fact, they placed the boundary at the edge of the Galena-Platteville, which was consistent with the traditional idea that the formation was part of the aquifer system.

In Wisconsin, Young (1976, map 13) apparently felt compelled to use the western edge of the Maquoketa Shale as a recharge boundary. For purposes of this report and to make the model more consistent with the stratigraphic constraints used in Wisconsin, the line of demarcation was subjectively shifted eastward to column 33. As a result, the western edge of the Maquoketa in the new model is more aptly described regionally as the eastern boundary of DeKalb County than it is by that of Boone County. While this is not entirely accurate, it appears to be an effective compromise.

Similarly, the southern edge of non-Maquoketa has been changed, and the new boundary is considered to be at row 70. Besides being more consistent with the geologic map,

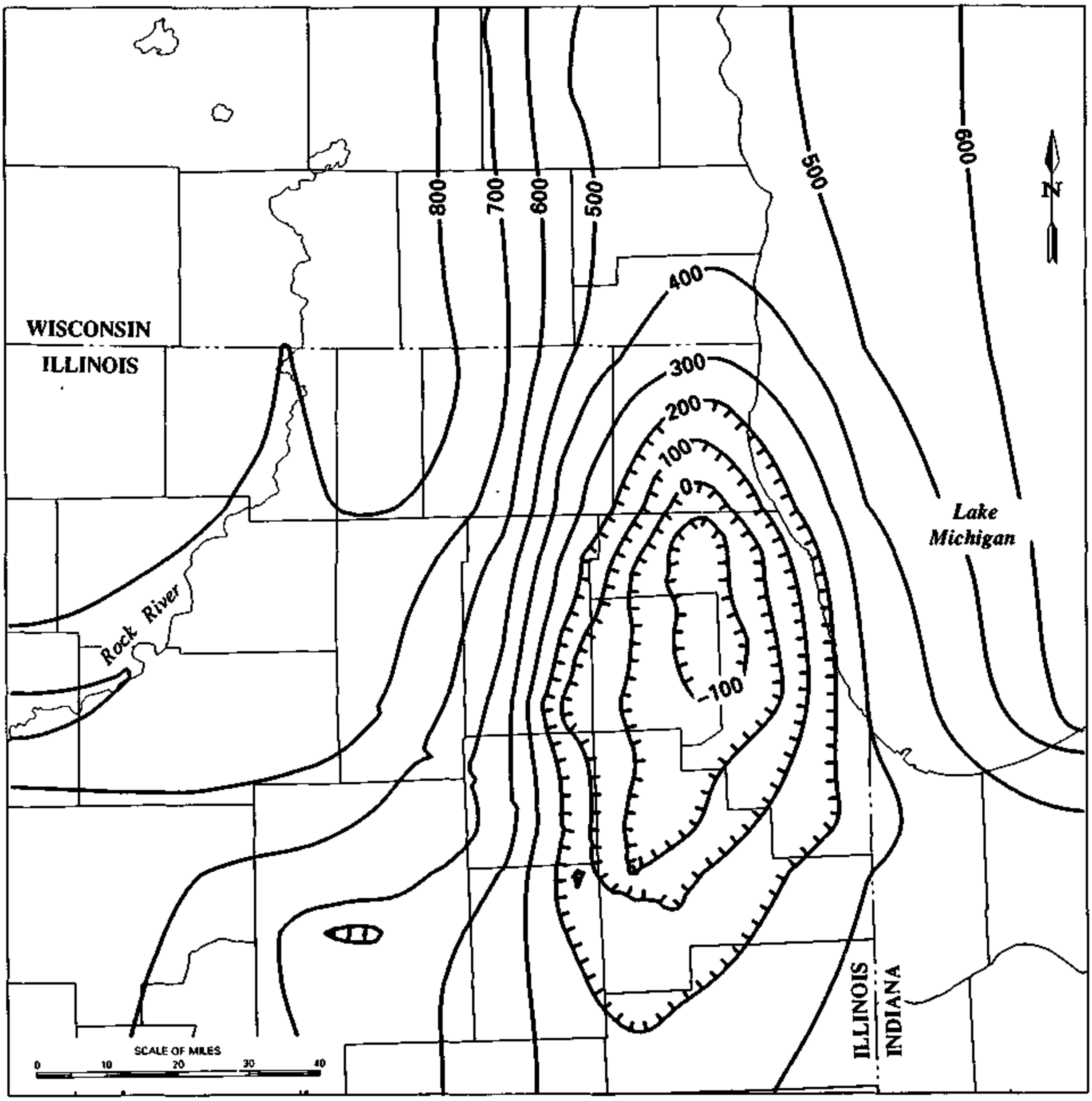


Figure 7. Calculated potentiometric surface in northeastern Illinois for 1985 (feet msl)

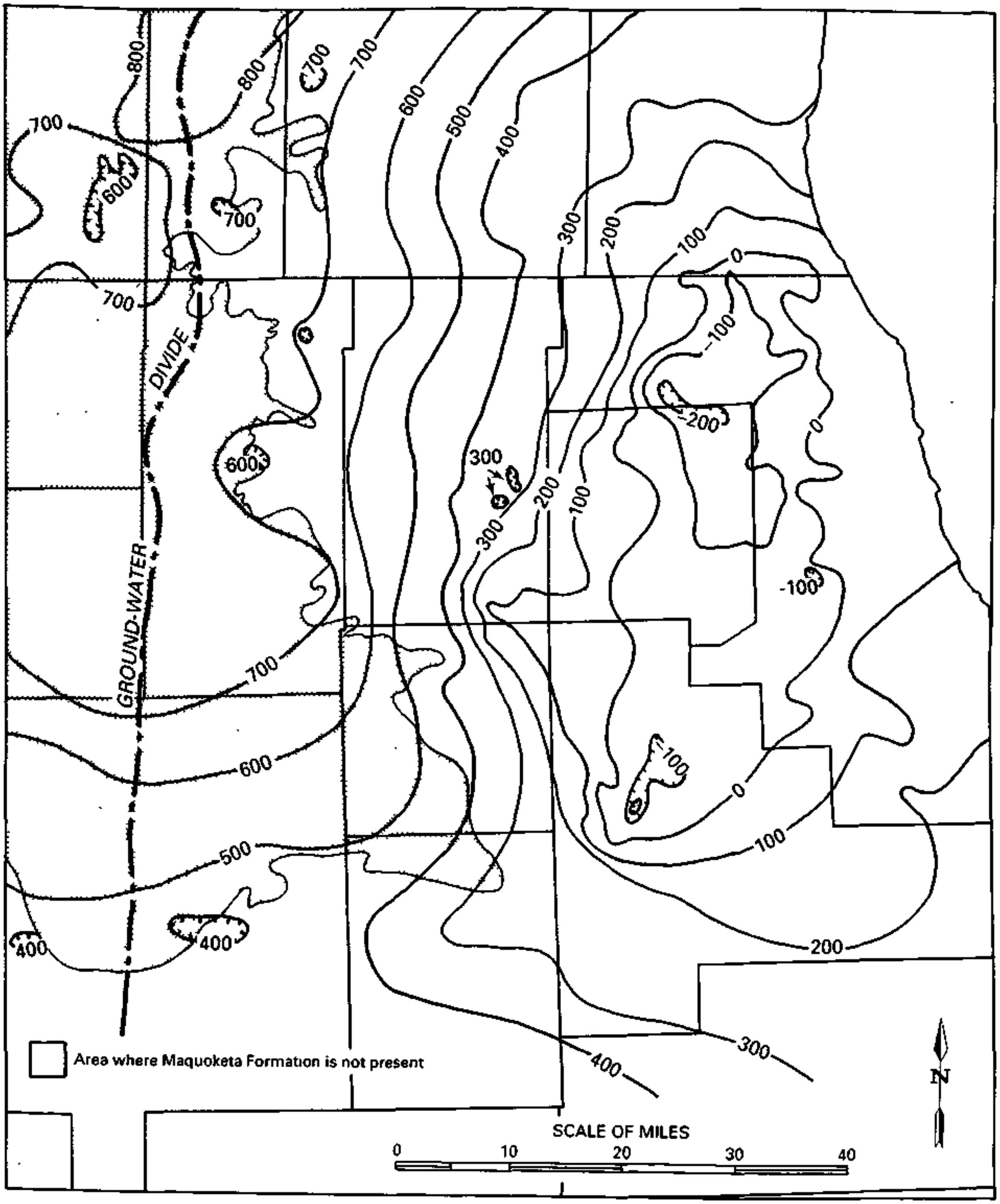


Figure 8. Observed potentiometric surface for 1985 (feet msl) in northeastern Illinois (after Sasman et at., 1986)

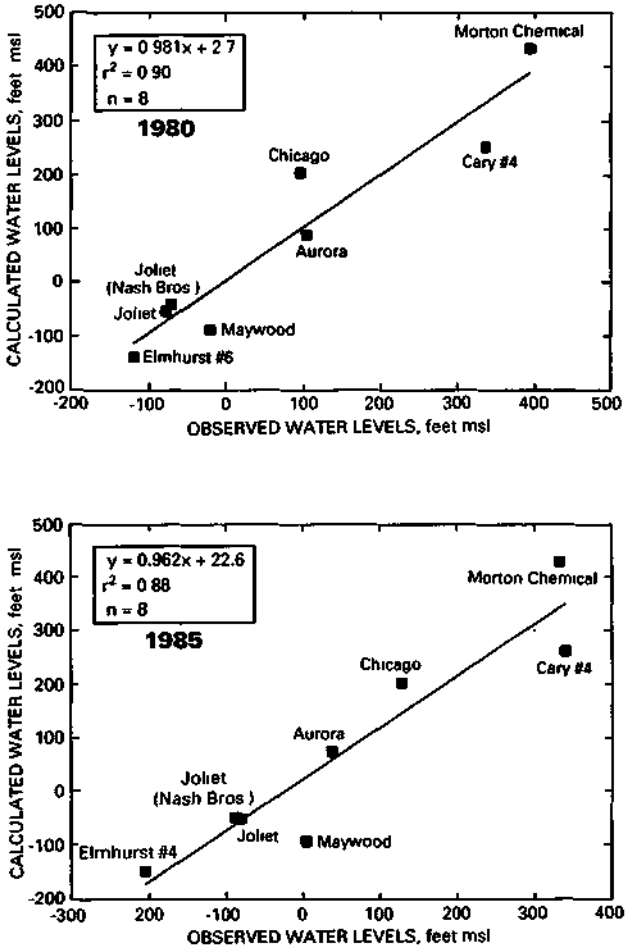


Figure 9. Comparison of calculated and observed ground-water elevations, 1980 and 1985

trial-and-error suggests that row 70 provides an adequate interval between the Rock River and the shale boundary.

Three rates of recharge were used in the New Chicago Model without reference to head difference. Their selection was based strictly on location, as illustrated by figure 11. The smallest rate, 2,100 gpd/sq mi, is assumed for areas overlain by the Maquoketa Shale, as explained previously. This value is an order of magnitude less than that used in the non-Maquoketa area defined by column 33 and row 70.

In the area where the Maquoketa is absent, two recharge rates are used. The state boundary was arbitrarily chosen as the line of demarcation between them. The Wisconsin recharge rate is 35,000 gpd/sq mi, while the Illinois rate is 30,000 gpd/sq mi. The slightly higher Wisconsin rate is designed to reflect greater occurrence of the Ironton-Galesville subcrops and the hydrogeologic connection with the lakes around Madison.

The values for recharge in the non-Maquoketa area are generally the same as those used previously. However, they are 50 percent greater than the rate Visocky et al. determined by flow-net analysis (1985). Calibration runs were made using values ranging down to 20,000 gpd/sq mi for both Illinois and Wisconsin, and the results were less than satisfactory.

Boundary Conditions

Just as a ground-water system in nature has boundaries, so must a numerical model. Conditions at model boundaries can be set to correspond to given physical processes, but the conditions at this boundary can only be estimated. Boundary conditions are generally of three types: 1) specified value, such as constant head; 2) specified flux, such as no-flow; or 3) value-dependent flux, in which flow is a function of head (Mercer and Faust, 1981). The choice of which boundary condition to specify frequently depends on the judgement of the hydrologist performing the study.

The New Chicago Model uses only two types of boundaries: specified value and specified flux. Different fluxes are specified along the perimeter of the model grid. Most frequently they are defined as zero, with two notable exceptions.

The first corresponds to the aquifer segment north of Milwaukee. A flux of 100,000 gpd/mi into the model was specified along the north boundary (row 1) of the model for columns 45 through 65. The flux value was determined by a series of trial-and-error calibration runs and calculations based on the potentiometric surface map for 1961 (Young, 1976). The hydraulic gradient between the 750 and 650 contours along the Washington-Waukesha county line was determined to be about 3×10^{-3}. Transmissivity in this area of Wisconsin was shown by Young (1976) to be about 10,000 to 15,000 gpd/ft, which results in a flux of about 158,000 to 237,000 gpd/mi. A value of 100,000 gpd/mi was selected to represent flux during calibration. This choice seems to compensate for the abnormally high ML Simon transmissivity (mentioned previously in this report) caused by modifying hydraulic conductivity to achieve calibration. Of course, were the model extended farther northward, this flux boundary would not be necessary.

The second area of nonzero flux is specified along the southern boundary (row 100) of the model for columns 60 through 80. It serves to prevent an orthogonal intersection of equipotential lines with the southern boundary of the model, particularly in Kankakee County. Experimentation during calibration runs showed that flux into the model could help shape the extreme southern end of the Chicago cone. Most of the effort focused on positioning the 100-foot water-level contour for 1985 as depicted by Sasman et al. (1986). Again a flux value can be calculated using hydraulic gradient and transmissivity. Although the gradient is smaller than at Milwaukee, a value of 100,000 gpd/mi is probably reasonable and consistent to use with the model.

Other than these two instances, zero-flux was used to specify the condition at other flux boundaries. That is, no-

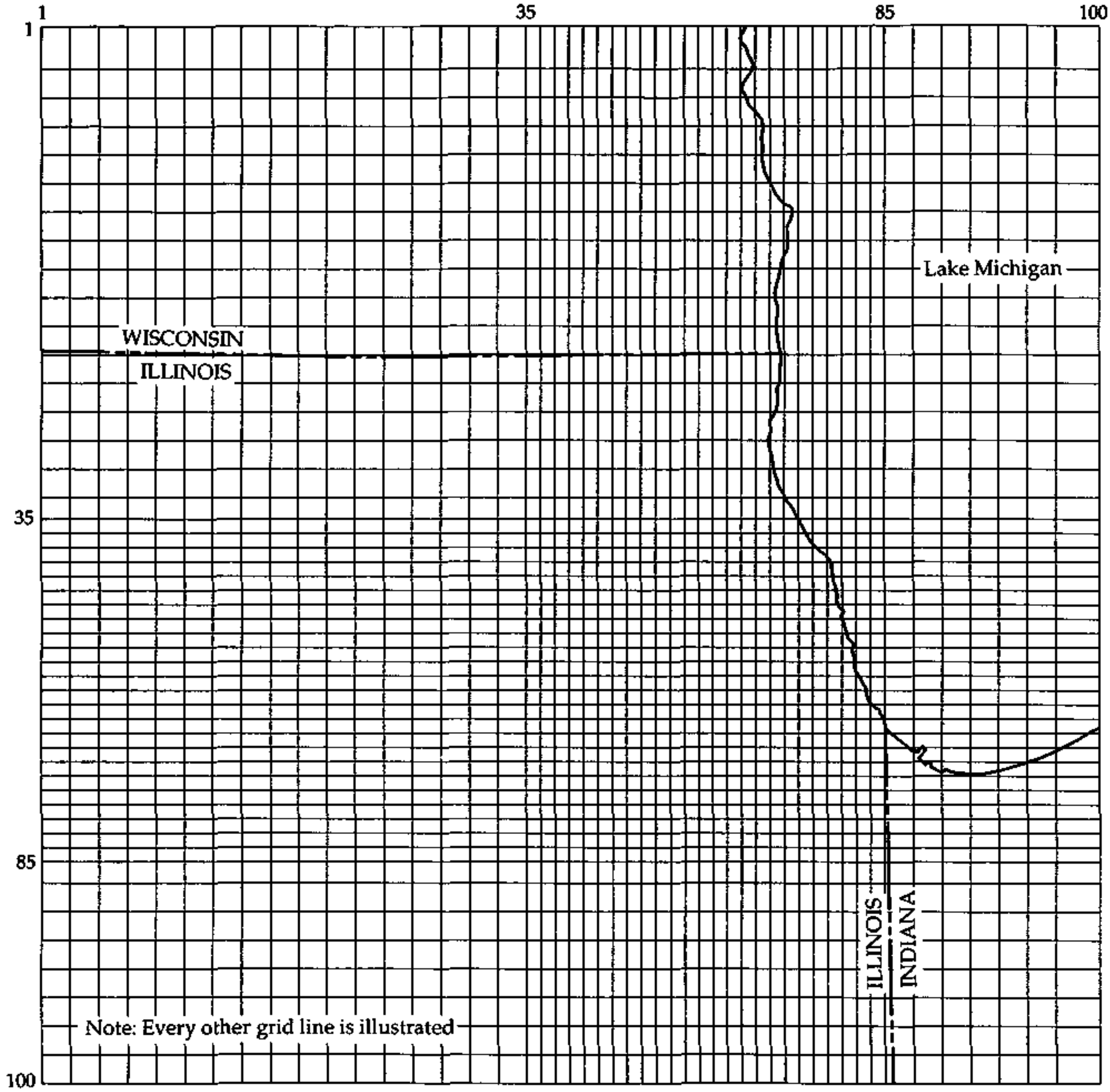


Figure 10. Finite-difference grid used with the New Chicago Model (after Prickett and Lonnquist, 1971)

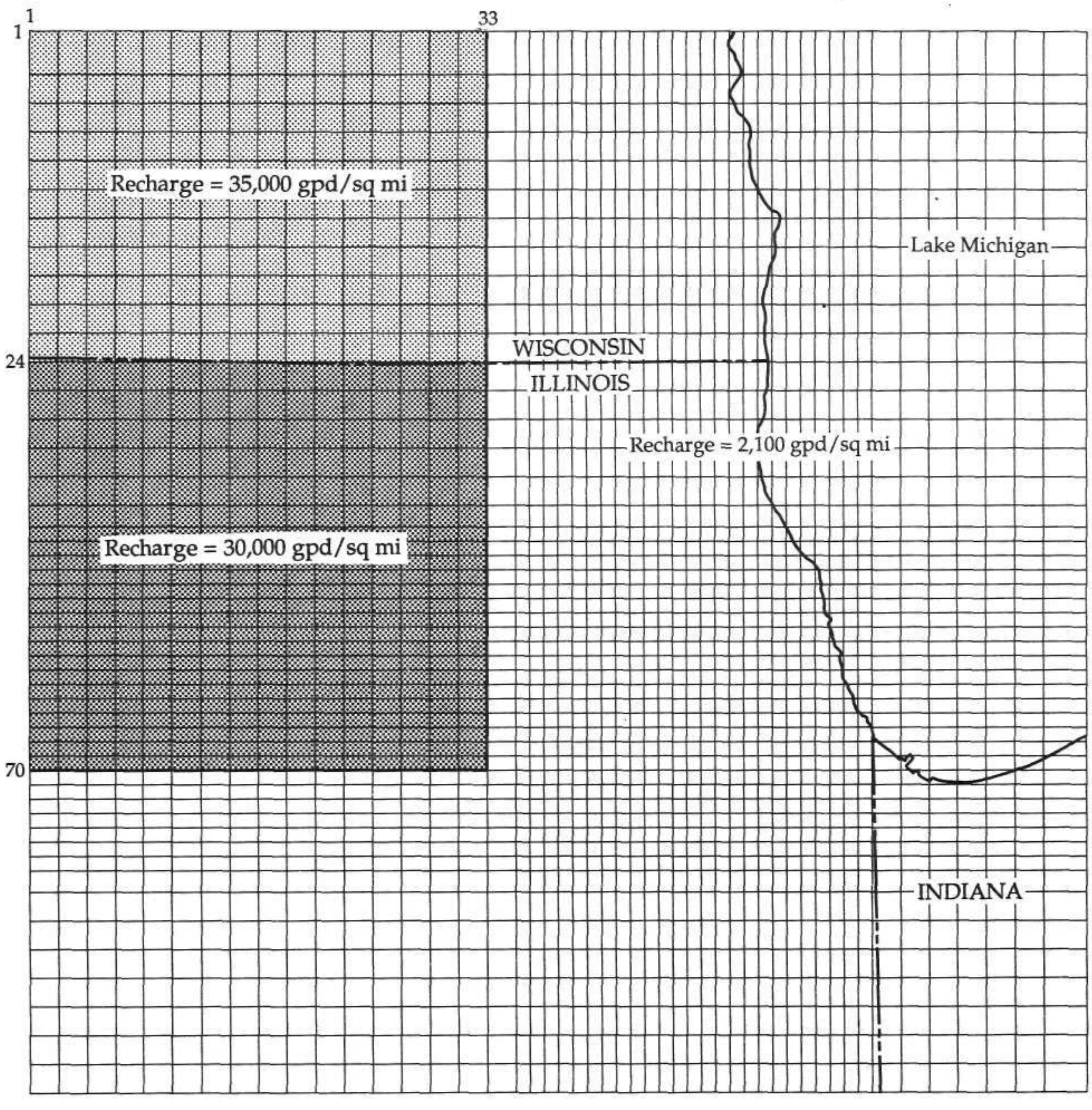


Figure 11. Recharge areas used with the New Chicago Model

flow boundaries were specified along the lower half of the western boundary (rows 36 through 100), along most of the southern boundary (columns 1 through 64 and 81 through 100), and along the lower third of the eastern boundaries (rows 66 through 100). Fewer columns along the northern edge of the model were specified as no-flow boundaries (columns 23 through 44 and 66 through 100).

Constant-head (or specified-value) boundary conditions were also used. These were applied cautiously, and frequently they coincide with permeable boundaries near large volumes of surface water connected to the aquifer system. One important constant-head boundary was intended to correspond with the recharge area in Wisconsin. Another coincides with the eastern edge of the model at Lake Michigan. A third lies within the model grid, instead of on an edge. That boundary represents the Rock River from about Janesville, Wisconsin, downstream to Rock Falls, Illinois.

The first constant-head boundary is located at column 1, rows 1 through 25; and at row 1, columns 1 through 22. In model simulations, these boundary segments serve to dissipate much of the recharge mound applied to the northwest corner of the grid.

The second constant-head boundary is a straight line corresponding to the eastern edge of the grid. It is defined in simulations as column 100, rows 1 through 65. This boundary assumption is perhaps the least likely to be represented in the physical world, because Lake Michigan is not considered to be responsible for maintaining the head condition. On the contrary, the condition is specified for convenience in constructing water-level contours. Without the constant-head boundary, the equipotential lines intersect the edge of the model in an unacceptable fashion. If data were available under the lake, then a better assumption would probably involve a flux out of the model. In the absence of these data, the next best choice is the one assumed: constant head.

The third constant-head boundary defines grid nodes corresponding to the position of the Rock River. Initially, the idea was tested by simulating high-capacity wells at some of these locations. The tests proved so successful that the source code for the simulation was modified to accomplish the constant-head condition. This was done by adding information at the beginning of the pumpage file. This information specifies the nodal location and negative values (e.g., -1) for each year of pumpage. The nodal locations representing the points at which the Rock River acts as a constant-head boundary are shown at the top of the next column.

Grid Locations Selected to Represent the Rock River

Col	*Row*	*Col*	*Row*	*Col*	*Row*	*Col*	*Row*	*Col*	*Row*
20	**20**	**20**	**27**	**18**	**37**	**12**	**49**	**6**	**61**
20	**21**	**20**	**28**	**17**	**39**	**10**	**54**	**4**	**62**
20	**22**	**20**	**29**	**16**	**41**	**11**	**54**	**2**	**63**
20	**23**	**20**	**31**	**15**	**43**	**9**	**57**		
20	**24**	**19**	**33**	**14**	**46**	**9**	**58**		
20	**25**	**19**	**34**	**13**	**46**	**8**	**59**		
20	**26**	**18**	**35**	**12**	**48**	**7**	**60**		

Storage Coefficients

During early calibration runs for this report, several values of storage coefficient were tested. In most cases, the eastern, western, and southern edges were still defined as constant-head boundaries. During calibration trials, the best approximation of the 1985 surface was determined with a coefficient of storage equal to 0.0003. This value, although greater than that used by other investigators, was used in final simulations. Satisfactory results were obtained using a water-table storage coefficient of 0.05.

Other Influences

During the calibration process, other geologic influences were also evaluated as part of the modeling effort. They sought to simulate the interaction of ground water and surface water near Ottawa, the effects caused by the Sandwich . Fault, and the impact of erosion on transmissivity near the fault.

Ottawa Cone of Depression

Geologic maps indicate that the Cambrian-Ordovician aquifer system outcrops along the Illinois River between Ottawa and LaSalle-Peru. Therefore, the potential exists for either discharge or recharge, depending on head conditions. The area has frequently been contoured as a depression on potentiometric maps, so the first assumption was that a discharge boundary could be present.

Hoover and Schicht (1967) summarized ground-water development along the Illinois River between Ottawa and LaSalle-Peru. They found that a water-level trough occurs along the river, and associated with it is a pronounced cone of depression centered at Ottawa. Because LaSalle is not one of the eight Illinois counties whose pumpage was included in the model, the area stymied many calibration runs. The problem was finally rectified by arbitrarily assuming pumpage at six nodes within the model grid. That pumpage was assumed to be 6 mgd along row 89 at columns 21 through 26.

Sandwich Fault

The Sandwich Fault was modeled as a line of zero transmissivity because of displacement and presumed recementation along the fault plane. The structural feature may actually be a system of two or more faults

(Buschbach, 1964). Figure 12 illustrates how the fault trends southeast from a point in DeKalb County into Will County. Displacement along the fault is slightly greater than 100 feet, although it appears to diminish at the easternmost extent Its simulation in calibration runs had almost no effect on water levels because the regional flow direction is virtually parallel to the fault trace. If the prevailing direction of ground-water flow were at right angles to the fault, then its impact would be more important. The arbitrary value of zero transmissivity along the trace of the fault does provide a slight kink in the calculated water-level contours. Although the Sandwich Fault has little bearing on regional flow, its inclusion does serve to add an aesthetic quality to the map.

Erosion of the St. Peter Sandstone along the Sandwich Fault

The Sandwich Fault and to a lesser extent the Ashton Arch have brought the St. Peter Sandstone to the surface and subjected it to erosion. As a result, the St. Peter is absent in some areas southwest of the fault (Visocky et al., 1985). More than 250 grid nodes were selected to outline that area (figure 12). The selection was based on an enlarged overlay of the map shown by Visocky et al. (1985, figure 15).

The elevation data provided as input to the model set the top elevation of this layer equal to its own bottom elevation. Thus its thickness is considered to be zero for transmissivity calculations.

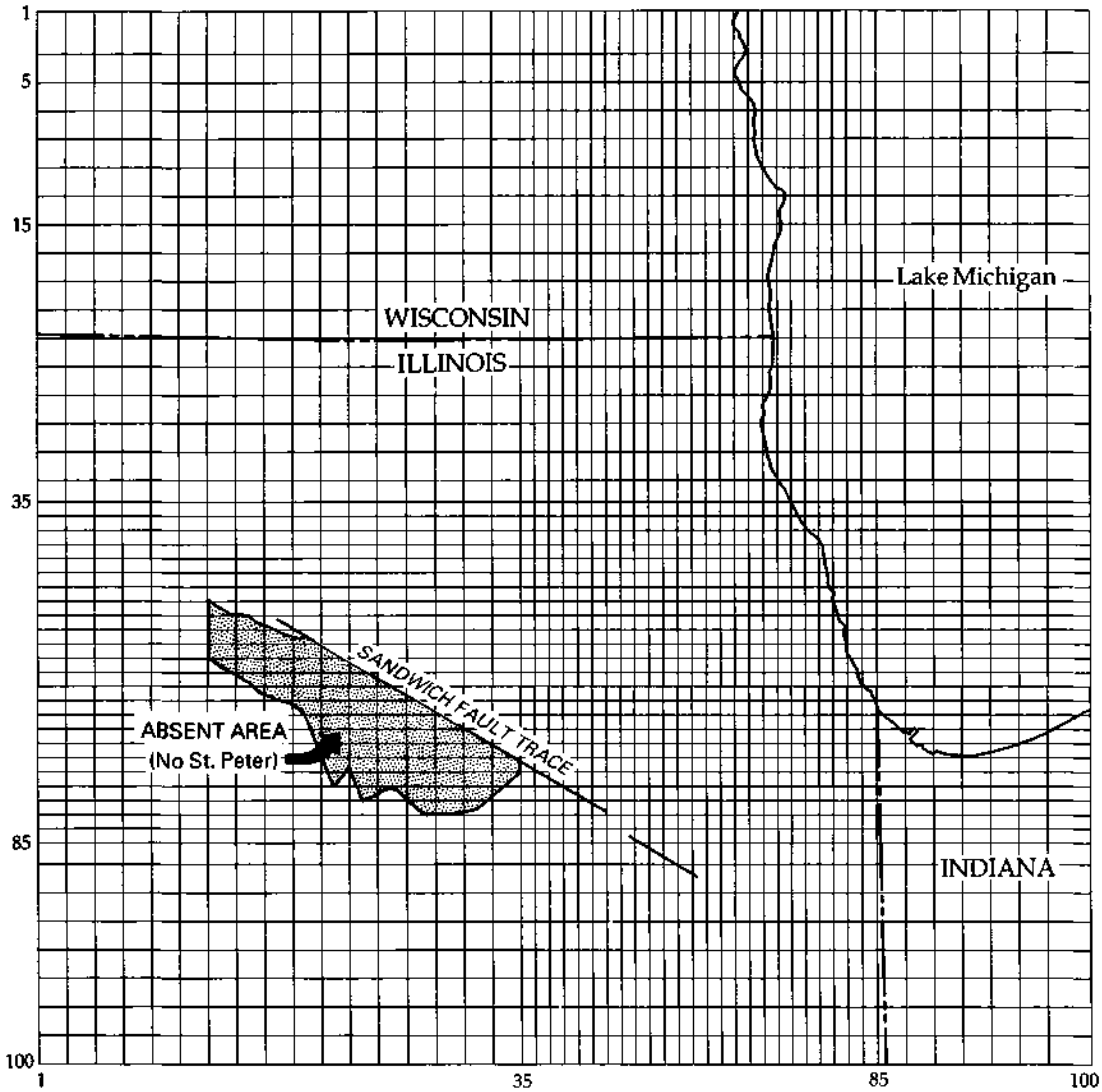


Figure 12. The model grid showing the trace of the Sandwich Fault and the area in which the St. Peter Sandstone is absent

4. ACTUAL MODEL SIMULATION: FORECAST DEVELOPMENT AND APPLICATION

The New Chicago Model was established as a tool for predicting future ground-water levels. It accurately represents the hydrogeologic system and has demonstrated its capability during the calibration process. It is now ready to simulate future water levels.

The Cambrian-Ordovician aquifer system will respond to future pumpage demands in northeastern Illinois. Therefore, the model user has only to input pumpage forecasts, and the model will calculate corresponding water levels. Specifically, the model makes use of data describing *where* the pumpage will occur, *how much* will occur, and *when* it will occur. The more accurate these data are, the more accurate the predictions will be.

Special Considerations

Because the goal of this investigation has been to determine the impact of the delivery of Lake Michigan water to DuPage and Lake Counties, two simulations were made: one assumed the delivery of lake water in 1992, and the other assumed there would be no delivery. It follows then that the difference in future ground-water levels will represent the impact of the delivery.

Forecasting the amount and location of water demand is an inexact science. Simple forecasts dependent upon variables such as population, economic factors, and other measurable criteria can be made for public water supply demands. But they fail to portray the exact quantity that will be needed from any particular aquifer system.

To be successful, the most effective method should acknowledge that some facilities obtain water from multiple ground-water sources. Some, such as the city of Elgin, might even use combined surface and ground-water sources. The new forecasting method also should recognize the impact of regulations for drinking water quality. For example, to meet the standards for radium in their drinking water, some communities are planning to blend waters. The result, therefore, might be decreased pumpage from the Cambrian-Ordovician aquifer, even though water demand is increasing. Consequently, forecasts extend only to the year 2010, ensuring greater reliability and accommodating the complexity of some situations.

Forecast Development

Forecasts of ground-water demand were made for both Wisconsin and the eight-county Chicago region. Actual observations for 1986 and 1987 were used in Illinois, and predictions were made for the period 1988 through 2010. Predictions for Wisconsin pumpage were made for the entire period of 1986 through 2010. In Illinois, corrections were made to factor out contributions to wells penetrating the Mt. Simon aquifer (Suter et al., 1959).

Demand forecasts were developed on the basis of trends at each facility utilizing the Cambrian-Ordovician aquifer. This differs from the individual well approach used during model calibration. Predicting future pumpage facility by facility was intended to compensate for such unknown variables as downtime for well maintenance, the fact that some old wells might be abandoned, and that new wells might be drilled at new locations.

Future well locations were determined simply by averaging the Lambert coordinates for each well at each of the 289 Illinois facilities. One or two wells would usually describe a public water supply. But in some cases, such as for the city of Elmhurst, nine wells might be needed to describe an average location for the facility. Any inaccuracies caused by averaging locations were considered tolerable, especially because pumpage forecasts would subsequently be distance-weighted to the appropriate grid-cell comers.

No adjustments were made for future Wisconsin pumpage locations. The latitudes and longitudes provided by the USGS in Madison, which were used to describe pumpage locations from 1964 through 1985, were used to make future estimates. The inaccuracies caused by this procedure were judged to be negligible in relation to our goal of describing recoveries for the Chicago pumping cone.

Application of the Forecasts to Model Simulations

Initial Estimate and Variables

The first approximation of future water demand was made using a simple linear regression. Time, which was measured in years for the period 1964 through 1987, was used as the independent variable, X. Annual summations of the pumpage reported to the Water Survey were used as the dependent variable, Y. The resulting prediction failed to show the decline in pumpage observed in the early 1980s by Sasman et al. (1986) because the data were not linear.

An inspection of the data revealed that the nonlinearity existed because of imposed pumping restrictions and/or sudden conversions to Lake Michigan water by many Cook County communities. It was obvious that an accurate forecast would have to be constructed facility by facility.

A special QuickBASIC program was written to display the corresponding pairs of X and Y values on a color monitor. Regression lines were determined for pumpage and displayed with the observed data at each Illinois facility using the Cambrian-Ordovician aquifer. Corrections were made for missing data, and subjective interpretations were imposed on some of the 289 predictions. These judgements typically involved holding industrial pumpages at 1987 levels. A few impositions were made on public water supplies for cases in which planners are attempting to meet radium standards by switching part of their demand to surface water.

Forecasts with Revised Pumpage Patterns

Conversion to lake water. In 1992, another 42 of the 289 facilities that have traditionally used the Cambrian-Ordovician aquifer are scheduled to switch to Lake Michigan water. When they do switch, the Illinois demand on the Cambrian-Ordovician aquifer system is expected to decline by about 34.7 mgd. This decline will extend the trend established during the 1980s (figure 13).

Table 1 lists total pumpages used in model simulations and makes an approximate distinction between Illinois and Wisconsin. The historical pumpage and demand forecast for Wisconsin are shown as figure 14.

Other pumpage changes. Additional changes in Illinois pumpage patterns will likely occur during the simulation period (1986 through 2010). The most notable change will occur when the Joliet and Wilmington public water supply systems shift their pumpage from ground water to the Kankakee River.

Decreases in pumpage from the Cambrian-Ordovician aquifer are also anticipated at Aurora, Batavia, Geneva, Montgomery, North Aurora, and Crystal Lake. A few communities are expected to hold their Cambrian-Ordovician

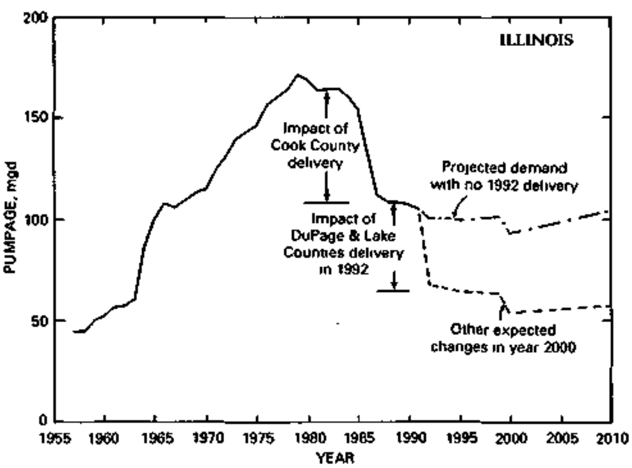


Figure 13. Impact of Lake Michigan water deliveries on Cambrian-Ordovician pumpage in northeastern Illinois: actual and forecast

Table 1. Summary of Annual Pumpage Used in Simulations, 1957-2010 (mgd)

Year	*Illinois, with lake delivery*	*Illinois, without lake delivery*	*Wisconsin Qs*
1957	44.30	44.30	36.06
1958	44.70	44.70	34.43
1959	50.20	50.20	36.24
1960	52.30	52.30	39.68
1961	56.40	56.40	39.74
1962	57.30	57.30	38.35
1963	60.50	60.50	40.99
1964	86.13	86.13	36.35
1965	99.91	99.91	37.36
1966	107.67	107.67	36.41
1967	105.48	105.48	42.24
1968	109.12	109.12	43.73
1969	112.92	112.92	45.10
1970	114.90	114.90	46.14
1971	124.76	124.76	46.38
1972	130.80	130.80	47.91
1973	139.20	139.20	45.98
1974	143.07	143.07	47.48
1975	145.80	145.80	46.48
1976	156.08	156.08	45.83
1977	159.93	159.93	44.28
1978	164.04	164.04	47.26
1979	171.28	171.28	48.78
1980	168.63	168.63	44.40
1981	163.78	163.78	42.64
1982	164.37	164.37	41.72
1983	164.33	164.33	41.22
1984	160.12	160.12	41.64
1985	153.56	153.56	42.74
1986	128.90	128.90	51.34
1987	111.67	111.67	52.45
1988	108.36	108.36	53.58
1989	108.14	108.14	54.72
1990	107.02	107.02	55.87
1991	104.94	104.94	57.04
1992	67.33	100.41	58.21
1993	66.52	100.37	59.44
1994	65.56	100.17	60.69
1995	64.21	99.58	61.99
1996	63.91	100.05	63.32
1997	63.66	100.57	64.64
1998	63.42	101.09	65.97
1999	63.20	101.63	67.30
2000	53.98	93.18	68.62
2001	54.29	94.26	69.96
2002	54.62	95.35	71.30
2003	54.99	96.48	72.67
2004	55.35	97.61	74.04
2005	55.72	98.74	75.41
2006	56.09	99.88	76.78
2007	56.45	101.01	78.16
2008	56.82	102.14	79.53
2009	57.19	103.27	80.91
2010	57.55	104.41	82.29

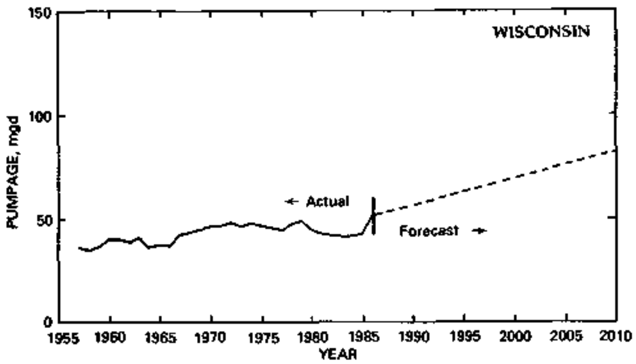


Figure 14. Impact of Lake Michigan water delivery on deep sandstone pumpage in southeastern Wisconsin: actual and forecast

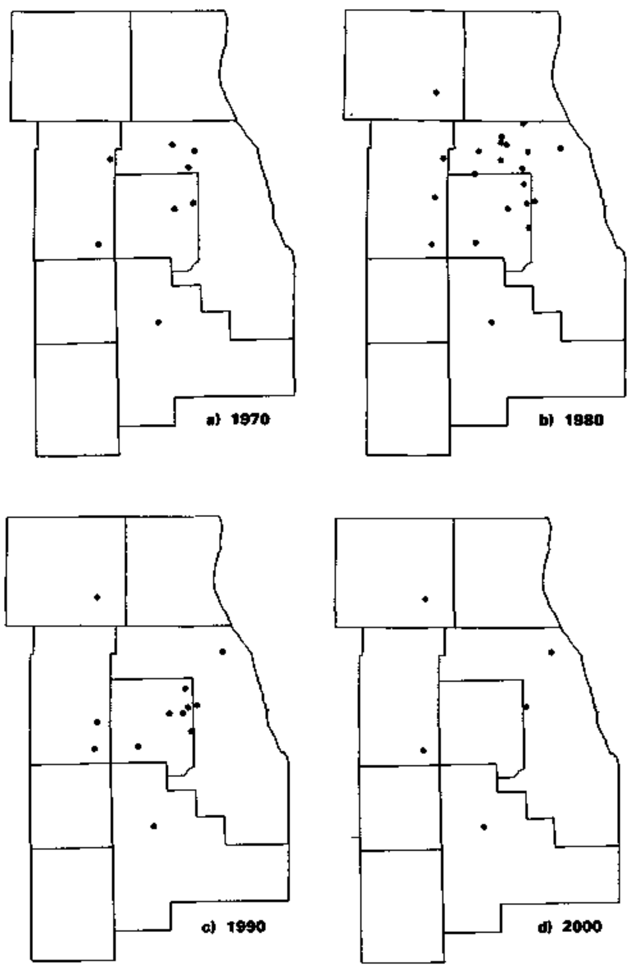


Figure 15. Pumping centers in northeastern Illinois withdrawing more than 2 million gallons per day from the Cambrian-Ordovician system, 1970 to 2000

pumpage steady at present levels and meet future growth from shallower aquifers. These communities include Sugar Grove, Cary, and Rockdale.

As a result of these expectations, Cambrian-Ordovician pumpage in northeastern Illinois is expected to fall below the practical sustained yield of the aquifer. If this occurs, it will mark the first time since the late 1950s. However, the pumping center locations will move much further west than those observed previously.

Decrease in the Number of Illinois Pumping Centers

In the next century, the locations of ground-water pumping centers will differ significantly from the pattern observed in the twentieth century. Not only will decreased demand affect the shape of the Chicago pumping cone, but it will modify the locations of the centers. Earlier reports (Suter et al., 1959; Schicht et al., 1976) clearly stated that such movement would enhance the practical sustained yield of the aquifer.

The movement of the pumping centers, however, is less important than the number of centers. This is obvious from a spatial comparison (figure 15) of centers whose pumpage exceeds 2.0 mgd. Public water supplies withdrawing more than 2.0 mgd for the years 1960, 1970, 1980, 1990, and 2000 are listed in table 2, which shows that the number of pumping centers withdrawing more than 2.0 mgd peaked in about 1980.

Tables 3 and 4 summarize demands for public water supply, industrial use, and irrigation periodically from 1985 through 2010. These values, as well as those for the intervening years, were used in the final simulations for this report. Decreased pumpage in Cook and DuPage Counties (table 4) was clearly the most significant change in demand upon the Cambrian-Ordovician aquifer.

Table 2. Illinois Public Water Supply Centers Withdrawing More than 2.0 Million Gallons per Day, 1960-2000

1960	*1970*	*1980*	*1990*	*2000*
Aurora	Arlington Hts.	Arlington Hts.	Aurora	Aurora
Chicago	Aurora	Aurora	Batavia	Crystal Lake
Des Plaines	Elk Grove	Bellwood	Bellwood	Joliet
Elgin	Elgin	Bensonville	Bensenville	Elmhurst
Elmhurst	Buffalo Grove	Crystal Lake	Crystal Lake	
Joliet	Joliet	Crystal Lake	Elmhurst	
	Lombard	Elgin	Joliet	
	Mt. Prospect	Elk Grove	Lombard	
		Elmhurst	Naperville	
		Hanover Park	*North Suburban	
		Hoffman Est.	Oak Brook	
		Joliet	Villa Park	
		Lombard		
		Mt. Prospect		
		Naperville		
		*North Suburban		
		Northern Aire Est.(Palatine)		
		Oak Brook		
		Rolling Meadows		
		St. Charles		
		Schaumburg		

*Public utility.

Table 3. Selected Estimates for Illinois Public Water Supply Pumpage Demands, 1985-2010 (mgd)

Facility name	*1985*	*1990*	*1992*	*1995*	*2000*	*2005*	*2010*
Cook County							
Arlington Hts.	5.40	0.00	0.00	0.00	0.00	0.00	0.00
Bartlett	0.52	0.54	0.59	0.67	0.80	0.94	1.07
Bellwood	3.53	2.69	0.00	0.00	0.00	0.00	0.00
Buffalo Grove	1.86	0.01	0.01	0.01	0.01	0.01	0.01
Chicago Suburban Utility Co.	1.84	0.00	0.00	0.00	0.00	0.00	0.00
Citizens Waycinden Div.	0.66	0.00	0.00	0.00	0.00	0.00	0.00
Citizens Fernway Util.	0.00	0.00	0.00	0.00	0.00	0.00	0.00
City of Chicago Hts.	2.06	0.00	0.00	0.00	0.00	0.00	0.00
Des Plaines	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Des Plaines Mobile Home Park	0.01	0.03	0.03	0.03	0.03	0.03	0.03
Divine Word Seminary	0.01	0.02	0.02	0.02	0.02	0.02	0.02
East Chicago Hts. Utility Corp	0.92	0.00	0.00	0.00	0.00	0.00	0.00
Elk Grove Village	6.82	0.00	0.00	0.00	0.00	0.00	0.00
Flossmoor	0.43	0.00	0.00	0.00	0.00	0.00	0.00
Glenview	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Glenwood	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hanover Park	2.41	0.00	0.00	0.00	0.00	0.00	0.00
Hickory Hills	0.38	0.17	0.00	0.00	0.00	0.00	0.00
Hoffman Estates	2.00	0.00	0.00	0.00	0.00	0.00	0.00
Homewood	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LaGrange	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lemont	0.56	0.73	0.74	0.75	0.77	0.79	0.81
Lynwood #3	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lyons	0.74	0.00	0.00	0.00	0.00	0.00	0.00
Mission Brook Sanitary Dist.	0.21	0.00	0.00	0.00	0.00	0.00	0.00
Mt. Prospect	4.60	0.00	0.00	0.00	0.00	0.00	0.00
North Suburban Public Utility	2.91	1.90	0.00	0.00	0.00	0.00	0.00
Northern Aire Estates	2.85	0.00	0.00	0.00	0.00	0.00	0.00
Orland Park	0.34	0.00	0.00	0.00	0.00	0.00	0.00
Plum Creek Condominiums	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Prospect Heights	0.05	0.14	0.14	0.14	0.14	0.14	0.14
Richton Park	0.18	0.33	0.38	0.46	0.58	0.71	0.83
Riverside	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rolling Meadows	2.91	0.00	0.00	0.00	0.00	0.00	0.00
Schaumburg	4.56	0.00	0.00	0.00	0.00	0.00	0.00
South Chicago Hts.	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Streamwood	0.64	0.00	0.00	0.00	0.00	0.00	0.00
Thornton	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Touhy Mobile Homes	0.07	0.06	0.06	0.06	0.06	0.06	0.06
Western Springs	1.39	1.26	1.28	1.31	1.36	1.41	1.46
Wheeling	2.24	0.01	0.00	0.00	0.00	0.00	0.00
Subtotals	53.15	7.94	3.30	3.50	3.82	4.16	4.48
DuPage County							
Bensenville	2.71	2.86	0.00	0.00	0.00	0.00	0.00
Bloomingdale	0.99	1.35	0.00	0.00	0.00	0.00	0.00
Carol Stream	1.27	0.95	0.00	0.00	0.00	0.00	0.00
Clarendon Hills	0.66	0.69	0.00	0.00	0.00	0.00	0.00
Darien	0.50	0.63	0.00	0.00	0.00	0.00	0.00

Table 3. (Continued)

Facility name	*1985*	*1990*	*1992*	*1995*	*2000*	*2005*	*2010*
DuPage County (continued)							
Elmhurst	4.89	4.66	0.00	0.00	0.00	0.00	0.00
Ill. Benedictine College	0.03	0.04	0.05	0.05	0.05	0.06	0.06
Lombard	3.92	3.62	0.00	0.00	0.00	0.00	0.00
Naperville	3.17	3.71	0.00	0.00	0.00	0.00	0.00
Oak Brook	3.57	4.24	0.00	0.00	0.00	0.00	0.00
Ovaltine Food	0.14	0.00	0.00	0.00	0.00	0.00	0.00
Roselle	0.65	0.00	0.00	0.00	0.00	0.00	0.00
Rosewood Trace	0.35	0.39	0.00	0.00	0.00	0.00	0.00
Villa Park	2.11	2.19	0.00	0.00	0.00	0.00	0.00
West Chicago	1.23	1.68	1.68	1.68	1.68	1.68	1.68
Westmont	1.93	1.89	0.00	0.00	0.00	0.00	0.00
Willowbrook	0.78	1.11	0.00	0.00	0.00	0.00	0.00
Wood Dale	0.07	0.35	0.00	0.00	0.00	0.00	0.00
Subtotals	28.97	30.36	1.73	1.73	1.73	1.74	1.74
Grundy County							
Bookwalter Woods Mobile Homes	0.01	0.03	0.03	0.03	0.03	0.03	0.03
Braceville	0.04	0.05	0.05	0.05	0.06	0.07	0.08
Carbon Hill	0.03	0.04	0.04	0.05	0.05	0.06	0.06
Coal City	0.38	0.41	0.44	0.48	0.54	0.61	0.68
Diamond	0.05	0.10	0.10	0.10	0.10	0.10	0.10
Gardner	0.10	0.09	0.10	0.10	0.11	0.12	0.13
Grundy County Home	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Heatherfield Subdivision	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Kinsman	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Minooka	0.20	0.24	0.26	0.28	0.33	0.37	0.41
Morris	1.09	1.16	1.18	1.20	1.24	1.28	1.31
Morris Country Club	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ridgecrest Utility Co.	0.02	0.02	0.02	0.02	0.02	0.02	0.02
South Wilmington	0.09	0.10	0.10	0.11	0.13	0.14	0.16
Subtotals	2.03	2.26	2.34	2.44	2.63	2.82	3.00
Kane County							
Aurora	10.37	9.90	8.94	7.66	3.02	3.37	3.71
Batavia	2.20	2.05	1.66	0.91	0.99	1.07	1.15
Breazeale Mobile Home Park	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Broadview Academy	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Burlington	0.06	0.05	0.05	0.05	0.05	0.05	0.05
Elburn	0.10	0.15	0.18	0.23	0.31	0.40	0.48
Elgin	3.65	1.42	1.46	1.52	1.63	1.73	1.83
Elgin Mental Health Center	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Geneva	1.91	1.90	1.90	1.90	1.90	1.90	1.90
Hampshire	0.16	0.28	0.29	0.30	0.32	0.34	0.37
Ill. Youth Center-St. Charles	0.11	0.15	0.15	0.15	0.15	0.15	0.15
Maple Park	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Margaret's Hi Acre Mobile Homes	0.02	0.03	0.03	0.03	0.03	0.03	0.03
Montgomery	1.34	1.67	0.90	1.01	1.02	1.02	1.02
Mooseheart Governors	0.18	0.14	0.14	0.14	0.14	0.14	0.14
North Aurora	0.99	1.00	1.00	1.00	0.00	0.00	0.00
St. Charles	1.89	1.67	1.67	1.67	1.68	1.68	1.69

Table 3. (Continued)

Facility name	*1985*	*1990*	*1992*	*1995*	*2000*	*2005*	*2010*
Kane County (continued)							
Sugar Grove	0.01	0.02	0.02	0.02	0.02	0.02	0.02
West Dundee	0.02	0.00	0.00	0.00	0.00	0.00	0.00
Subtotals	23.09	20.51	18.47	16.67	11.34	11.98	12.62
Kendall County							
Farm Colony	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fox Lawn Utility Co.	0.02	0.03	0.03	0.03	0.04	0.04	0.05
Hollis Park Subdivision	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Newark	0.08	0.07	0.07	0.08	0.09	0.10	0.11
Oswego	0.31	0.36	0.38	0.41	0.46	0.51	0.56
Valley Water Co.	0.12	0.13	0.13	0.13	0.13	0.13	0.13
Yorkville	0.37	0.42	0.46	0.51	0.60	0.69	0.78
Subtotals	0.91	1.02	1.08	1.17	1.33	1.48	1.64
Lake County							
Colonial Park Apartments	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Commonwealth Edison Dist. Ofc.	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Countryside Manor Subdivision	0.05	0.02	0.02	0.02	0.02	0.02	0.02
Fox Lake	0.38	0.22	0.22	0.22	0.22	0.22	0.22
Grayslake	0.20	0.21	0.00	0.00	0.00	0.00	0.00
Gurnee	0.42	0.30	0.00	0.00	0.00	0.00	0.00
Heiden Gardens Condominiums	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Lake Barrington Shores Estates	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lake View Trailer Park	0.04	0.04	0.04	0.04	0.05	0.05	0.05
Lake Zurich	1.20	1.56	1.63	1.75	1.93	2.12	2.31
Libertyville	0.15	0.25	0.00	0.00	0.00	0.00	0.00
Lincolnshire	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mundelein	1.38	0.00	0.00	0.00	0.00	0.00	0.00
Park City Mobile Homes	0.10	0.13	0.13	0.13	0.13	0.13	0.13
Round Lake	0.10	0.15	0.00	0.00	0.00	0.00	0.00
Round Lake Beach	0.00	0.51	0.00	0.00	0.00	0.00	0.00
Shoreline Terrace Mobile Homes	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Vernon Hills	1.25	1.42	0.00	0.00	0.00	0.00	0.00
Wadsworth Oaks Subdivision	0.01	0.02	0.02	0.02	0.02	0.02	0.02
Wauconda	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Wildwood Subdivision	0.56	0.07	0.00	0.00	0.00	0.00	0.00
Winthrop Harbor	0.23	0.00	0.00	0.00	0.00	0.00	0.00
Subtotals	6.19	5.02	2.18	2.30	2.49	2.68	2.87
McHenry County							
Algonquin	0.07	0.00	0.00	0.00	0.00	0.00	0.00
Arnold Engineering	0.14	0.16	0.16	0.16	0.16	0.17	0.17
Cary	0.49	0.10	0.10	0.10	0.10	0.10	0.10
Crystal Lake	2.64	2.28	1.36	1.45	1.59	1.74	1.89
Lake-in-the-Hills	0.05	0.04	0.04	0.04	0.04	0.04	0.04
Subtotals	3.39	2.58	1.66	1.75	1.89	2.05	2.20

Table 3. (Concluded)

Facility name	*1985*	*1990*	*1992*	*1995*	*2000*	*2005*	*2010*
Will County							
Braidwood	0.39	0.40	0.41	0.44	0.47	0.51	0.55
Camelot Subd.	0.04	0.05	0.05	0.06	0.07	0.08	0.09
Channahon	0.01	0.02	0.03	0.03	0.03	0.04	0.04
Imperial Trailer Park	0.03	0.02	0.02	0.02	0.02	0.02	0.02
Joliet	9.38	9.62	9.35	8.94	3.15	3.15	3.15
Joliet Correctional Center	0.26	0.27	0.27	0.27	0.27	0.27	0.27
Lakewood Shores Subdivision	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Lewis College	0.05	0.03	0.03	0.03	0.03	0.03	0.03
Lockport	1.03	0.97	0.98	0.00	0.00	0.00	0.00
Plainfield	0.59	0.70	0.76	0.86	1.02	1.18	1.33
Rockdale	0.47	0.34	0.34	0.34	0.34	0.34	0.34
Romeoville	0.79	0.73	0.75	0.77	0.82	0.86	0.90
Stateville Correctional Center	0.60	0.32	0.20	0.02	0.00	0.00	0.00
Will County Water Co.	0.00	0.05	0.05	0.05	0.05	0.05	0.05
Wilmington	0.62	0.59	0.30	0.00	0.00	0.00	0.00
Subtotals	14.31	14.16	13.59	11.88	6.32	6.58	6.82
Public Water Supply Totals	132.04	83.85	44.35	41.44	31.55	33.49	35.37

Note: Data have been rounded to the nearest one-hundredth.

Table 4. Summary of Industrial, Irrigation, and Public Water Supply Pumpage Demands in the Chicago Region, 1985-2010 (mgd)

Type of pumpage	*1985*	*1990*	*1992*	*1995*	*2000*	*2005*	*2010*
Industrial							
Cook County	8.64	6.61	6.61	6.61	6.61	6.61	6.61
DuPage County	0.04	0.02	0.02	0.02	0.02	0.02	0.02
Grundy County	7.24	7.93	7.83	7.69	7.46	7.38	7.38
Kane County	0.14	0.11	0.11	0.11	0.11	0.11	0.11
Kendall County	0.90	0.52	0.52	0.52	0.52	0.52	0.52
Lake County	0.80	0.87	0.88	0.91	0.95	0.99	1.03
McHenry County	0.79	0.70	0.70	0.70	0.70	0.70	0.70
Will County	6.31	5.55	5.43	5.33	5.17	5.05	4.95
Subtotals	24.87	22.30	22.10	21.89	21.54	21.39	21.32
Irrigation							
Subtotals	0.82	0.86	0.86	0.86	0.86	0.86	0.86
Public Water Supply							
Subtotals	132.04	83.85	44.35	41.44	31.55	33.49	35.37
Totals	157.73	107.01	67.31	64.19	53.95	55.74	57.55

Note: Data have been rounded to the nearest one-hundredth.

5. RESULTS OF MODEL SIMULATION

This investigation was intended to predict future ground-water levels in northeastern Illinois. Those predictions were produced by computer simulations based upon assumptions about future demands on the Cambrian-Ordovician aquifer. The aquifer system will respond according to hydrologic principles, and the model has attempted to duplicate them mathematically. Computation of the 1985 water-level surface has been used to verify the model's capabilities. Based on that success, the model should be able to predict future water levels. This section discusses the potentiometric surfaces predicted by the model and the differences among them.

Digital Water-Level Map Preparation

The New Chicago Model code determines water level, or head, at each node of an irregularly spaced, 100 by 100-node grid as described by Prickett and Lonnquist. Like the original version, the new model is referenced from the upper left corner. As a result, the numerical calculations are output sequentially by column and row. That is, head values are output first for row 1, columns 1 through 100; then for row 2; and so on. In a sense, this represents the fourth quadrant of a Cartesian coordinate system.

The geographic coordinate system used to locate wells, county boundaries, and other features, however, is based on a first-quadrant assumption. That is, the reference point is presumed to be at the lower left corner. Therefore, a conversion problem arises between the contouring software and the model results. A lesser problem involves the conversion from the irregularly spaced 100 by 100 model grid to a regularly spaced grid, 149 by 149, corresponding to every mile within the study area. Once these problems are solved, the results can be plotted or visually displayed using SURFER, a commercially available software package (Golden Software, 1987).

The postprocessing program, called "CHI2SURF," was custom-written in Microsoft QuickBASIC (Microsoft, 1988) to make the two conversions. The program reads the model results, makes the two conversions, and then outputs the water-level data into what SURFER recognizes as a ".GRD" file format. SURFER then contours the water-level data and can subtract one map from the other. The numeric difference between maps can then be contoured to illustrate where the greatest impacts will occur. The CHi2SURF program (appendix A) is available on diskette from the Illinois State Water Survey, telephone (217) 333-2210.

Future Water Levels in the Chicago Region

1992

Historically the Water Survey has conducted mass measurements of water levels about every five years in northeastern Illinois. More frequent measurements were made at selected points, but it was recognized that these intermittent reports were more practical. Scheduling difficulties were encountered in 1990. A measurement is tentatively scheduled for 1991, and it should be completed by 1992.

The water levels predicted by the end of the year 1992 are illustrated in figure 16. The most prominent feature on the map continues to be the deep cone of depression centered near Elmhurst. A steep hydraulic gradient from the west brings flow in from that direction, and ground water also enters the cone from the east, north, and south. The importance of the contribution from the east had not been obvious in previous studies.

The calculated potentiometric surface for 1992 was compared with the calculated 1985 surface (figure 7) to guide investigators to areas of significant water-level change. The resulting change map (figure 17) illustrates how decreased pumpage from the Cambrian-Ordovician aquifer in Cook County during the late 1980s has affected Illinois ground-water levels.

A significant rise is predicted by 1992 in the Arlington Heights/Wheeling area of Cook County, where water levels may be as much as 150 to 200 feet higher than they were in 1985. This rise is attributed to the fact that users in that area have since switched to Lake Michigan water. Some beneficial impacts will spread into central Lake County and along an axis from Elgin to Lake Michigan. The model also predicts that water levels will rise throughout most of Cook County. In the southeastern part of the county, changes of 25 to 50 feet should be observed in an area extending from Oak Lawn, Illinois, to Hammond, Indiana.

Water-level declines also are anticipated to occur between 1985 and 1992. The largest of these will occur near Aurora, Joliet, and Elmhurst. Lesser declines will be observed at Downers Grove, Naperville, and in southeastern Wisconsin. The declines may be as much 100 feet at Aurora, 50 feet at Joliet, and 25 to 50 feet at the other locales.

It is interesting to note that a zero-change line is predicted to trend across Lake and southeastern McHenry Counties. This suggests that while Illinois water levels have benefited from the changes made during the 1980s, the Wisconsin levels declined in response to their demands.

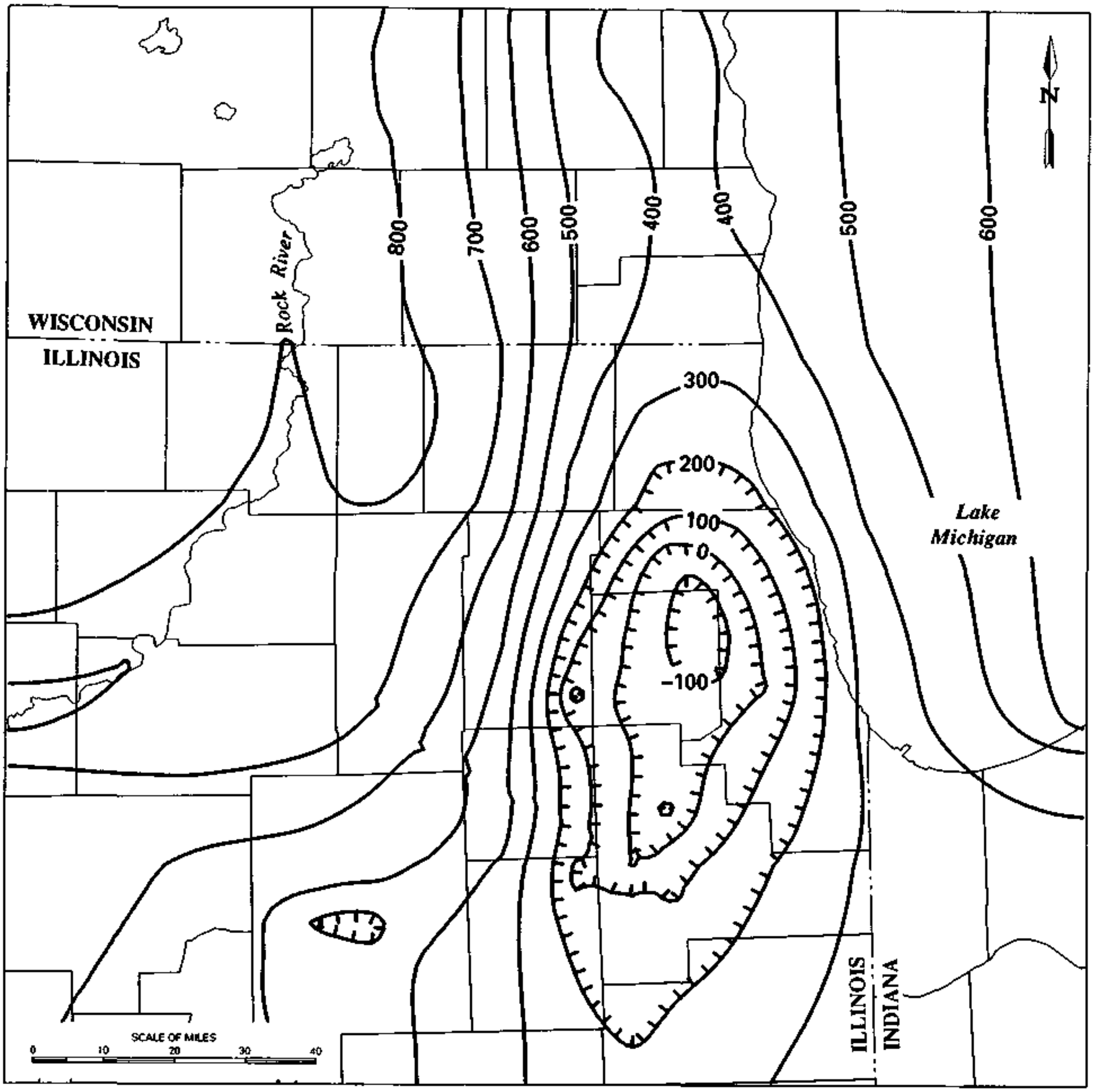


Figure 16. Calculated potentiometric surface, 1992 (feet msl)

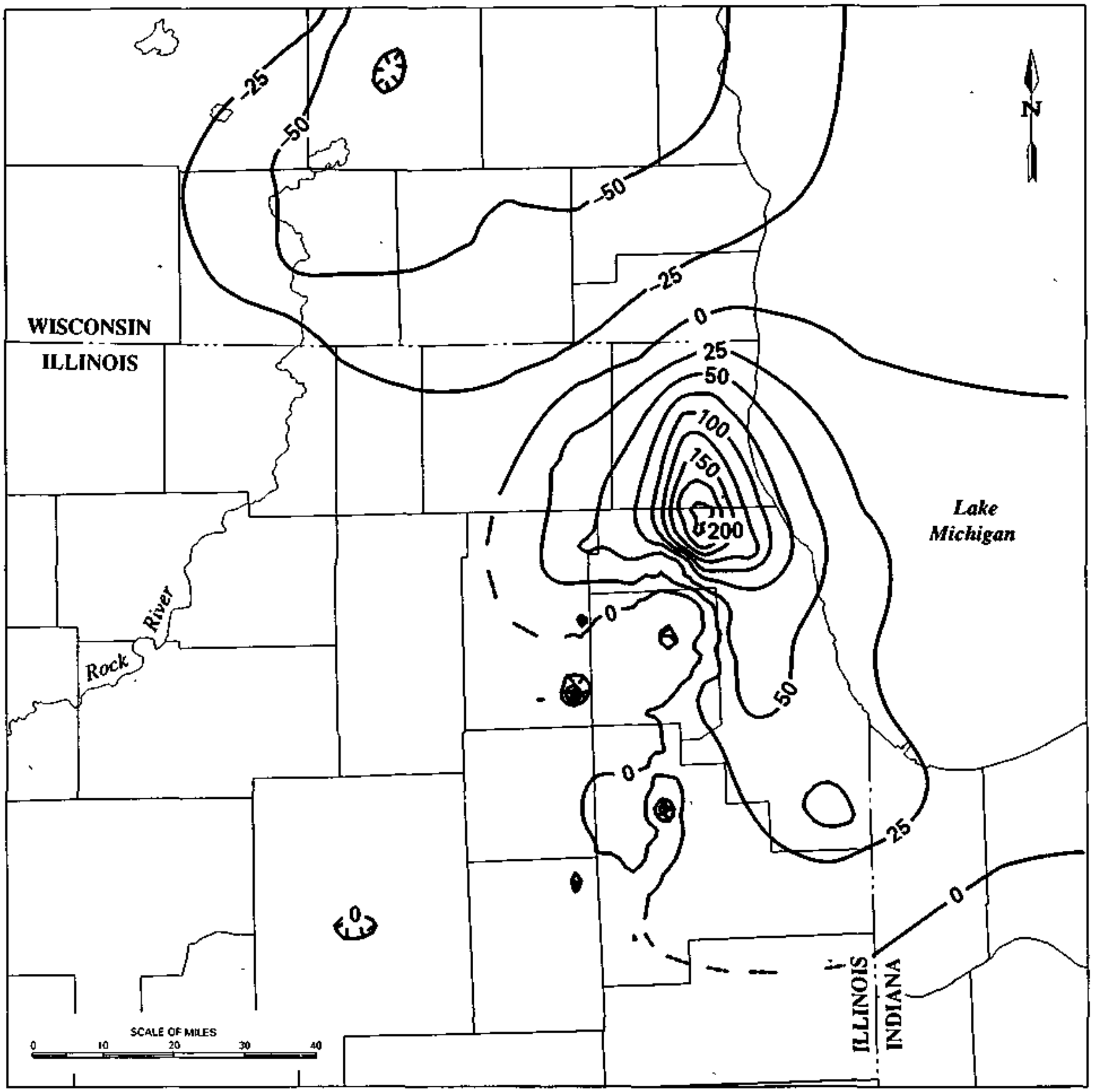


Figure 17. Predicted water-level changes between 1985 and 1992 (feet)

1995

Water levels predicted by the end of the year 1995 are illustrated in figure 18. This map can be considered to represent the first reaction to the 1992 delivery of Lake Michigan water to DuPage and Lake Counties. It is, in fact, a prediction of what might happen during the first four years after the switch.

The model predicts that the Chicago-area regional pumping cone will initially become more shallow without becoming significantly smaller in areal extent. The 100-, 200-, and 300-foot contours will shift southward in Lake County, while most other contours will remain stationary.

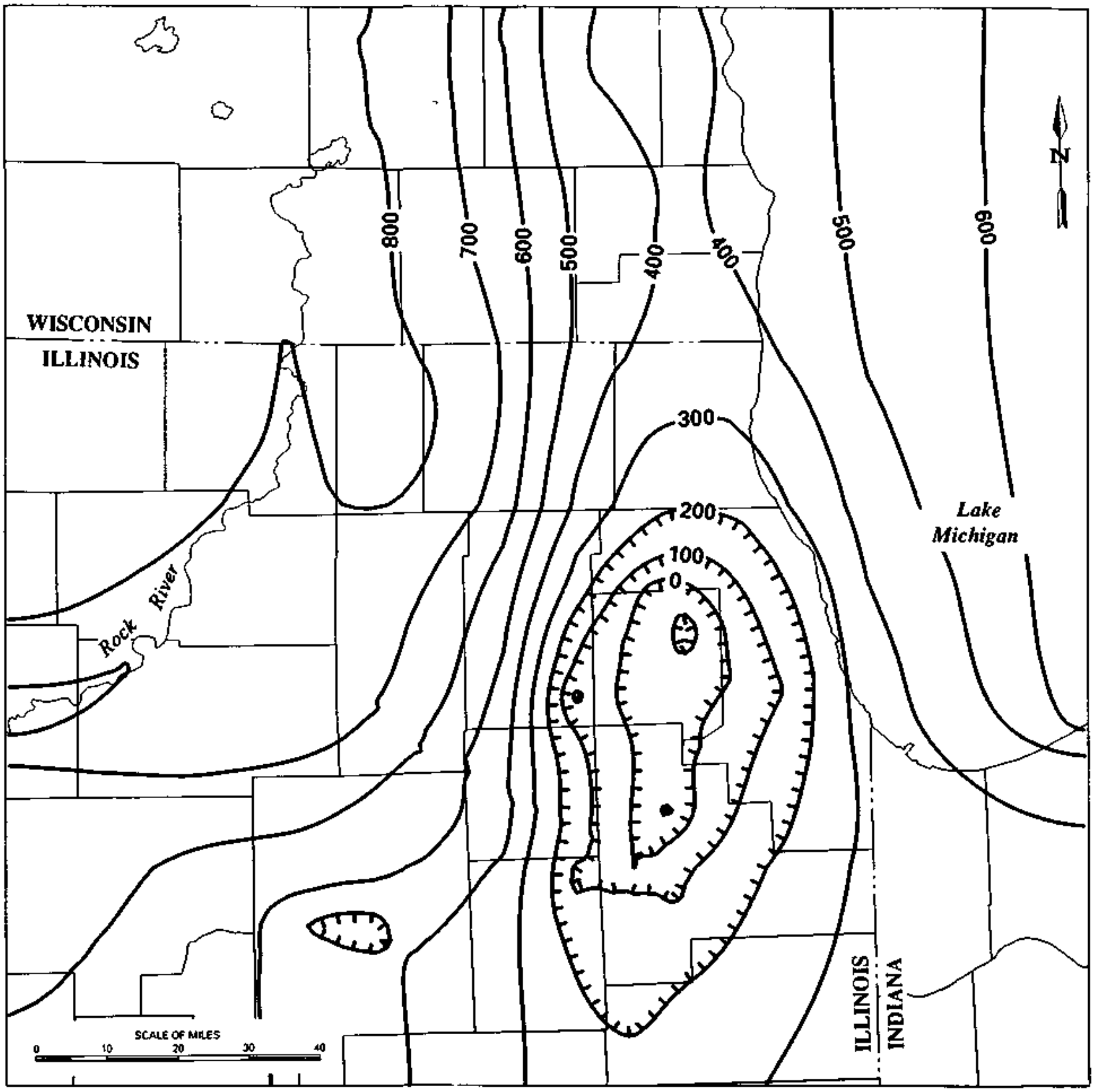


Figure 18. Calculated potentiometric surface for 1995 (feet msl), assuming delivery of Lake Michigan water to DuPage and Lake Counties in 1992

2000

By the end of the year 2000, water levels will have recovered dramatically. Everywhere in DuPage and Cook Counties, levels will rise above the 200-foot elevation, as shown in figure 19. This has not been observed since 1958 when the Water Survey began documenting Chicago's regional water levels. The area encompassed by the pumping cone of depression will shrink rapidly.

Other benefits will also be seen in northeastern Illinois. Water levels in parts of southern Lake County will have risen by more than 150 feet. At Elgin, levels are predicted to rise 200 feet. In fact, Cambrian-Ordovician water levels all along me Fox River Valley in Kane County will improve significantly. Major changes will also be observed at Aurora as that community diversifies its sources of water.

Further south, in Will and southern Cook Counties, significant improvements will also be observed. The Joliet pumping cone will disappear and fade into a more regional cone of depression. Water levels near Bolingbrook will rise by more than 200 feet. Some of this recovery will occur when DuPage County changes to lake water, but it will also result from Joliet diverting 5 to 6 mgd of its demand to surface water sources.

The water levels predicted for the year 2000 represent something of a landmark in charting ground-water manage-

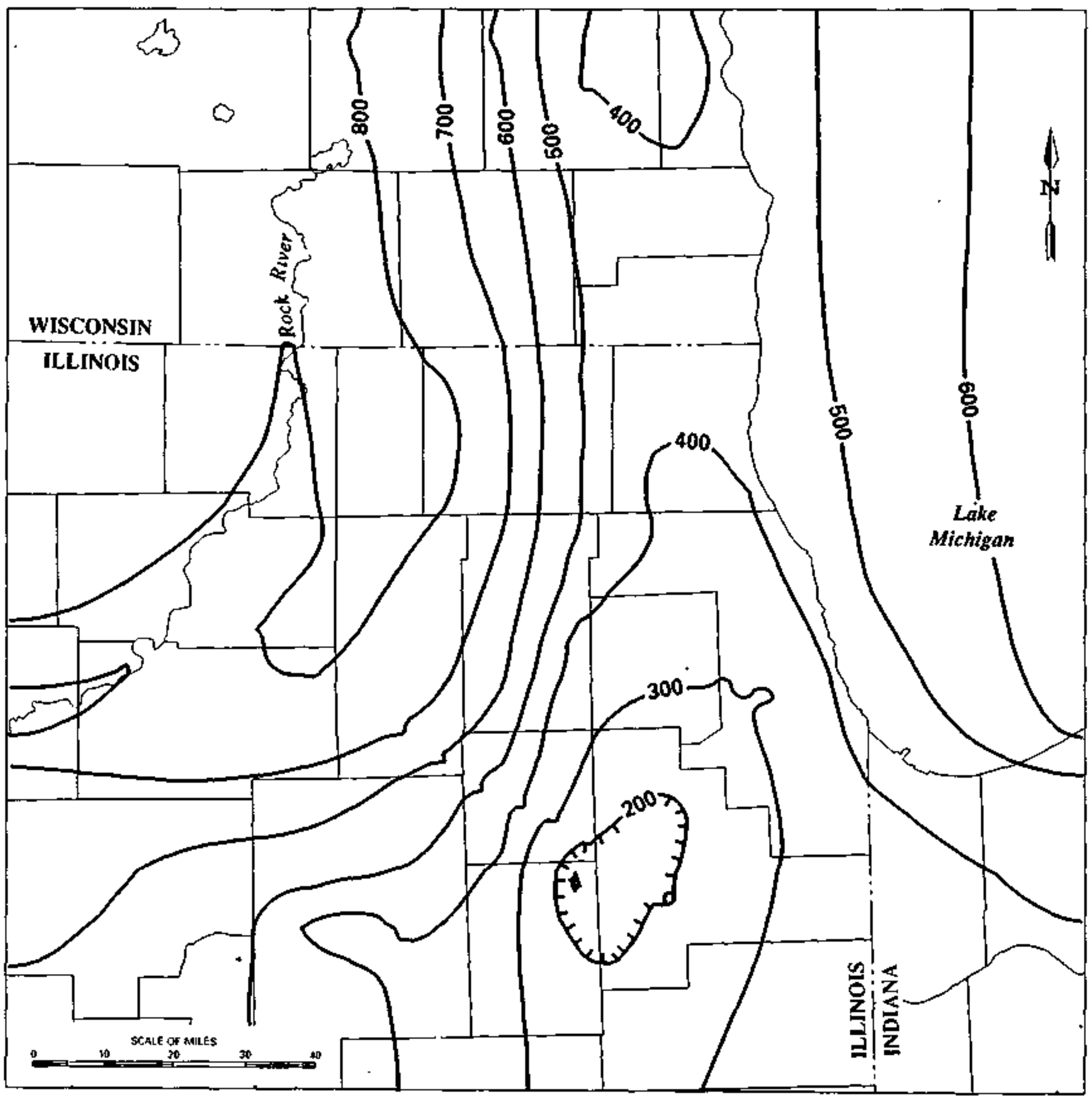


Figure 19. Calculated potentiometric surface for 2000 (feet msl), assuming delivery of Lake Michigan water to DuPage and Lake Counties in 1992

ment: they will be the result of the *projected minimum pumpage* in northeastern Illinois (see forecasts in section 4). Estimates indicate that Cambrian-Ordovician withdrawals will bottom out at about 54 mgd. Beyond the year 2000, demand will increase once more, and the cycle of overpumpage will begin again.

2005

Although pumpage will have increased slightly by 2005, it will not overcome the momentum of rising water levels at the beginning of the new century. Although the predicted rate of improvement in water levels will slow by the end of the year 2005, Lake and Cook County levels will continue to rise. At that point, Illinois will be realizing nearly maximum benefits of its twentieth-century conversion to the use of Lake Michigan water. Even northwestern Indiana will see water-level rises of about 100 feet in wells tapping the Cambrian-Ordovician aquifer system.

The most notable feature on the map for the year 2005 (figure 20) is the continued separation of the Milwaukee and Chicago cones of depression. The respective 400-foot contours will spread farther apart, suggesting that the Lake Michigan allocation program in Illinois, as managed by the Division of Water Resources, will indeed have reached regional proportions.

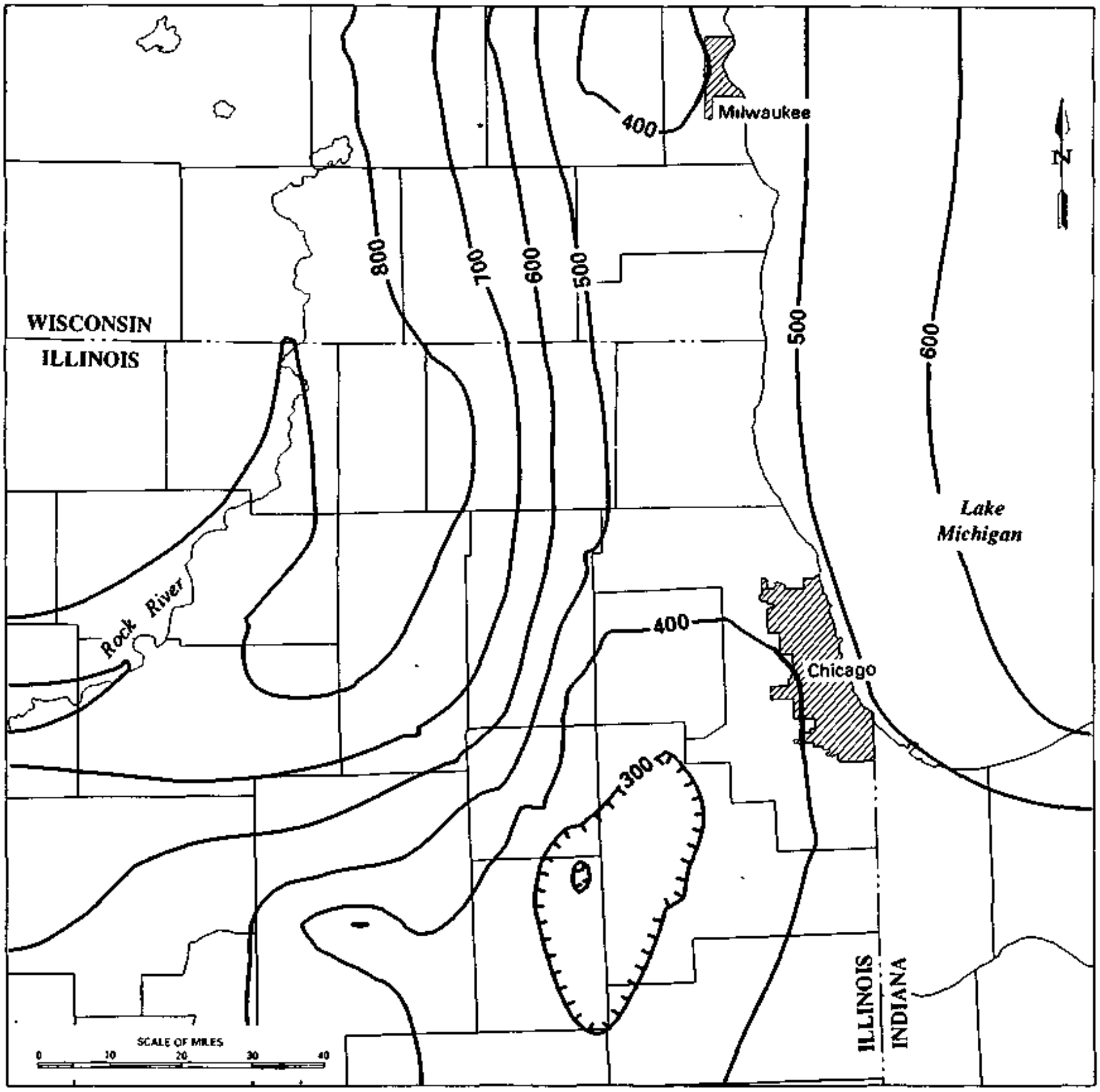


Figure 20. Calculated potentiometric surface for 2005 (feet msl), assuming delivery of Lake Michigan water to DuPage and Lake Counties in 1992

2010

Water levels predicted for the end of the year 2010 are depicted in figure 21. In Illinois water levels will still be rising, although the rate will have slowed. The map for the year 2010 represents the last water-level prediction, as well as the last of the model's simulations. Its resemblance to the 2005 map is obvious, indicating that stability has been achieved. Consequently, the potentiometric surface predicted for 2010 is an ideal basis from which to quantify the impact of diverting Lake Michigan water to DuPage and Lake Counties in 1992.

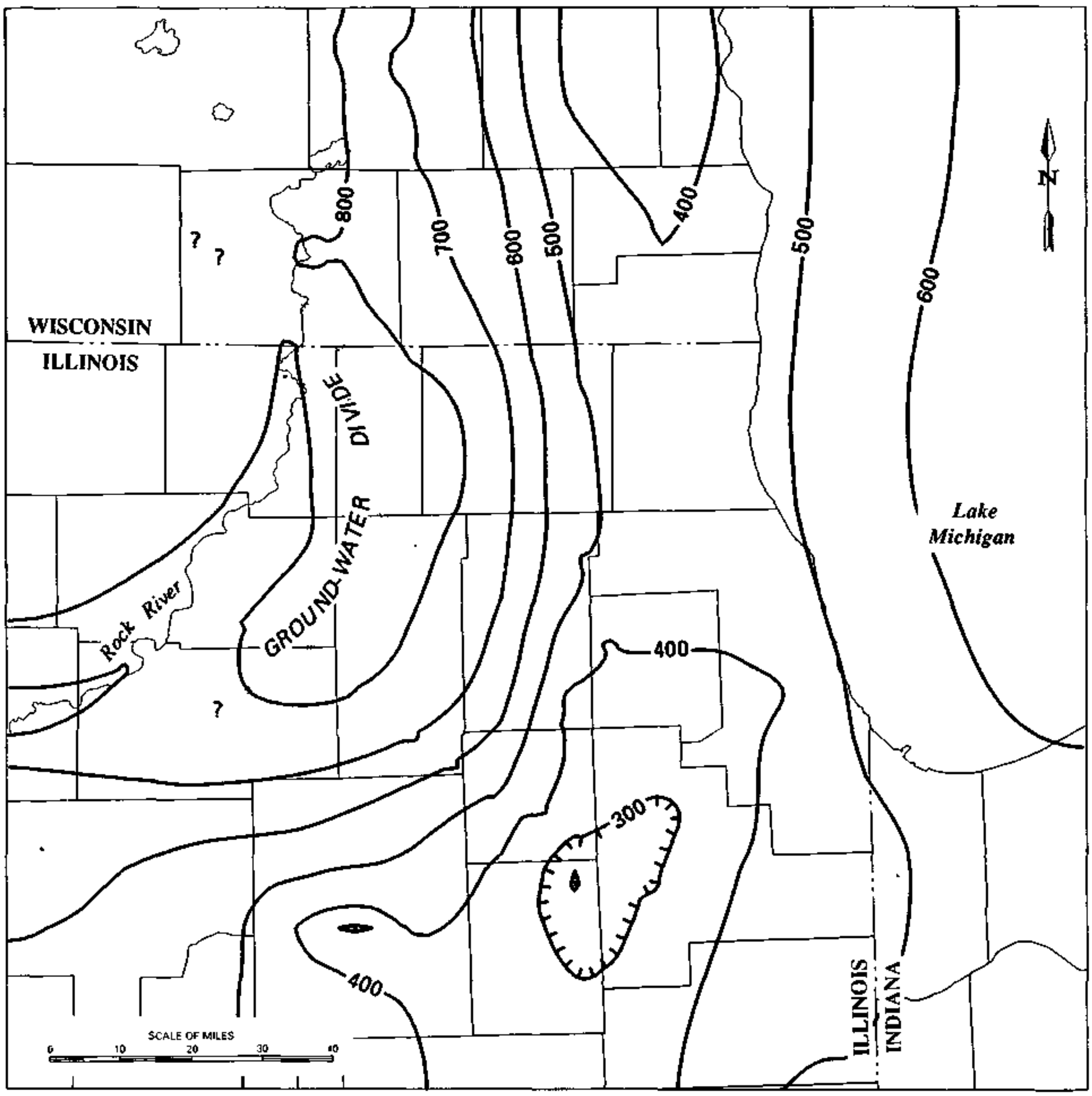


Figure 21. Calculated potentiometric surface for 2010 (feet msl), assuming delivery of Lake Michigan water to DuPage and Lake Counties in 1992

Impact of Projected 1992 Lake Michigan Water Deliveries

A major concern of this investigation was to determine how the delivery of Lake Michigan water would impact ground-water levels in DuPage and Lake Counties. The prediction in olved the use of two simulations: one assumed the delivery of lake water in 1992, and the other assumed the water would not be delivered. Water-level predictions were made for both assumptions and extended to the year 2010. The difference represents the impact of the Lake Michigan water deliveries plus other forecasted changes in demand.

The predicted impact of the delivery of lake water is illustrated in figure 22. Ground-water levels in the Cambrian-Ordovician aquifer are expected to rise in northeastern Illinois by almost 650 feet! Levels will also rise in southeastern Wisconsin and northwestern Indiana in response to actions taken in Illinois. The recovery will be centered on Elmhurst, but water levels are predicted to rebound by 350 feet or more throughout DuPage and much of western Cook Counties as well. It is expected that levels will rise by 50 feet or more in areas as far away as Belvidere, DeKalb, Morris, and Kankakee.

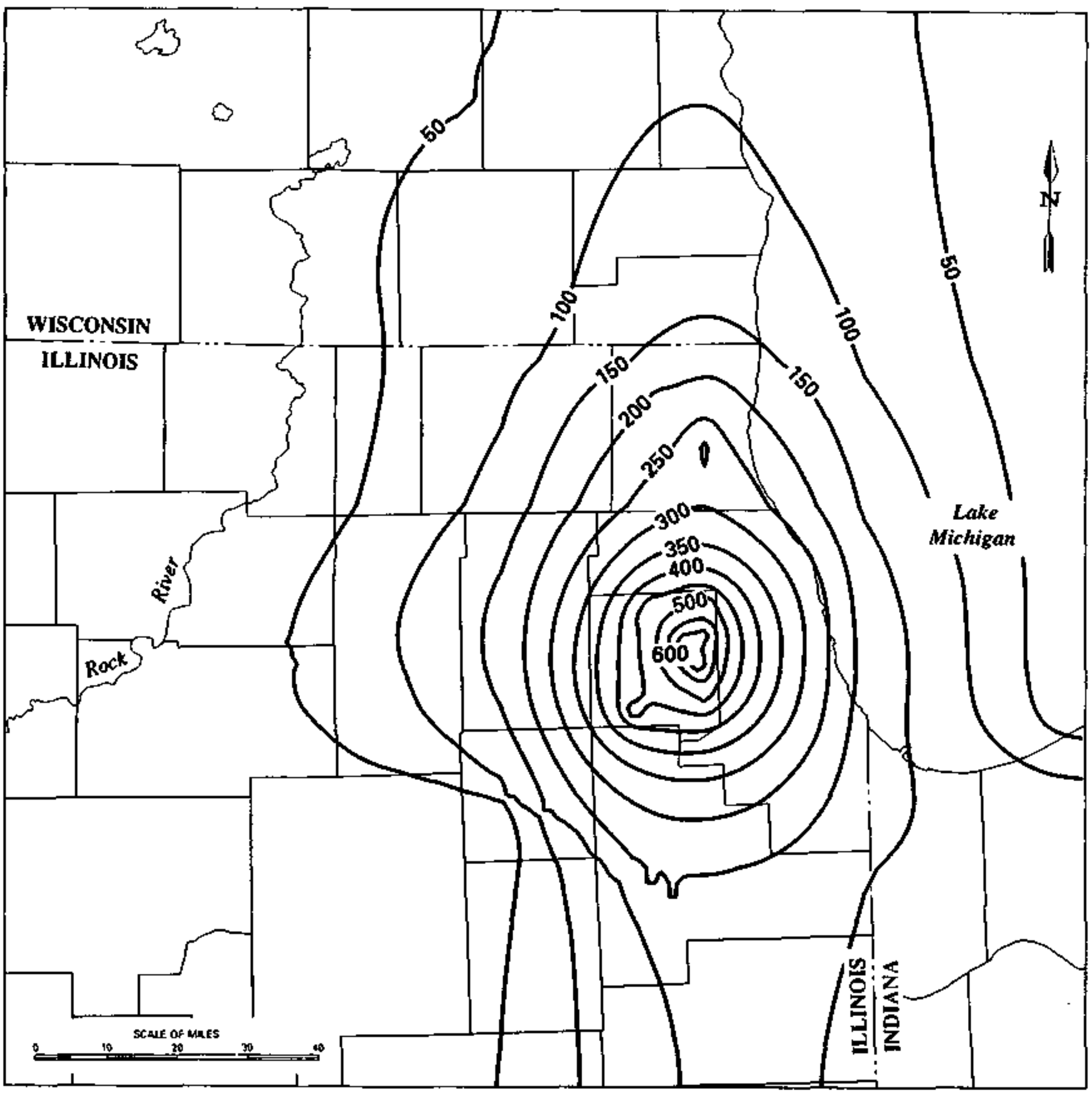


Figure 22. Relative changes in water levels by 2010: impact of the delivery of Lake Michigan water to DuPage and Lake Counties in 1992 (feet)

Conclusions and Restatement of Key Points

An enhanced version of Prickett and Lonnquist's traditional Chicago model was developed for this project The model is a numerical ground-water flow representation of the physical aquifer system that supplies large quantities of water to northeastern Illinois and southeastern Wisconsin.

Hydrogeologic Conditions

This study differs from previous studies in its interpretation of hydrogeologic conditions, and it excludes the Galena-Platteville as part of the aquifer system. Elimination of the Galena-Platteville has implications for the storage coefficient The original model was designed to change storage coefficients when dewatering caused the aquifer to convert from artesian conditions to water-table conditions. The conversion "was keyed to the position of the potentiometric head relative to the top of the Galena-Platteville. Because these formations are no longer considered part of the upper aquifer layer, this criterion is not applicable. Instead, the conversion to water table is determined in the new model by the relationship of water levels to the top of the St. Peter Sandstone, which is now considered the uppermost water-bearing layer of the aquifer system.

Discretized structure contour data can be used to produce an even better model. These data allow the thickness of each aquifer layer to be calculated at each grid node. Thus realistic geologic descriptions can be used, rather than assuming that the entire sequence of strata has a uniform thickness, dipping eastward at 13 feet per mile.

Six geologic surfaces were used in the new model to define a five-layer aquifer system. Each layer varies in hydraulic conductivity and thickness, and therefore its ability to transmit water. The lowest layer, the Mt. Simon, is an important producer in Wisconsin and in the northernmost tier of Illinois counties. The second layer from the bottom describes the Ironton-Galesville, while the third from the bottom is the Franconia-St. Lawrence. The Prairie du Chien Group (layer four) is important to modeling efforts because it rapidly thickens in the southern part of the study area and because it has very low hydraulic conductivity. The fifth and uppermost layer refers to the St. Peter Sandstone of the Ancell Group. The key to understanding the stratigraphic controls on the new model is that the Cambrian-Ordovician aquifer system is bounded above by the Galena-Platteville Formation, which serves as a confining bed, rather than as part of the aquifer.

Less important but nevertheless distinctive stratigraphic controls are exerted by the Prairie du Chien Group in Illinois and the Mt. Simon in Wisconsin. These two layers help incorporate regional differences into the New Chicago Model, resulting in a transmissivity map (figure 4) that reflects the real world more accurately. At the same time, it refutes the simplistic assumption of uniform transmissivity (17,000 gpd/ft) that governed earlier models.

The Sandwich Fault was modeled as a line of zero transmissivity. It has almost no effect on water levels because the regional flow direction is virtually parallel to the fault trace. If the prevailing direction of ground-water flow were at right angles to the fault, then its impact would be more important. The assumed zero transmissivity along the trace of the fault does provide a slight kink in the calculated water-level contours. Its inclusion in the model thus provides a somewhat better aesthetic quality to the maps, but it need not be included in future models.

An examination of the starting head map reveals the significant and previously unrecognized fact that the Rock River is of great hydrologic importance to any model of the Chicago area, since it controls the location of the ground-water divide in DeKalb County. The divide, which has been shown on maps for more than 30 years, is usually regarded as the western edge of the Cambrian-Ordovician flow regime. However, the calibration of the New Chicago Model revealed that the position of this divide is maintained by ground-water discharges to the Rock River. Consequently the importance of the Rock River on the aquifer system has been underestimated.

Water-Level Changes

Ground-water levels will rise throughout much of northeastern Illinois between 1985 and 1990, particularly in Cook County, since it was the first to switch to Lake Michigan water. However, levels will probably decline near Aurora, Joliet, and Elmhurst. Lesser declines will be observed at Downers Grove, Naperville, and in southeastern Wisconsin. The declines may be as much 100 feet at Aurora, 50 feet at Joliet, and 25 to 50 feet at the other locales.

A zero-change line is predicted to trend across Lake and southeastern McHenry Counties. This suggests that while Illinois water levels have benefited from the changes made during the 1980s, Wisconsin levels declined in response to their own demands.

Chicago's regional pumping cone will initially become shallower without becoming significantly smaller in areal extent. The 100-, 200-, and 300-foot contours will shift southward in Lake County, while most other contours will remain stationary. By the end of the year 2000, water levels will have recovered dramatically.

The area encompassed by the pumping cone will shrink rapidly, and the model predicts that water levels will rise in some places by almost 650 feet! The recovery will be centered on Elmhurst, but water levels are predicted to rebound by 350 feet or more throughout DuPage and much of western Cook Counties. Water levels will rise by 50 feet or more as far away as Belvidere, DeKalb, Morris, and Kankakee. The actions taken in Illinois will even cause water levels to rise in southeast Wisconsin and northwest Indiana.

Practical Significance

The recovery of ground-water levels will be important to both users and resource managers. The rise will return ground-water levels to their positions during the first part of this century. Pumping costs will be reduced because the lifts required to bring ground water to the surface will be lessened. For example, the depth to water in deep sandstone wells at Elmhurst will be about 300 feet instead of 900 feet

The decrease in Cambrian-Ordovician pumpage will be important to resource managers too. The reduction to less than 65 mgd means that discharge from the ground-water system will approximately equal recharge. Thus, for the first time since the late 1950s, Illinois will not be mining its ground water in northeastern Illinois. And that translates to judicious use of a renewable natural resource.

Significant Accomplishments

The New Chicago Model makes several noteworthy improvements over its predecessors. They include:

- Translating the code from Fortran to QuickC.
- Using six elevations of geologic formations to describe the surfaces that control transmissivity calculations within the model.
- Changing the conceptual model of the system to incorporate the importance of the Mt. Simon aquifer in Wisconsin, while eliminating the Galena-Platteville dolomite as part of the Cambrian-Ordovician aquifer system.
- Recognizing the importance of the Rock River as a constant-head discharge boundary, making the New Chicago Model the first to identify this feature.
- Using more than 1,300 nodes to describe pumpage distribution throughout the model's area. (Previously only 112 had been used.)
- Successfully running and developing the model on a personal computer. The code design allows the model to handle more grid nodes than commonly allowed by most personal computer codes.

Recommendations for Further Study

Great changes are expected in northeastern Illinois, and they should be documented carefully. With respect to water levels, two investigations are recommended:

1. A mass measurement of water levels in wells reaching the Cambrian-Ordovician aquifer is essential at the beginning of the changeover to Lake Michigan water. Subsequent measurements will also be needed in 1995, 2000, 2005, and 2010.
2. The shallow dolomite aquifer, which is an important source of ground water in DuPage County, must be observed closely. Water-level recoveries are expected to occur in the shallow dolomite, but the Water Survey has little data on current conditions.

Finally, recovery and recharge are not the same concept. One cannot equate the 650-foot recovery of water levels with the balance between average annual recharge and annual discharge. The entire issue of the recharge to the Cambrian-Ordovician aquifer system supplying northeastern Illinois and southeastern Wisconsin must be addressed as a separate study. Preliminary thinking envisions the need for a two-year investigation.

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Appendix A. Source Code for CHI2SURF:
A Post-Processing Program to Convert Model Calculations to SURFER Format
by Evan P. Mills

```
REM This QuickBasic 4.0 program is used to post-process output from
REM the new Chicago Model.  It inverts the output from the fourth
REM quadrant and writes it in what SURFER (Golden Software, Inc.)
REM recognizes as a *.GRD file.  Consequently, it's ready for contouring.
DECLARE SUB GetMinMax ()
DECLARE SUB GetFileNames ()
DECLARE SUB InterpSurf ()
DECLARE SUB FillSurf ()
DECLARE SUB FillMod ()
DECLARE SUB OutputSurf ()
DECLARE SUB Fill ()
CONST modlength - 100, surflength - 149

COMMON SHARED model(), surf()
COMMON SHARED minz, maxz
COMMON SHARED infile$, outfile$
DIM model(modlength, modlength)
DIM surf(surflength, surflength)
CLS : COLOR 14
CALL GetFileNames
CALL FillMod
CALL FillSurf
CALL InterpSurf
CALL GetMinMax
CALL OutputSurf

SUB FillMod
    LOCATE 10, 1: PRINT "Filling model array."
    OPEN infile$ FOR INPUT AS #1
    LINE INPUT #1, a$
    LINE INPUT #1, a$
    FOR row - modlength TO 1 STEP -1   'Flips model output from fourth quadrant
        FOR col - 1 TO modlength
            INPUT #1, model(row, col)
            NEXT col
        NEXT row
    CLOSE #1
END SUB

SUB FillSurf
    LOCATE 11, 1: PRINT "Filling surfer array."
    FOR mrow - 1 TO 100
        FOR mcol - 1 TO 100
            SELECT CASE mrow     'To compensate for flip
                CASE 1 TO 16
                    srow - 2 * mrow - 1
                CASE 17 TO 66
                    srow - (mrow - 16) + 31
                CASE ELSE
                    srow - 2 * (mrow - 66) +81
```

```
            END SELECT
            SELECT CASE mcol
                CASE IS < 35
                    scol - 2 * mcol - 1
                CASE IS <- 85
                    scol - 1 * mcol + 34
                CASE ELSE
                    scol - 2 * mcol - 51
            END SELECT
            surf(srow, scol) - model(mrow, mcol)
        NEXT mcol
    NEXT mrow
END SUB

SUB GetFileNames
    INPUT "Enter the name of the input file containing the raw data: ", infile$
    IF ipos > 0 THEN ipos - ipos - 1 ELSE ipos - LEN(infile$)
    PRINT
    INPUT "Enter the name of the output file to contain the grid data: ", outfile$
    IF INSTR(outfile$, ".") - 0 THEN outfile$ - outfile$ + ".GRD"
    PRINT "Taking input from file:     <"; infile$; ">."
    PRINT "Putting Surfer grid in file: <"; outfile$; ">."
END SUB
SUB GetMinMax
   LOCATE 13, 1: PRINT "Calculating min & max values."
   minz - 99999: maxz - -99999
   FOR row - 1 TO surflength
      FOR col - 1 TO surflength
         IF surf(row, col) > maxz THEN maxz - surf(row, col)
         IF surf(row, col) < minz THEN minz - surf(row, col)
         NEXT col
      NEXT row
END SUB

SUB InterpSurf
    LOCATE 12, 1: PRINT "Interpolating surfer array."
    FOR row - 82 TO 148 STEP 2
        FOR col - 2 TO 68 STEP 2        ' Upper left
            surf(row, col - 1) - (surf(row - 1, col - 1) + surf(row + 1, col - 1)) / 2
            surf(row, col + 1) - (surf(row - 1, col + 1) + surf(row + 1, col +1) ) / 2
            surf(row - 1, col) - (surf(row - 1, col - 1) + surf(row - 1, col +1) ) / 2
            surf(row + 1, col) - (surf(row + 1, col - 1) + surf(row + 1, col + 1)) / 2
            surf(row, col) - (surf(row, col - 1) + surf(row, col + 1)) / 2
            NEXT col
        FOR col - 120 TO 148 STEP 2     ' Upper right
            surf(row, col - 1) - (surf(row - 1, col - 1) + surf(row + 1, col - 1)) / 2
            surf(row, col + 1) - (surf(row - 1, col + 1) + surf(row + 1, col +1) ) / 2
            surf(row - 1, col) - (surf(row - 1, col - 1) + surf(row - 1, col +1) ) / 2
            surf(row + 1, col) - (surf(row + 1, col - 1) + surf(row + 1, col + 1)) / 2
            surf(row, col) - (surf(row, col - 1) + surf(row, col + 1)) / 2
            NEXT col
        NEXT row
    FOR row - 2 TO 30 STEP 2
```

```
     FOR col - 2 TO 68 STEP 2       'Lower left
         surf(row, col - 1) - (surf(row - 1, col - 1) + surf(row + 1, col - 1)) / 2
         surf(row, col + 1) - (surf(row - 1, col + 1) + surf(row + 1, col +1)) / 2
         surf(row - 1, col) - (surf(row - 1, col - 1) + surf(row - 1, col +1)) / 2
         surf(row + 1, col) - (surf(row + 1, col - 1) + surf(row + 1, col +1)) / 2
         surf(row, col) - (surf(row, col - 1) + surf(row, col +1)) / 2
         NEXT col
     FOR col - 120 TO 148 STEP 2    ' Lower right
         surf(row, col - 1) - (surf(row - 1, col - 1) + surf(row + 1, col - 1)) / 2
         surf(row, col + 1) - (surf(row - 1, col + 1) + surf(row + 1, col +1)) / 2
         surf(row - 1, col) - (surf(row - 1, col - 1) + surf(row - 1, col +1)) / 2
         surf(row + 1, col) - (surf(row + 1, col - 1) + surf(row + 1, col +1)) / 2
         surf(row, col) - (surf(row, col - 1) + surf(row, col +1)) / 2
         NEXT col
        NEXT row
    FOR row - 31 TO 81
        FOR col - 2 TO 68 STEP 2       ' Middle left
            surf(row, col) - (surf(row, col - 1) + surf(row, col + 1)) / 2
            NEXT col
        FOR col - 120 TO 148 STEP 2    ' Middle right  .
            surf(row, col) - (surf(row, col - 1) + surf(row, col + 1)) / 2
            NEXT col
        NEXT row
    FOR col - 69 TO 119
        FOR row - 82 TO 148 STEP 2       ' Upper central
            surf(row, col) - (surf(row - 1, col) + surf(row + 1, col)) / 2
            NEXT row
        FOR row - 2 TO 30 STEP 2     ' Lower central
            surf(row, col) - (surf(row - 1, col) + surf(row + 1, col)) / 2
            NEXT row
        NEXT col

END SUB

SUB OutputSurf
    LOCATE 15, 1: PRINT "Outputting grid.
    OPEN outfile$ FOR OUTPUT AS #2
    PRINT #2, "DSAA"
    PRINT #2, "149 149"
    PRINT #2, "2911457 3692897"
    PRINT #2, "2899770 3681210"
    PRINT #2, minz, maxz
    PRINT #2,
    FOR row - 1 TO surflength
        FOR col - 1 TO surflength
            PRINT #2, USING "#######. "; surf(row, col);
            IF (col MOD 10) - 0 THEN PRINT #2,
            NEXT col
        PRINT #2, : PRINT #2,
        NEXT row
    CLOSE #2
END SUB
```

Appendix B. Grid Location Details

(Lambert feet)

Column (i)	*Row (J)*	*X (Lambert feet)*	*Y (Lambert feet)*
1	1	2911457.5	3681210.5
2	1	2922017.5	3681210.5
3	1	2932577.5	3681210.5
4	1	2943137.5	3681210.5
5	1	2953697.5	3681210.5
6	1	2964257.5	3681210.5
7	1	2974817.5	3681210.5
8	1	2985377.5	3681210.5
9	1	2995937.5	3681210.5
10	1	3006497.5	3681210.5
11	1	3017057.5	3681210.5
12	1	3027617.5	3681210.5
13	1	3038177.5	3681210.5
14	1	3048737.5	3681210.5
15	1	3059297.5	3681210.5
16	1	3069857.5	3681210.5
17	1	3080417.5	3681210.5
18	1	3090977.5	3681210.5
19	1	3101537.5	3681210.5
20	1	3112097.5	3681210.5
21	1	3122657.5	3681210.5
22	1	3133217.5	3681210.5
23	1	3143777.5	3681210.5
24	1	3154337.5	3681210.5
25	1	3164897.5	3681210.5
26	1	3175457.5	3681210.5
27	1	3186017.5	3681210.5
28	1	3196577.5	3681210.5
29	1	3207137.5	3681210.5
30	1	3217697.5	3681210.5
31	1	3228257.5	3681210.5
32	1	3238817.5	3681210.5
33	1	3249377.5	3681210.5
34	1	3259937.5	3681210.5
35	1	3270497.5	3681210.5
36	1	3275777.5	3681210:5
37	1	3281057.5	3681210.5
38	1	3286337.5	3681210.5
39	1	3291617.5	3681210.5
40	1	3296897.5	3681210.5
41	1	3302177.5	3681210.5
42	1	3307457.5	3681210.5
43	1	3312737.5	3681210.5
44	1	3318017.5	3681210.5
45	1	3323297.5	3681210.5
46	1	3328577.5	3681210.5
47	1	3333857.5	3681210.5
48	1	3339137.5	3681210.5
49	1	3344417.5	3681210.5
50	1	3349697.5	3681210.5
51	1	3354977.5	3681210.5
52	1	3360257.5	3681210.5

Column (i)	Row (J)	X (Lambert feet)	Y (Lambert feet)
53	1	3365537.5	3681210.5
54	1	3370817.5	3681210.5
55	1	3376097.5	3681210.5
56	1	3381377.5	3681210.5
57	1	3386657.5	3681210.5
58	1	3391937.5	3681210.5
59	1	3397217.5	3681210.5
60	1	3402497.5	3681210.5
61	1	3407777.5	3681210.5
62	1	3413057.5	3681210.5
63	1	3418337.5	3681210.5
64	1	3423617.5	3681210.5
65	1	3428897.5	3681210.5
66	1	3434177.5	3681210.5
67	1	3439457.5	3681210.5
68	1	3444737.5	3681210.5
69	1	3450017.5	3681210.5
70	1	3455297.5	3681210.5
71	1	3460577.5	3681210.5
72	1	3465857.5	3681210.5
73	1	3471137.5	3681210.5
74	1	3476417.5	3681210.5
75	1	3481697.5	3681210.5
76	1	3486977.5	3681210.5
77	1	3492257.5	3681210.5
78	1	3497537.5	3681210.5
79	1	3502817.5	3681210.5
80	1	3508097.5	3681210.5
81	1	3513377.5	3681210.5
82	1	3518657.5	3681210.5
83	1	3523937.5	3681210.5
84	1	3529217.5	3681210.5
85	1	3534497.5	3681210.5
86	1	3545057.5	3681210.5
87	1	3555617.5	3681210.5
88	1	3566177.5	3681210.5
89	1	3576737.5	3681210.5
90	1	3587297.5	3681210.5
91	1	3597857.5	3681210.5
92	1	3608417.5	3681210.5
93	1	3618977.5	3681210.5
94	1	3629537.5	3681210.5
95	1	3640097.5	3681210.5
96	1	3650657.5	3681210.5
97	1	3661217.5	3681210.5
98	1	3671777.5	3681210.5
99	1	3682337.5	3681210.5
100	1	3692897.5	3681210.5

Appendix B (Continued)

Column (i)	Row (j)	X (Lambert feet)	Y (Lambert feet)
1	2	2911457.5	3670650.5
1	3	2911457.5	3660090.5
1	4	2911457.5	3649530.5
1	5	2911457.5	3638970.5
1	6	2911457.5	3628410.5
1	7	2911457.5	3617850.5
1	8	2911457.5	3607290.5
1	9	2911457.5	3596730.5
1	10	2911457.5	3586170.5
1	11	2911457.5	3575610.5
1	12	2911457.5	3565050.5.
1	13	2911457.5	3554490.5
1	14	2911457.5	3543930.5
1	15	2911457.5	3533370.5
1	16	2911457.5	3522810.5
1	17	2911457.5	3512250.5
1	18	2911457.5	3501690.5
1	19	2911457.5	3491130.5
1	20	2911457.5	3480570.5
1	21	2911457.5	3470010.5
1	22	2911457.5	3459450.5
1	23	2911457.5	3448890.5
1	24	2911457.5	3438330.5
1	25	2911457.5	3427770.5
1	26	2911457.5	3417210.5
1	27	2911457.5	3406650.5
1	28	2911457.5	3396090.5
1	29	2911457.5	3385530.5
1	30	2911457.5	3374970.5
1	31	2911457.5	3364410.5
1	32	2911457.5	3353850.5
1	33	2911457.5	3343290.5
1	34	2911457.5	3332730.5
1	35	2911457.5	3322170.5
1	36	2911457.5	3316890.5
1	37	2911457.5	3311610.5
1	38	2911457.5	3306330.5
1	39	2911457.5	3301050.5
1	40	2911457.5	3295770.5
1	41	2911457.5	3290490.5
1	42	2911457.5	3285210.5
1	43	2911457.5	3279930.5
1	44	2911457.5	3274650.5
1	45	2911457.5	3269370.5
1	46	2911457.5	3264090.5
1	47	2911457.5	3258810.5
1	48	2911457.5	3253530.5
1	49	2911457.5	3248250.5
1	50	2911457.5	3242970.5
1	51	2911457.5	3237690.5
1	52	2911457.5	3232410.5

Appendix B (Continued)

Column (i)	*Row (3)*	*X (Lambert feet)*	*Y (Lambert feet)*
1	53	2911457.5	3227130.5
1	54	2911457.5	3221850.5
1	55	2911457.5	3216570.5
1	56	2911457.5	3211290.5
1	57	2911457.5	3206010.5
1	58	2911457.5	3200730.5
1	59	2911457.5	3195450.5
1	60	2911457.5	3190170.5
1	61	2911457.5	3184890.5
1	62	2911457.5	3179610.5
1	63	2911457.5	3174330.5
1	64	2911457.5	3169050.5
1	65	2911457.5	3163770.5
1	66	2911457.5	3158490.5
1	67	2911457.5	3153210.5
1	68	2911457.5	3147930.5
1	69	2911457.5	3142650.5
1	70	2911457.5	3137370.5
1	71	2911457.5	3132090.5
1	72	2911457.5	3126810.5
1	73	2911457.5	3121530.5
1	74	2911457.5	3116250.5
1	75	2911457.5	3110970.5
1	76	2911457.5	3105690.5
1	77	2911457.5	3100410.5
1	78	2911457.5	3095130.5
1	79	2911457.5	3089850.5
1	80	2911457.5	3084570.5
1	81	2911457.5	3079290.5
1	82	2911457.5	3074010.5
1	83	2911457.5	3068730.5
1	84	2911457.5	3063450.5
1	85	2911457.5	3058170.5
1	86	2911457.5	3047610.5
1	87	2911457.5	3037050.5
1	88	2911457.5	3026490.5
1	89	2911457.5	3015930.5
1	90	2911457.5	3005370.5
1	91	2911457.5	2994810.5
1	92	2911457.5	2984250.5
1	93	2911457.5	2973690.5
1	94	2911457.5	2963130.5
1	95	2911457.5	2952570.5
1	96	2911457.5	2942010.5
1	97	2911457.5	2931450.5
1	98	2911457.5	2920890.5
1	99	2911457.5	2910330.5
1	100	2911457.5	2899770.5

Appendix B (Concluded)
Grid Corners for the New Chicago Model
(in Lambert feet)

```
xmin = 2911457 ymin = 2899770
xmin = 2911457 ymax = 3681210
xmax = 3692897 ymin = 2899770
xmax = 3692897 ymax = 3681210
```

In Lambert feet

Lower Left	2911457	2899770
Upper Left	2911457	3681210
Lower Right	3692897	2899770
Upper Right	3692897	3681210

In longitude-latitude

Lower Left	89	49	20.28	40	59	46.07
Upper Left	89	49	57.78	43	8	57.05
Lower Right	86	58	41.74	40	58	12.16
Upper Right	86	53	48.53	43	7	20.34

Appendix C. Source Code for Distance-Weighting Program

by Mark A. Collins

Note: *This particular application was used to distance-weight the forecast estimates (1985-2010) for Wisconsin. Consequently it assumed the variable "nyrs" was equal to 25. Adjustments are necessary when other assumptions are made.*

```
REM     This program distributes the value of a parameter, pumpage {q(iyr)},
REM     within a grid cell to the four corners of that cell by an inverse
REM     distance-weighting method.

REM    INPUT DATA ARE EXPECTED TO BE IN MILLIONS OF GALLONS PER DAY (MGD).
REM       * * *  BE SURE TO SET "nyrs" TO THE PROPER VALUE.   * * *

TYPE mydata
   qq AS SINGLE
END TYPE

SHELL "copy null.fil scratch.fil"

REM   "NULL.FIL" is a 250,000 times 4 bytes of null "chr$(0)"
REM   creating an EMPTY array for use as scratch.fil
REM   zero = 0
REM   OPEN "R", #2, "NULL.FIL", 4
REM   for i=l to 250,000
REM      put #2,,zero
REM   next i
REM   close #2
   DEFINT I-N
   CONST False% = 0, True% = NOT False, nc = 100, nr = 100, nyrs = 25
   DIM xcol(nc), yrow(nr), q(nyrs)
   DIM wt(0 TO 1, 0 TO 1), qw(4) AS mydata, id AS SINGLE, iprint(100, 100)

   CLS
   INPUT "Enter the INPUT data file name ==> ", infile$
   PRINT : INPUT "Enter the OUTPUT file name ==> ", outfile$
REM    *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
REM
REM   Read in the Lambert coordinates of the grid nodes.
REM
REM    *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
   OPEN "Grid.dat" FOR INPUT AS #1
   FOR i = 1 TO nc
      INPUT #1, xcol(i), yrow(i)
   NEXT i
   CLOSE #1

REM    *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
REM   Open the random access file, which is used instead of a large
REM   three-dimensional array.
REM
REM    *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
   OPEN infile$ FOR INPUT AS #1
   OPEN "R", #2, "scratch.fil", 4
   OPEN outfile$ FOR OUTPUT AS #3
```

```
REM    *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
REM   Input actual pumpage data for each facility.
REM    *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
   DO UNTIL EOF(l)
      INPUT #1, id, xwell, ywell
      FOR iyr = 1 TO nyrs
         INPUT #1, q(iyr)
      NEXT iyr


      iFound = False
      FOR i = 1 TO nc
         IF xcol(i) > xwell THEN
            icol = i - 1
            iFound = True
            EXIT FOR
         END IF
      NEXT i
      IF NOT iFound THEN
         PRINT "Error encountered for x = "; xwell
         STOP
      END IF

      iFound = False
      FOR i = 1 TO nr
         IF yrow(i) < ywell THEN
            irow = i - 1
            iFound = True
            EXIT FOR
         END IF
      NEXT i
      IF NOT iFound THEN
         PRINT "Error encountered for y = "; ywell
         STOP
      END IF

      iprint(icol, irow) = True
      iprint(icol + 1, irow) = True
      iprint(icol, irow +1 ) = True
      iprint(icol + 1, irow + 1) = True


REM    *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
REM
REM   Begin determination of distance from the well to the four surrounding
REM   grid nodal points.
REM
REM    *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
      sum = 0                      'Initialize for each well'
      FOR i = 0 TO 1
         dx = xwell - xcol(icol + i)
         FOR j = 0 TO 1
            dy = ywell - yrow(irow + j)
            wt(i, j) = 1 / (SQR((dx * dx) + (dy * dy)))
            sum = sum + wt(i, j)
         NEXT j
      NEXT i

      FOR i = 0 TO 1
         FOR j = 0 TO 1
```

```
            wt (i, j) = wt (i, j) / sum
         NEXT j
      NEXT i


      FOR iyr = 1 TO nyrs
         baseadd = 10000! * CSNG(iyr - 1) + (100! * CSNG(irow - 1)) +
             CSNG(icol)
         GET #2, baseadd, qw(l).qq
         GET #2, baseadd + 1, qw(2).qq
         GET #2, baseadd + 100, qw(3).qq
         GET #2, baseadd + 101, qw(4).qq
         FOR i = 1 TO 4
            IF qw(i).qq < 1 OR qw(i).qq > 1E+07 THEN
               qw(i).qq = 0
            END IF
         NEXT i
         CLS
         FOR i = 0 TO 1
            FOR j = 0 TO 1
               i i = 2 * i + j + l
               qw(ii).qq = qw(ii).qq + q(iyr) * wt(i, j)
            NEXT j
         NEXT i
         PUT #2, baseadd, qw(l).qq
         PUT #2, baseadd + 1, qw(2).qq
         PUT #2, baseadd + 100, qw(3).qq
         PUT #2, baseadd + 101, qw(4).qq
      NEXT iyr
   LOOP

   CLOSE #1                       'Done with actual pumpages '
REM    *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
REM
REM   Begin writing weighted pumpages to grid nodes.
REM
REM    *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *

   FOR i = 1 TO nc
      FOR j = 1 TO nr
         IF iprint(i, j) THEN
            baseadd = (100! * (CSNG(j) - 1)) + CSNG(i)
            FOR iyr = 1 TO nyrs
               GET #2, 10000! * CSNG(iyr - 1) + baseadd, qw(l).qq
               q(iyr) = qw(l).qq
            NEXT iyr
            Col$ = LTRIM$(STR$(i))
            PRINT #3, col$; TAB(5); j;
            FOR iyr = 1 TO nyrs
                  PRINT #3, USING " ##.######"; q(iyr);
            NEXT iyr
            PRINT #3,
         END IF
      NEXT j
   NEXT i

   CLOSE #2
   CLOSE #3

END
```

[redacted]