HYDROGEOLOGY AND SIMULATION OF GROUND-WATER FLOW IN THE ROCHESTER AREA, SOUTHEASTERN MINNESOTA, 1987-88

By Geoffrey N. Delin

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MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information
write to:

District Chief
U.S. Geological Survey
702 Post Office Building
St. Paul, Minnesota 55101

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
foot (ft)	0.3048	meter
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
gallon (gal)	3.785	liter
million gallons (M/gal)	3,785	cubic meters
foot per day (ft/d)	0.3048	meter per day
foot per day per foot [(ft/d)/ft]	1.000	meter per day per meter
foot squared per day (ft^2/D)	0.09290	meter squared per day
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon per minute (gal/min)	0.06308	liter per second
million gallons per year (Mgal/yr)	0.0001200	cubic meter per second
inches per year (in/yr)	25.4	millimeter per year

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

HYDROGEOLOGY AND SIMULATION OF GROUND-WATER FLOW IN THE ROCHESTER AREA, SOUTHEASTERN MINNESOTA, 1987-88

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ABSTRACT

Ground-water flow in the St. Peter-Prairie du Chien-Jordan aquifer was studied in a 700 square-mile area surrounding Rochester, Minnesota. The aquifer consisting of sandstone, limestone, and dolomite is locally confined by the Decorah-Platteville-Glenwood sequence of shales and limestones. Regional flow in the aquifer is from a ground-water divide on the western, southern, and eastern sides of the city toward various rivers. A 140-square-mile area of the aquifer is a source of water supply for the Rochester area.

A cone of depression in the potentiometric surface of the aquifer throughout most of the year is centered around high-capacity (greater than about 200 gallons per minute) wells in downtown Rochester. The cone covered an area of about 2.3 square miles in August 1988.

Most streams in the area gain water from the ground-water system. One reach of the South Fork Zumbro River, however, loses water to the system. This loss is probably caused by the pumping of nearby high-capacity wells.

A ground-water-flow model was used to simulate the effects of an extended drought near Rochester. Conclusions based on the simulations are that (1) reduced recharge and increased pumping, conditions that could exist during a 3-year drought, would probably lower water levels 5 to 10 feet regionally and more than 30 feet in the city; (2) pumping of six additional municipal wells on the perimeter of the city would lower regional water levels about 1 to 5 feet; and (3) that water levels would recover 1 to 18 feet if pumping from six municipal wells in downtown Rochester were discontinued.

The area encompasses five recharge zones that can be delineated on the basis of recharge rate. About 54 percent of recharge to the aquifer in the area contributing water to Rochester is from a zone along the edge of the Decorah-Platteville-Glenwood confining unit. About 10 percent of recharge in this contributing area is to the sewered area of Rochester.

INTRODUCTION

The principal source of ground water for the city of Rochester, Olmsted County, southeastern Minnesota (fig. 1), is the St. Peter-Prairie du Chien-Jordan aquifer. Part of this aquifer is a karstic dolomite that is exposed or is near land surface in low-lying areas. In some areas, nitrate concentration of water in the aquifer exceeds the U.S. Environmental Protection Agency drinking-water regulation of 10 mg/L (milligrams per liter) (U.S. Environmental Protection Agency, 1976). Officials are concerned that additional ground-water withdrawals and the use and the disposal of agricultural, industrial, and household chemicals might adversely affect the quantity and the quality of the ground water.

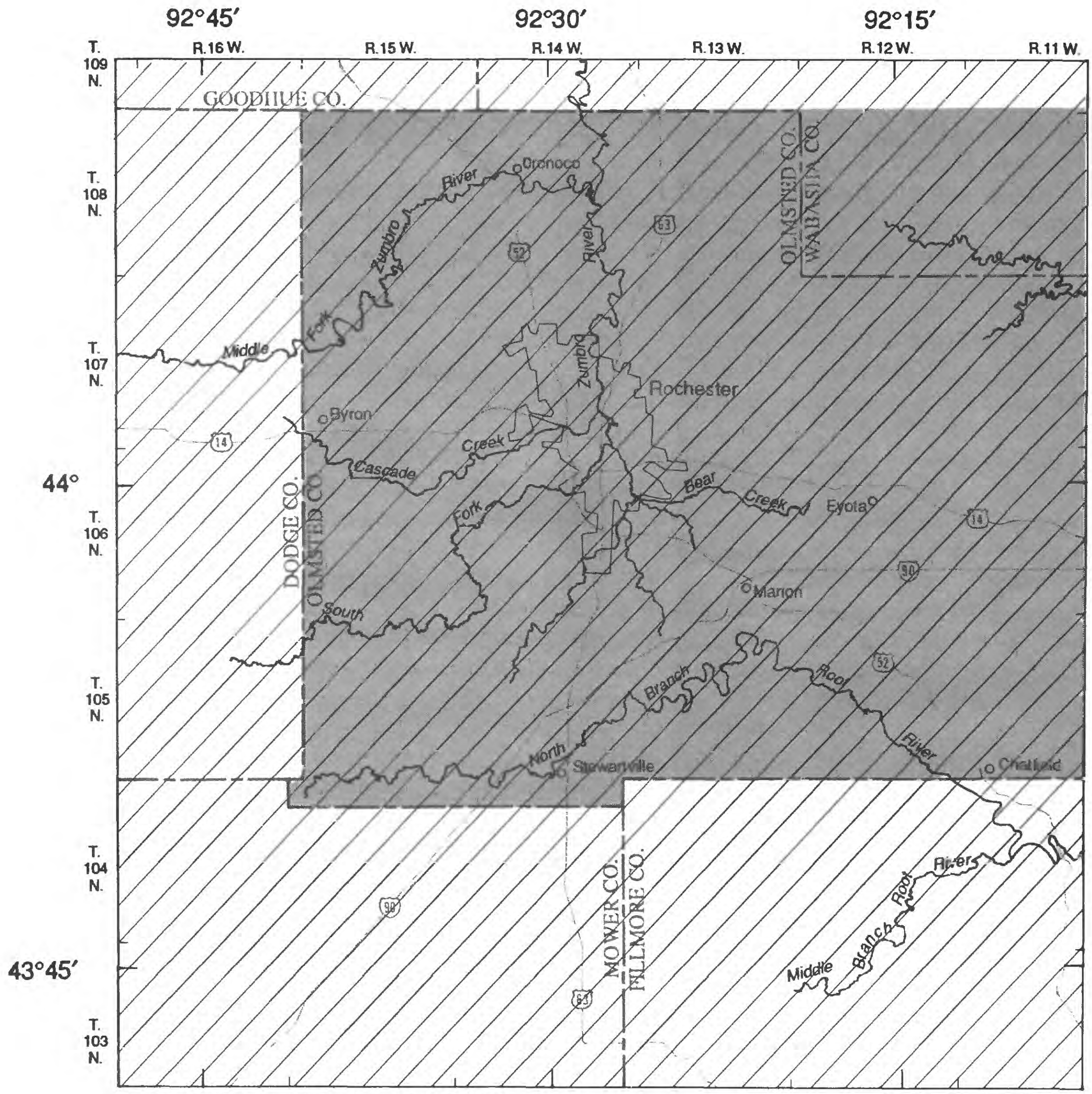
In order to manage the ground-water supply and to plan for additional development, Rochester Public Utilities (RPU) needed information on the availability and movement of ground water near Rochester. The U.S. Geological Survey, in cooperation with RPU, made a 3-year study (1987-89) to describe the hydrogeology and the ground-water flow in the Rochester area. Specific objectives of the study were to (1) estimate the effects of present and future ground-water withdrawals on ground-water levels, direction of movement, storage, and streamflow; (2) describe the hydraulic properties of the major aquifers in the Rochester area, particularly the St. Peter-Prairie du Chien-Jordan aquifer; and (3) determine the direction and the flow of water in the St. Peter-Prairie du Chien-Jordan aquifer.

Purpose and Scope

This report (1) describes the hydrogeology and ground-water flow in the Rochester, Minn. area; (2) describes the construction, calibration, testing, and application of a numerical model used to simulate ground-water flow in the St. Peter-Prairie du Chien-Jordan aquifer near Rochester, Minn.; and (3) evaluates the possible consequences of various hypothetical ground-water-development plans. The report provides a detailed description of water-level fluctuations and areal recharge to the aquifer. The limitations of the ground-water-flow model are also discussed.

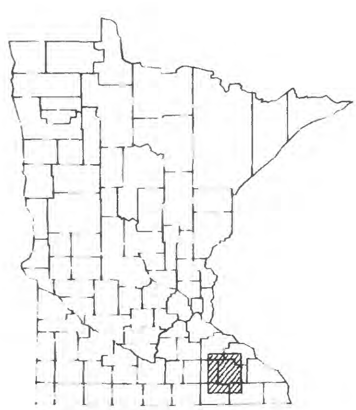
Location and Description of Study Area

The study area covers about 700 mi^2 (square miles) in Olmsted County and parts of surrounding counties in southeastern Minnesota (Fig. 1). The city of Rochester is in the west central part of Olmsted County. The modeled area covers approximately 1,050 mi^2 in parts of Olmsted, Fillmore, Mower, Dodge, Goodhue, and Wabasha Counties. This area is larger than the study area because the modeled area includes regional ground-water boundaries. The study area is drained by the Zumbro, the Whitewater, and the Root Rivers, tributaries of the Mississippi River. Topography is rolling to undulating in upland areas and steep near streams and drainageways. Most of the approximately 27.5 in. (inches) of mean annual precipitation (Baker and Kuehnast, 1978) is rainfall in May through September.



Base from U.S. Geological Survey 1:100,000
Digital Line Graph Maps; Austin, 1985, Rochester, 1989

0 5 10 MILES
0 5 10 KILOMETERS



EXPLANATION

STUDY AREA

AREAL EXTENT OF GROUND-WATER-FLOW MODEL

Figure 1.--Location of study area and extent of ground-water-flow model.

Previous Investigations

The hydrogeology of the area has been described in several publications. Hall and others (1911, p. 290-294) and Theil (1944, p. 338-348) investigated the hydrology of southern Minnesota including Olmsted County. A general description of the hydrogeology of the study area was presented in the hydrologic atlases of the Zumbro River watershed by Anderson and others (1975) and the Root River watershed by Broussard and others (1975). A general description of ground water in the study area was provided by Lindholm and Norvitch (1976). Hydrogeologic and water-quality characteristics of the area were discussed by Ruhl and Wolf (1984) for the upper carbonate aquifer, by Ruhl and Wolf (1983) for the St. Peter aquifer, by Ruhl and others (1983) for the Prairie du Chien-Jordan aquifer, by Ruhl and others (1982) for the Ironton-Galesville aquifer, and by Wolf and others (1983) for the Mount Simon-Hinckley aquifer. Delin and Woodward (1984) described the hydrogeologic setting and potentiometric surfaces of regional aquifers in southeastern Minnesota. Municipal water use and aquifer utilization were presented by Woodward (1985). Woodward (1986) described the hydraulic properties of regional aquifers in southeastern Minnesota. Balaban (1988) provided a detailed description of geology; hydrogeology; sensitivity of the ground-water system to pollution, sinkholes and sinkhole probability; and the water-well data base in Olmsted County.

Methods of Investigation and Sources of Data

A three-dimensional, finite-difference model (McDonald and Harbaugh, 1988) was used to simulate ground-water flow. The model, constructed with geologic data collected by the Minnesota Geological Survey (Balaban, 1988), was calibrated to steady state primarily with hydrologic data collected for this study. Transient simulations were based on 12 years of water-level and pumping data provided by RPU and the Minnesota Department of Natural Resources (MDNR). The model was used to estimate the effects of hypothetical pumping on regional ground-water levels and streamflow.

Values of mean horizontal hydraulic conductivity were determined through analysis of data from 21 pumping tests run on Rochester municipal wells. Aquifer horizontal hydraulic conductivity was also estimated from specific-capacity data at approximately 250 other locations by the method of Theis and others (1963). The technique is based on the assumption that large specific capacities indicate that an aquifer has a large transmissivity.

A network of 129 domestic, municipal, commercial, industrial, and observation wells (fig. 2 and appendix A) was used to monitor water levels in the study area. An altimeter was used to estimate land-surface elevations for most wells in the network to within plus or minus 2 ft (feet). The remaining well elevations were estimated to within about 5 ft with U.S. Geological Survey 7 1/2-minute quadrangle maps. Most of the wells are completed in the St. Peter Sandstone, Prairie du Chien Group, or Jordan Sandstone; these formations comprise the major aquifer used in the study area. Several wells were completed in the upper carbonate aquifer and glacial drift. Water-level fluctuations were measured monthly in 40 of the wells.

Water-level and streamflow data were used to calibrate the ground-water flow model to steady state. Synoptic measurements of water levels in most observation wells were made during August 1987, January 1988, and August 1988 to map the potentiometric surface of the St. Peter-Prairie du Chien-Jordan aquifer. Streamflow gain or loss for area streams was measured during base-flow in March and August 1987 to estimate ground-water contribution to stream-flow. Twenty-six test holes were drilled along major streams to determine the hydraulic connection between each stream and the underlying bedrock aquifer.

Water levels measured in a pair of domestic wells completed in the upper carbonate and St. Peter-Prairie du Chien-Jordan aquifers, about 100 ft apart, were used to estimate the change in hydraulic head across the Decorah-Platteville-Glenwood confining unit. Such a set of wells is herein termed a well cluster.

Numbering System for Wells and Test Holes

The system of numbering wells and test holes is based on the U.S. Bureau of Land Management's system of land subdivision (township, range, and section). The system of numbering data-collection points is shown in figure 3. In this system, the first numeral of a location number indicates the township; the second, the range; and the third, the section in which the point is located. Lower-case letters after the section number indicate the location within the section; the first letter denotes the 160-acre tract; the second, the 40-acre tract; and the third, the 10-acre tract. Letters A, B, C, and D are assigned in a counterclockwise direction, beginning in the northeast corner of each tract. The number of lower-case letters indicates the accuracy of the location number; if a point can be located within a 10-acre tract, three lower-case letters are shown in the location number. For example, the number 106.14.15ADC indicates a test hole or well in the southwest 1/4 of the south-east 1/4 of the northeast 1/4 of section 15, township 106 north, range 14 west.

Acknowledgments

The author is grateful to Rochester Public Utilities for providing technical assistance and water-use and other information that were instrumental in the investigation. Thanks are given also to the Minnesota Geological Survey, which provided maps, information, and assistance in preparing input for the ground-water-flow model; to the Olmsted County Health Department, which provided valuable technical assistance for the study; and to Bruce Liesch & Assoc., consultants to the city of Rochester, who provided pumping-test information for the Rochester municipal wells.

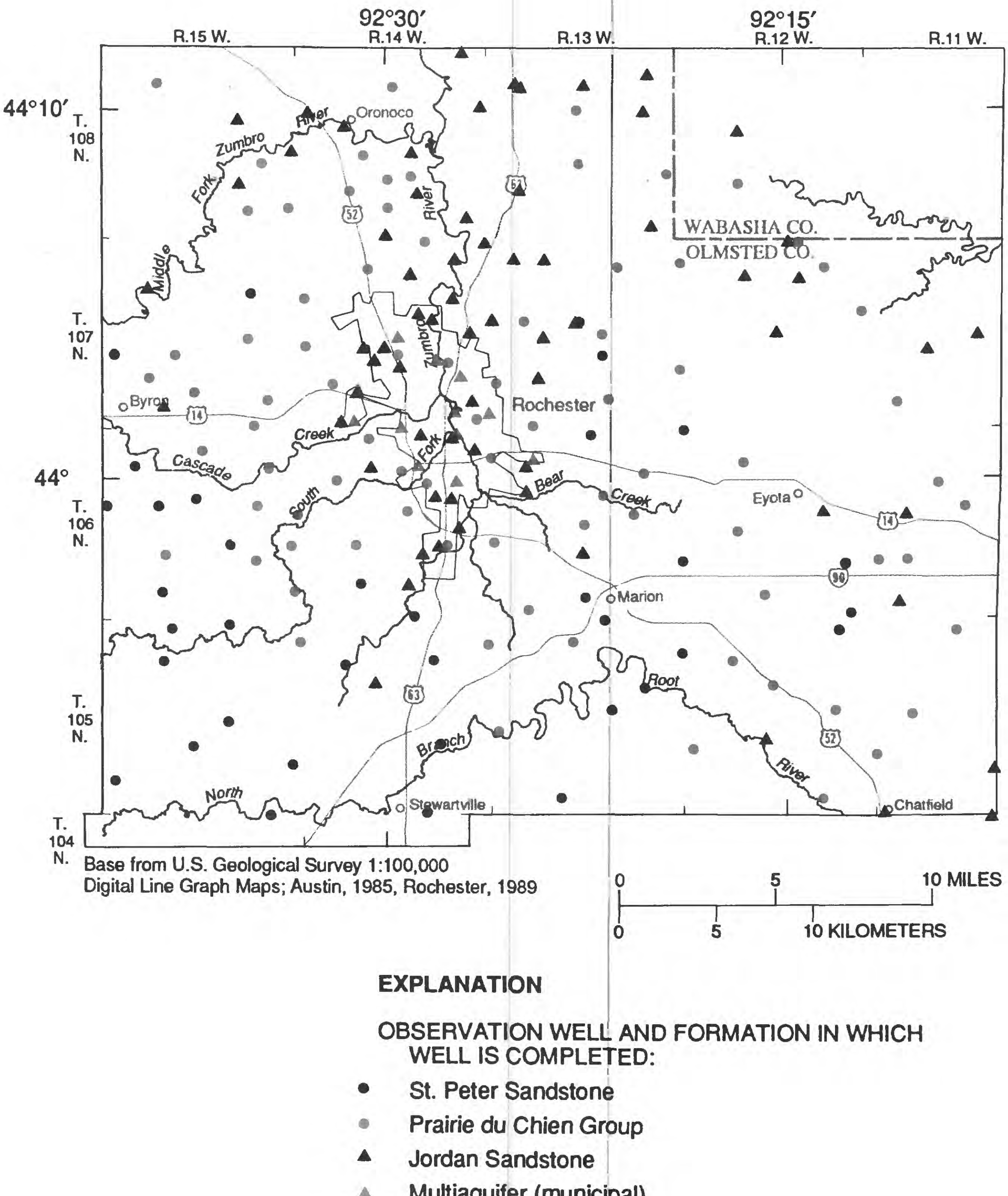


Figure 2.--Locations of observation wells in the study area.

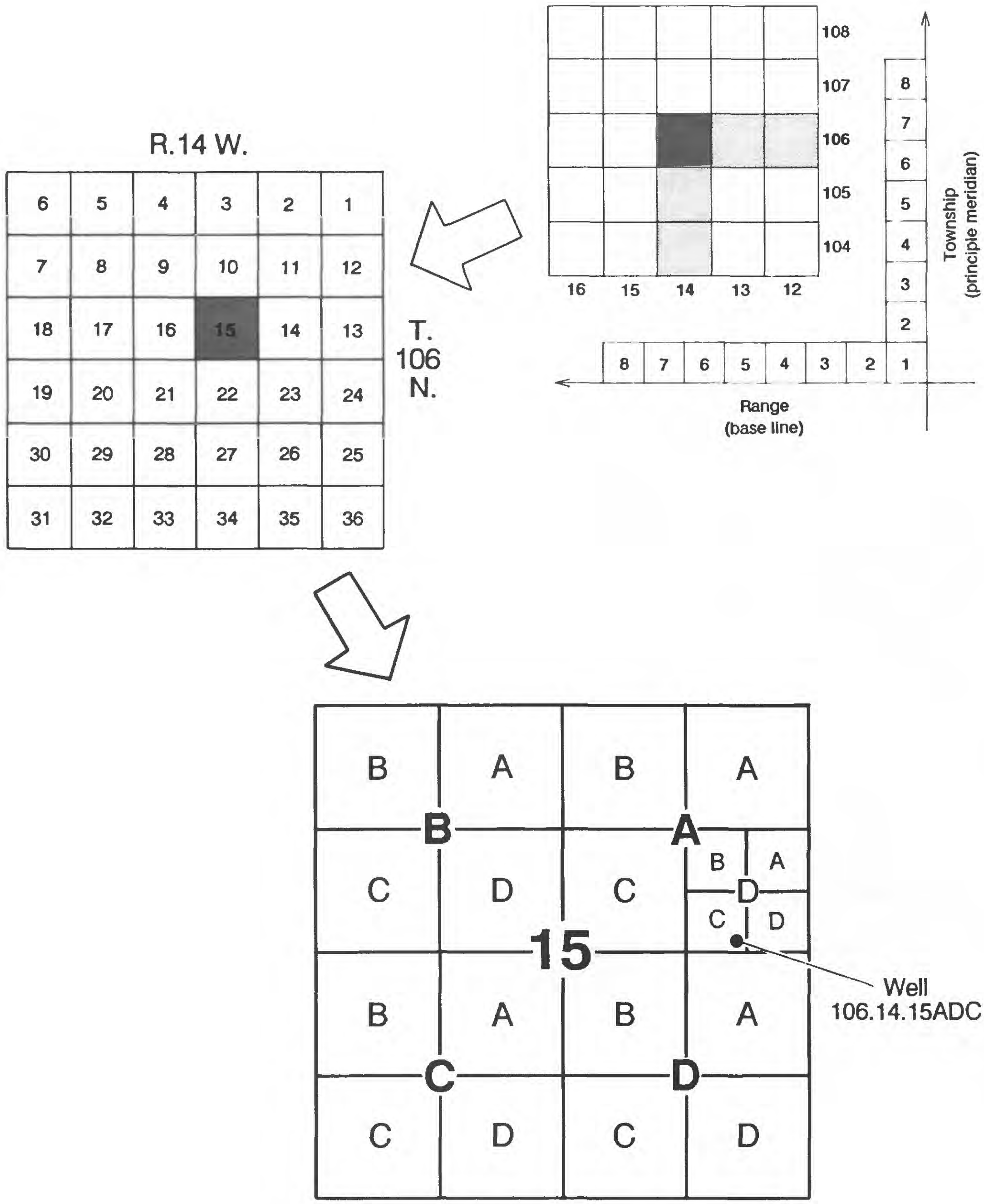


Figure 3.--Numbering system for wells and test holes.

HYDROGEOLOGY

The sequence of sedimentary rocks in the Rochester area (fig. 4) has been divided into hydrogeologic units of regional aquifers and regional confining units (Delin and Woodward, 1984; Balaban, 1988). Regional bedrock aquifers, in descending order, are the upper carbonate, St. Peter-Prairie du Chien-Jordan, Franconia-Ironton-Galesville, and the Mount Simon (Balaban, 1988). Regional bedrock confining units, in descending order, are the Decorah-Platteville-Glenwood, St. Lawrence, and Eau Claire. Glacial deposits in the area locally confine the underlying bedrock aquifers. A generalized hydrogeologic column illustrating the vertical distribution of each unit and its water-bearing characteristics is shown in figure 4. The surface extent of the hydrogeologic units is shown in figure 5 and a cross-sectional view of the hydrogeologic units above the St. Lawrence confining unit is shown in figure 6.

Although the St. Peter-Prairie du Chien-Jordan aquifer was the focus of the study, many of Rochester's municipal wells are open to one or more of the underlying formations. Current results, and results from a previous study (Delin and Woodward, 1984), support the author's conclusion that some water recharging the St. Peter-Prairie du Chien-Jordan aquifer is from the upper carbonate aquifer. Thus, description of the hydrogeologic characteristics of these aquifers is essential to an understanding of ground-water flow in the St. Peter-Prairie du Chien-Jordan aquifer. Consequently, a brief description of the lithology and the hydraulic characteristics of the nine hydrogeologic units in the area is included in the sections that follow. Balaban (1988) provides a detailed description of the lithology in Olmsted County.

Aquifers and Confining Units

An aquifer is a formation, a group of formations, or a part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells or springs. Hydraulic conductivity is the capacity of a porous material, such as aquifers and confining units, to transmit water under pressure. It is the rate of flow of water passing through a unit section of area under a unit hydraulic gradient at unit kinematic viscosity. Hydraulic-conductivity data are sparse for all aquifers in the area. Transmissivity is a property used to describe the flow of water through aquifers and is described by the following equation:

$$T = kb, \tag{1}$$

where

- T is aquifer transmissivity $[L^2/t]$,
- k is aquifer hydraulic conductivity $[L/t]$, and
- b is aquifer thickness $[L]$.

Data are insufficient to accurately map areal variations in the hydraulic properties of local aquifers.

A confining unit is a hydrogeologic unit of lower vertical hydraulic conductivity relative to an overlying aquifer. The vertical hydraulic conductivity of confining units is much lower than the horizontal and the vertical hydraulic conductivity of aquifers. Thus, confining units retard the vertical flow of ground water to and between aquifers. Hydraulic-conductivity data for confining units in the area are scarce. Descriptions of the regional aquifers and confining units in order of increasing depth below land surface follow this paragraph.

Glacial Drift

Glacial drift overlying bedrock locally is typically 0 to 50 ft thick (Balaban, 1988). Thickness is greater than 250 ft in a drift-filled bedrock valley west of Rochester (fig. 5; Balaban, 1988). Glacial drift is till, loess, and outwash. Till, an unsorted, unstratified sediment deposited directly by glacial ice, contains a high percentage of clay and silt. Loess, an unstratified sediment, is composed predominantly of silt that is deposited by wind. Outwash is sorted and stratified sand and gravel deposited beyond the glacial-ice front by meltwater. For simplification, recently deposited river alluvium comprised of silt, sand, and gravel is included with the glacial drift.

Hydraulic properties of the drift are variable, partly because of the wide range and the distribution of material in it. Consequently, glacial drift can be either an aquifer or a confining unit. Where till is relatively thick, as in the bedrock valley west of Rochester (fig. 5), drift is a confining unit for the underlying bedrock aquifers. The vertical hydraulic conductivity of till typically ranges from 10^{-6} to 1 ft/d (Freeze and Cherry, 1979, p. 29). Movement of water in the drift is primarily intergranular. Glacial outwash and alluvial deposits although not considered to be a regional aquifer locally could supply water to wells. Horizontal hydraulic conductivities for glacial aquifers typically range from 10^{1} to 10^{4} ft/d (feet per day) (Freeze and Cherry 1979, p. 29).

Upper Carbonate Aquifer

The upper carbonate aquifer is composed of the Maquoketa Shale, Dubuque Formation, and Galena Dolomite of limestone, dolomite, dolomitic limestone, and shale. The aquifer, whose thickness exceeds 300 ft locally (Balaban, 1988), underlies areas west, south, and east of Rochester (fig. 5).

Transmissivity of the upper carbonate aquifer generally ranges from 300 to 12,000 ft^2/d (feet squared per day) on the basis of horizontal hydraulic conductivities of 3 to 40 ft/d (Kanivetsky and Walton, 1979). The upper carbonate aquifer yields water primarily to wells that intersect fractures, joints, and solution channels in the carbonate rocks.

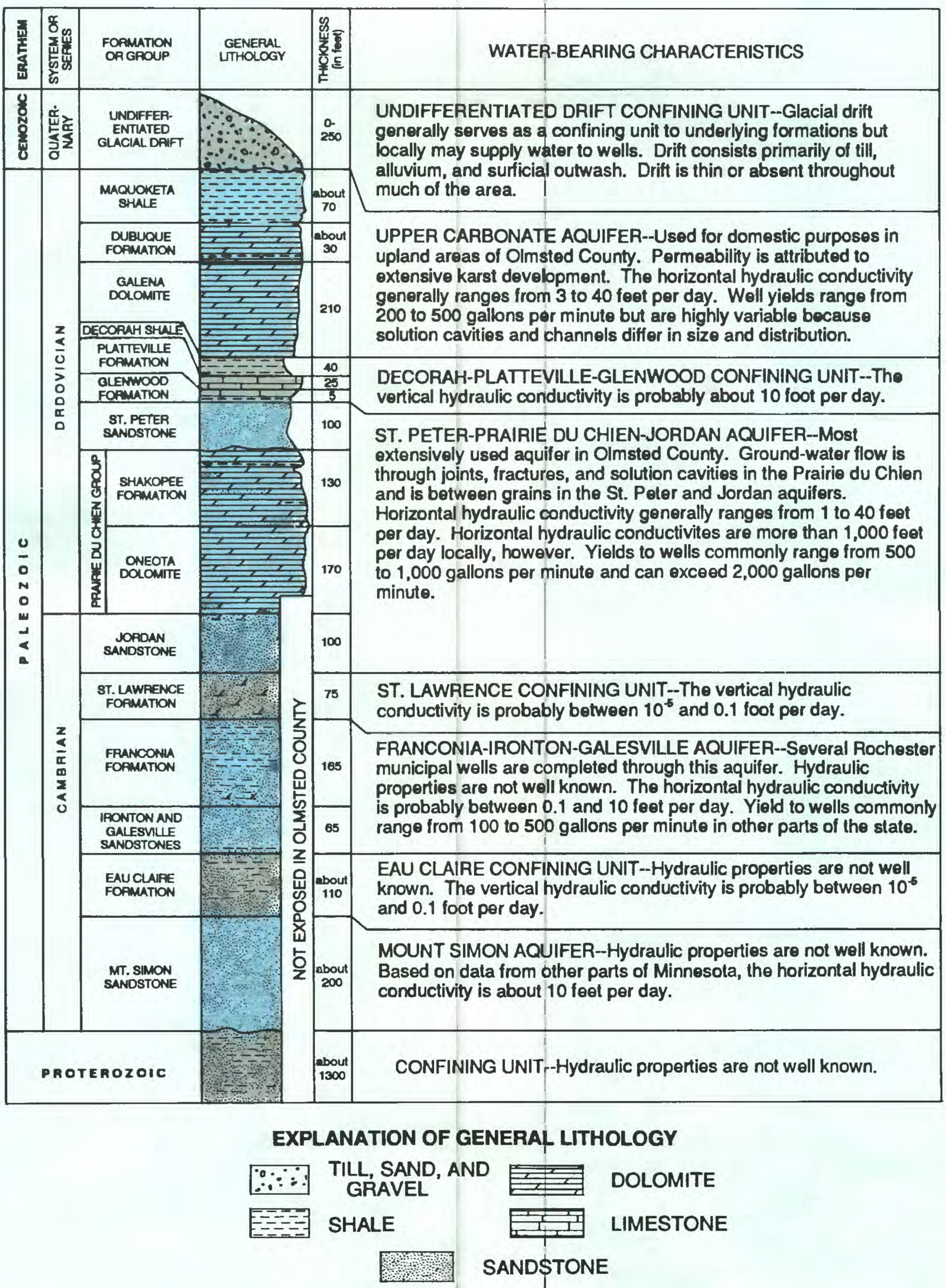
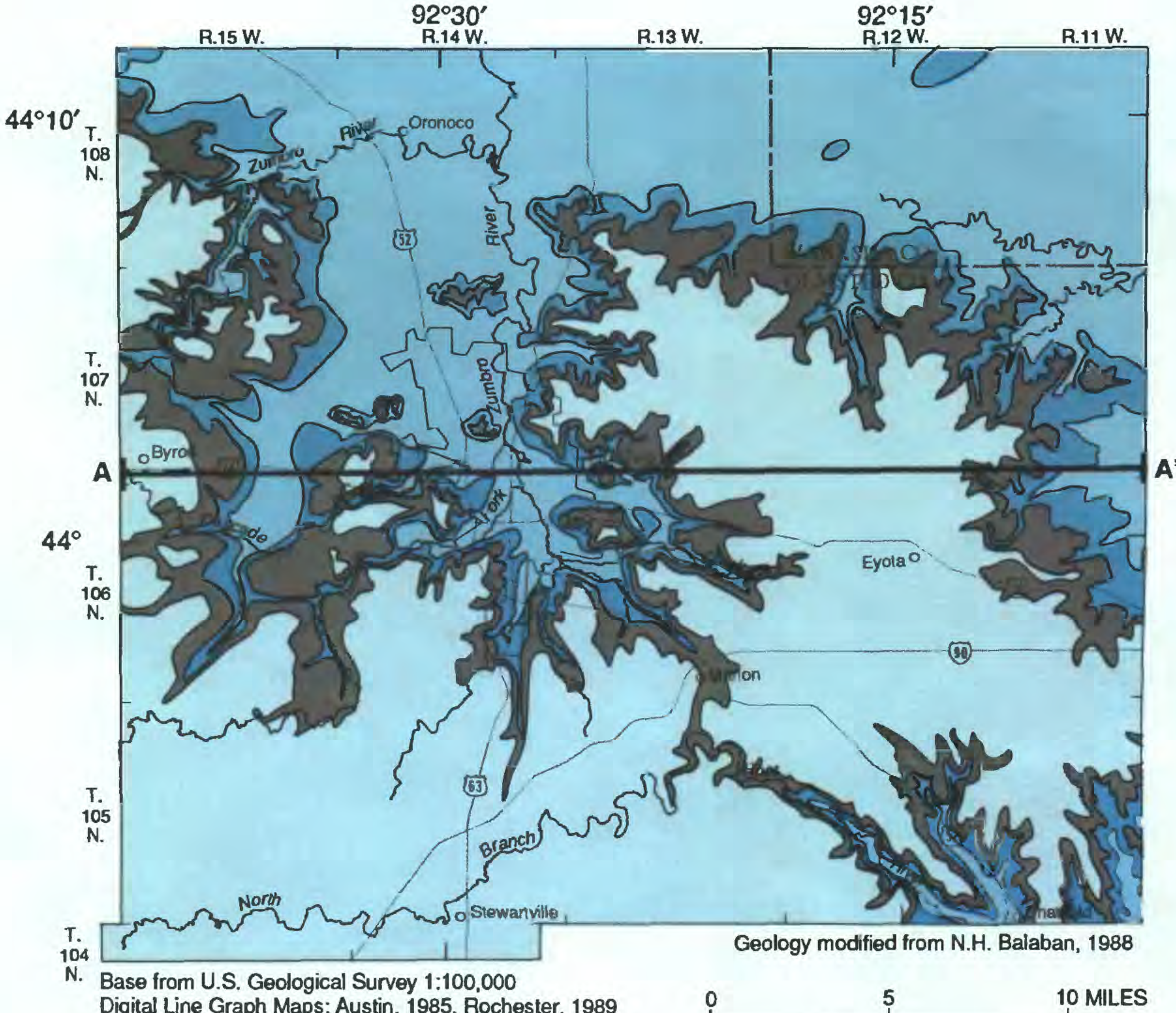


Figure 4.--Generalized hydrogeologic column of regional aquifers and confining units, Olmsted County, Minnesota (geology modified from N.H. Balaban, 1988).

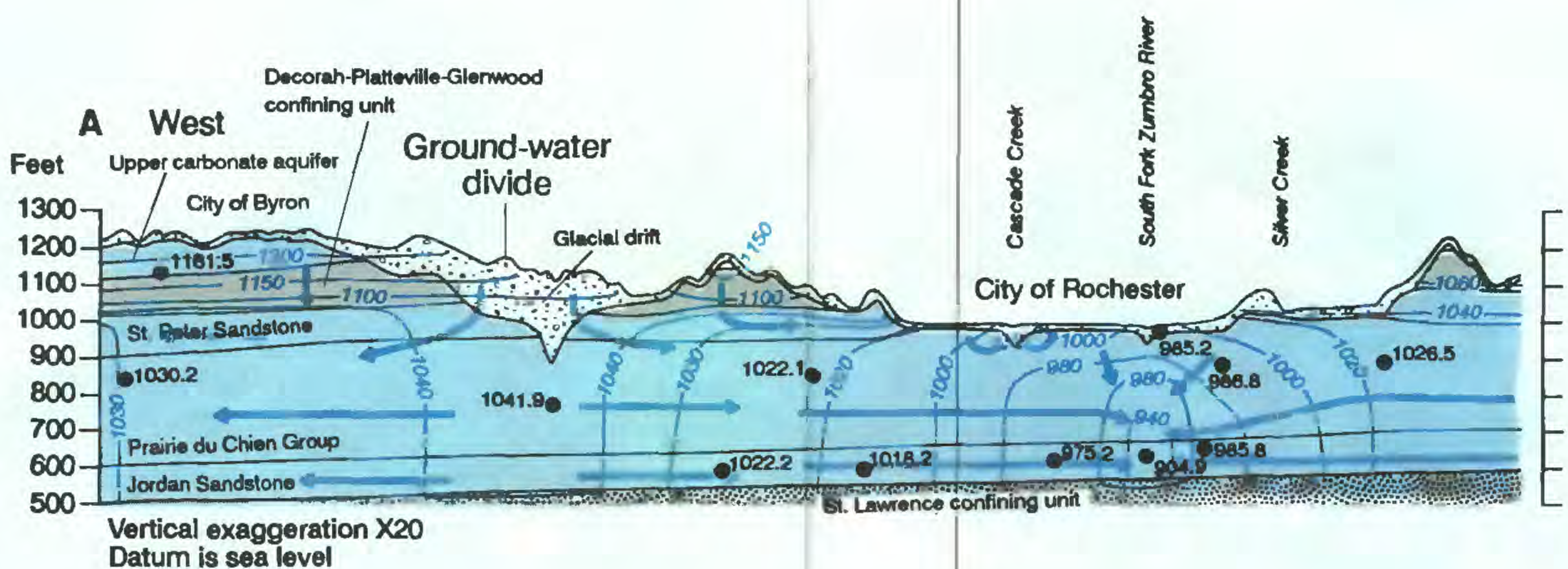


EXPLANATION

EXTENT OF BEDROCK UNITS:

- Upper carbonate aquifer
- Decorah-Platteville-Glenwood confining unit
- St. Peter Sandstone (aquifer)
- Prairie du Chien Group (aquifer)
- A—A' Trace of hydrogeologic section

Figure 5.--Bedrock hydrogeology and trace of hydrogeologic section A-A'.



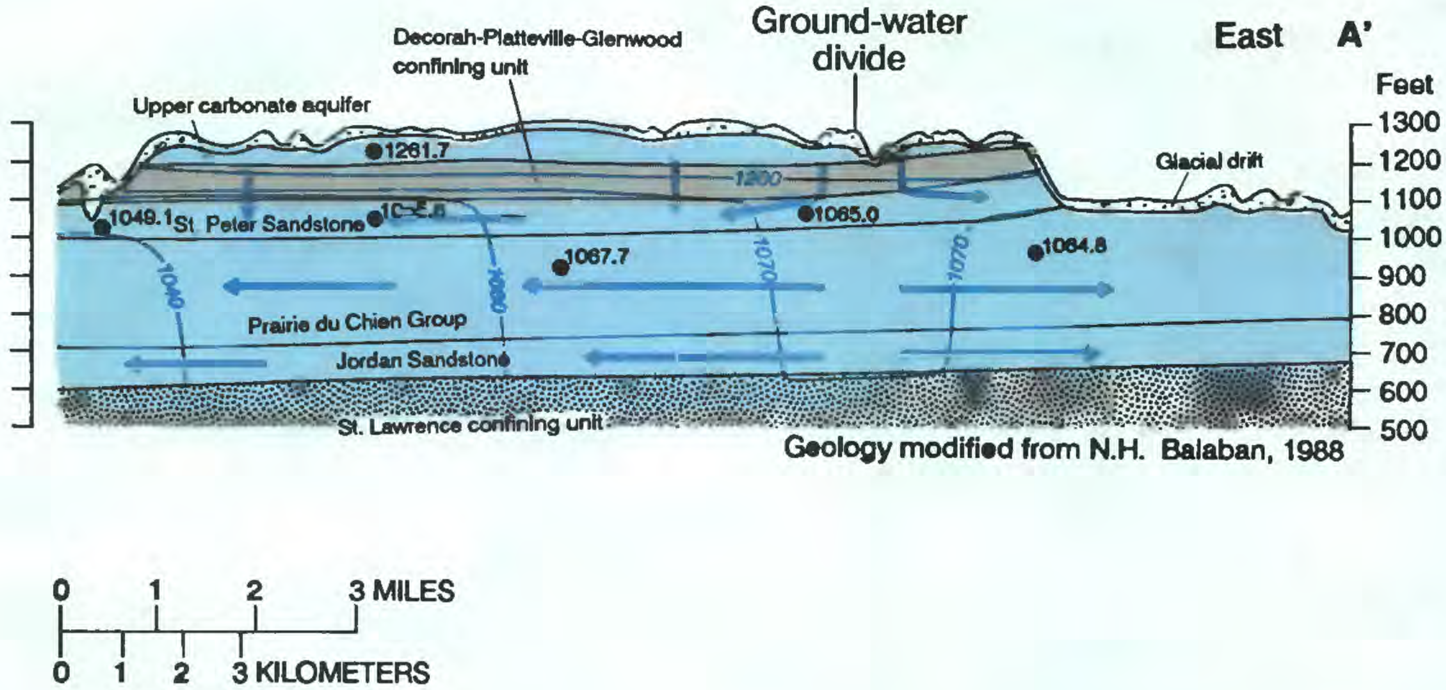
EXPLANATION

—1100— POTENTIOMETRIC CONTOUR. Interval variable.

1059.3● POINT OF KNOWN HYDRAULIC HEAD

← DIRECTION OF GROUND-WATER FLOW

Figure 6.–Hydrogeologic section A-A' through Olmsted County,



Minnesota, August 1987 (line of section shown on Figure 5).

Decorah-Platteville-Glenwood Confining Unit

The Decorah-Platteville-Glenwood confining unit is composed of shale, shaley dolomite and limestone, and dolomitic limestone (fig. 4). This confining unit occurs in areas west, south, and east of Rochester (fig. 5). The Decorah-Platteville-Glenwood is the primary confining unit for the underlying St. Peter-Prairie du Chien-Jordan aquifer. Average thickness of the confining unit is about 70 ft (Balaban, 1988), and its maximum known thickness, 113 ft, is in the southwest part of Olmsted County (Minnesota Geological Survey, written commun., 1987).

A vertical hydraulic conductivity of 10^{-4} ft/d was estimated for the Decorah-Platteville-Glenwood confining unit from ground-water flow-model analyses in the area around Minneapolis-St. Paul (M. E. Schoenberg, written commun., 1987). Hydraulic conductivities for shale typically range from 10^{-7} to 10^{-3} ft/d (Freeze and Cherry, 1979, p. 29).

Water-level declines in two well clusters in the Rochester area suggest a 200-foot decline in hydraulic head across the Decorah-Platteville-Glenwood confining unit. This decline corresponds to a vertical head gradient of about 2.9 ft per ft of confining-unit thickness. The vertical hydraulic conductivity of the confining unit can be approximated by use of the above information and Darcy's Law as follows:

$$k = Q/(dh/dl), \tag{2}$$

where

- k is the vertical hydraulic conductivity of the confining unit [L/t],
- Q is the leakage through the confining unit per unit area [L/t],
- dh is the change in hydraulic head through the confining unit per unit area [L], and
- dl is the confining unit thickness [L].

A vertical hydraulic conductivity of 10^{-5} ft/d is probable from application of the following assumptions to equation 2: a change in hydraulic head through the confining unit of 200 ft, a thickness of 70 ft, and a 0.5 in/yr leakage rate through the confining unit.

St. Peter-Prairie du Chien-Jordan Aquifer

The St. Peter-Prairie du Chien-Jordan aquifer is composed of the St. Peter Sandstone, the Prairie du Chien Group (limestones and dolomites), and the Jordan Sandstone (fig. 4). The St. Peter is a fine- to medium-grained sandstone; well-sorted and poorly cemented; its average thickness is about 100 ft (Balaban, 1988). The St. Peter, which underlies areas west, south, and east of Rochester (fig. 5), is exposed along road cuts and outcrops in the city. The underlying Prairie du Chien Group is composed of the Shakopee Formation, a sandy, shaley, thin-bedded dolomite, and the thick-bedded Oneota Dolomite. Average thickness of the Prairie du Chien is about 300 ft (Balaban, 1988). The Prairie du Chien, which underlies the entire area, is generally the uppermost bedrock unit beneath Rochester. The South Fork Zumbro

River and Bear Creek flow on top of this formation near 4th Street SE in Rochester. The underlying Jordan is a friable to well-cemented, fine- to coarse-grained sandstone whose average thickness is about 100 ft (Balaban, 1988). The Jordan underlies the entire area.

The range of transmissivity of the St. Peter Sandstone part of the aquifer, from 200 to 3,000 ft^2/d is based on results of 58 specific-capacity tests in Olmsted County and on results of laboratory analyses of rocks from the Minneapolis-St. Paul area (Norvitch and others, 1974, p. 114-115). Hydraulic data from outside the study area, however, do not necessarily represent the hydraulic properties of aquifers and confining units in the Rochester area. Transmissivities are generally uniform for the St. Peter; however, values greater than 30,000 ft^2/d were estimated from data obtained in specific-capacity tests. Movement of water in the St. Peter is primarily intergranular.

Transmissivity of the Prairie du Chien Group part of the aquifer is highly variable owing to secondary permeability caused by fractures and solution cavities. The Prairie du Chien transmits water primarily through fractures, joints, and solution channels. The typical range of transmissivity of the Prairie du Chien, from 300 to 1,000 ft^2/d, is based on results of 101 specific-capacity measurements in Olmsted County. Transmissivities greater than 100,000 ft^2/d were calculated at some wells. Transmissivities were computed under the assumption that the formation is isotropic. Data are insufficient to determine the degree of anisotropy in the Prairie du Chien in southeastern Minnesota.

On the basis of results of aquifer tests at four municipal wells in Rochester, transmissivity of the Jordan Sandstone part of the aquifer ranges from 900 to 1,700 ft^2/d in the city. Transmissivities ranging from 100 to 5,000 ft^2/d were calculated with data from 54 specific-capacity tests in Olmsted County. Transmissivities greater than 30,000 ft^2/d were calculated at some wells. Transmissivity based on results of laboratory analyses of rocks from the Minneapolis-St. Paul area also exceeded 30,000 ft^2/d (Norvitch and others, 1974, p. 114-115). Movement of water in the Jordan is predominantly intergranular.

St. Lawrence Confining Unit

The St. Lawrence confining unit consists of the St. Lawrence Formation and is composed of dolomitic siltstone and is about 75 ft thick (Balaban, 1988) (fig. 4). It occurs throughout the area and immediately underlies the St. Peter-Prairie du Chien-Jordan aquifer.

Packer-test data in the St. Paul area (Miller, 1984) are indicative of a vertical hydraulic conductivity of 10^{-3} ft/d for the St. Lawrence. A vertical hydraulic conductivity of 10^{-5} ft/d was estimated from ground-water-flow model analyses in the Minneapolis-St. Paul area (M. E. Schoenberg, written commun., 1987).

Franconia-Ironton-Galesville Aquifer

The Franconia Formation part of the Franconia-Ironton-Galesville aquifer is a fine-grained glauconitic sandstone and shale about 230 ft thick (Balaban, 1988) (fig. 4). Although the Franconia Formation is included as part of this aquifer, it does not typically yield significant quantities of water to wells. Locally, the Franconia Formation and the overlying St. Lawrence Formation are considered to be confining unit (Delin and Woodward, 1984 and Woodward, 1986). The Ironton-Galesville part of the aquifer consists of fine- to medium-grained, poor- to well-sorted sandstone whose average thickness is about 65 ft (Balaban, 1988).

Transmissivity of the Ironton-Galesville Sandstones part of the aquifer is calculated to be about 600 ft^2/d, on the basis of regional specific-capacity data in southeast Minnesota (Woodward, 1986). Transmissivity of the Ironton-Galesville, which ranges from 6 to 120 ft^2/d, is based on laboratory analyses of rocks in the Minneapolis-St. Paul area (Norvitch and others, 1974, p. 114-115). Horizontal hydraulic conductivities of the Ironton and Galesville, calculated on the basis of packer-test data in the St. Paul area, were 4.0 and 1.0 ft/d, respectively (Miller). Horizontal hydraulic conductivities calculated similarly for the upper and lower parts of the Franconia, were 2.0 and 0.1 ft/d, respectively (Miller, 1984). Miller (1984) suggests a ratio of vertical to horizontal hydraulic conductivity of 10 to 1 for the Ironton, the Galesville, and the upper part of the Franconia; the ratio is 100 to 1 for the lower part of the Franconia. Flow in the Franconia-Ironton-Galesville aquifer is primarily intergranular.

Eau Claire Confining Unit

The Eau Claire confining unit consists of the Eau Claire Formation and is composed primarily of siltstone and shale and lesser amounts of fine-grained sandstone (fig. 4). The confining unit, which occurs throughout the area, is about 110 ft thick (Balaban, 1988).

Hydraulic-head data are not available in the Rochester area for estimating the gradient across the Eau Claire confining unit. Packer-test data in the St. Paul area (Miller, 1984) are indicative of a horizontal hydraulic conductivity of 0.1 ft/d for the Eau Claire. Hydraulic conductivity for shale typically ranges from 10^{-7} to 10^{-3} ft/d (Freeze and Cherry, 1979, p. 29). Packer-test data (Miller, 1984) are indicative of a vertical hydraulic conductivity of 10^{-3} ft/d for the Eau Claire. A vertical hydraulic conductivity of 10^{-5} ft/d was calculated on the basis of results of laboratory analyses of rocks from the Minneapolis-St. Paul area (Norvitch and others, 1974, p. 114-115).

Mount Simon Aquifer

The Mount Simon Sandstone aquifer consists of poorly cemented, moderate- to well-sorted, fine- to coarse-grained sandstone with interbeds of siltstone and shale (fig. 4). The thickness of the aquifer is about 200 ft (Balaban, 1988).

Transmissivity of the Mt. Simon aquifer, calculated on the basis of regional specific-capacity data, is about 2,000 ft^2/d (Woodward, 1986). Transmissivities calculated on the basis of laboratory analyses of rocks from the Minneapolis-St. Paul area are in the range from 6 to 1,000 ft/d (Norvitch and others, 1974, p. 114-115). Movement of water in the Mount Simon is primarily intergranular.

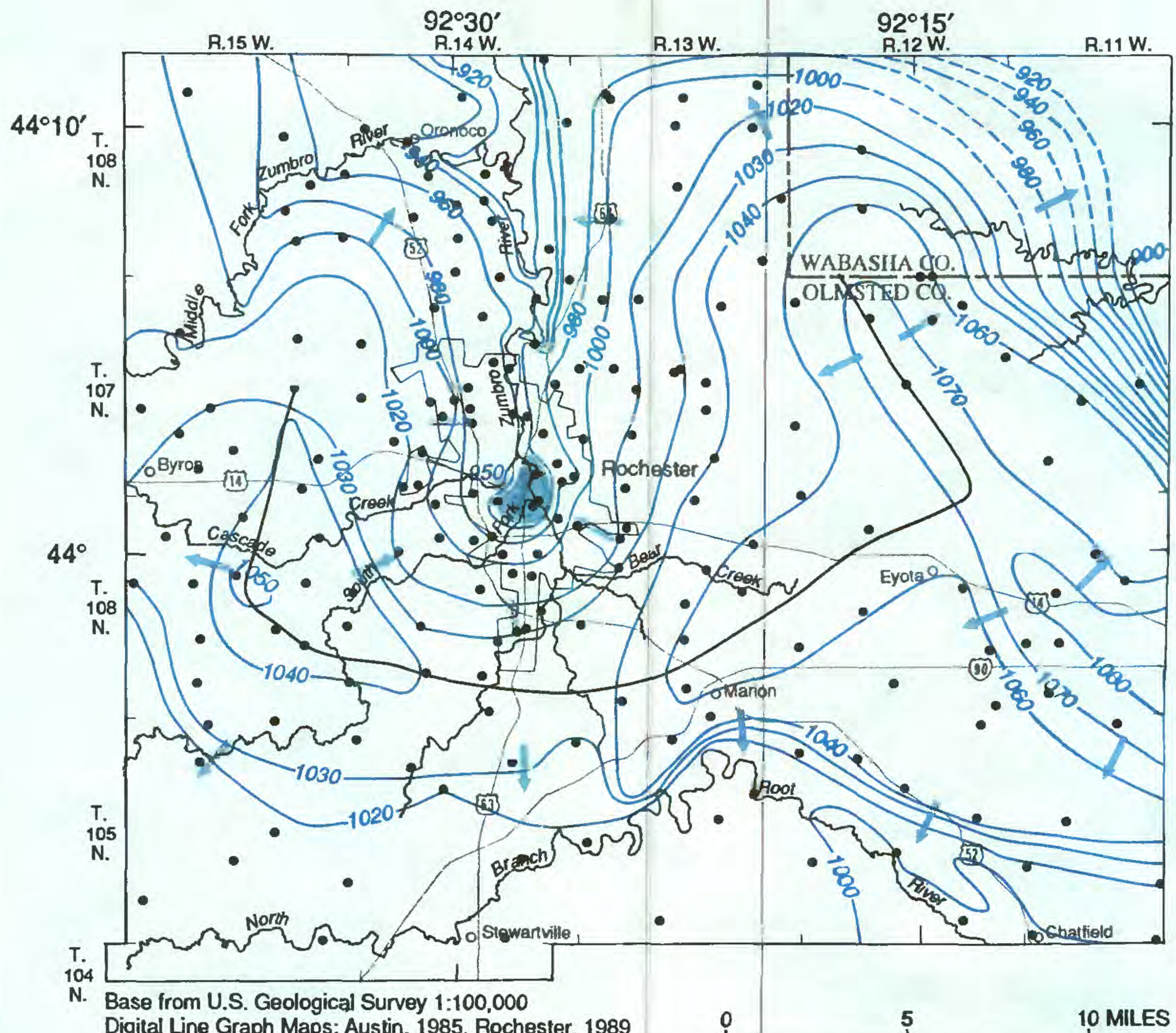
Ground-Water Flow

Ground water flows from areas of high hydraulic head toward areas of low hydraulic head. The direction of movement is related to locations of recharge to and discharge from the ground-water system. The rate of movement is related to the hydraulic conductivity of aquifer material and to the hydraulic gradient. Aquifers are less resistant to the horizontal flow of ground water than confining units are because the hydraulic conductivity of aquifers is much greater than that of confining units. Flow in aquifers is predominantly horizontal, whereas flow in confining units is predominantly vertical (fig. 6).

Water levels in the observation wells were measured during August 1987, January 1988, and August 1988 to map the St. Peter-Prairie du Chien-Jordan potentiometric surface during summer, winter, and drought. The potentiometric surface of this aquifer in August 1987 is presented in figure 7. A potentiometric surface is defined by the levels to which water will rise in tightly cased wells. The water table is a potentiometric surface.

Regional flow in the St. Peter-Prairie du Chien-Jordan aquifer generally is from a ground-water divide in the potentiometric surface, west, south, and east of Rochester, toward the South Fork Zumbro River (fig. 7). The divide bisects highs in the potentiometric surface. A ground-water divide represents a line of highest hydraulic head in the potentiometric surface that, in general, separates flow toward and away from Rochester. The ground-water divide moves in response to seasonal fluctuations in recharge to and discharge from the ground-water system. Ground-water discharge from the St. Peter-Prairie du Chien-Jordan aquifer is to major streams in the area, to production wells completed in the aquifer, and to underlying units as leakage. The regional hydraulic gradient is about 10 to 20 ft/mi. This gradient increases near the South Fork Zumbro River.

The potentiometric surface was used to define the approximate area of the St. Peter-Prairie du Chien-Jordan aquifer, contributing water to the city of Rochester (fig. 8). This roughly 140-mi^2 (square-mile) area is defined by the ground-water divide west, south, and east of Rochester. However, at the north boundary, there is no ground-water divide or other natural hydrologic boundary. The author arbitrarily selected a flow line paralled to the general direction of ground-water flow on that area; this line is treated as a no-flow boundary. The flow lines, which extend from the divide to the South Fork Zumbro River, represent the approximate northern limit of water flowing toward Rochester's municipal wells (fig. 8). The area shown in figure 8 represents conditions associated with the pumping during August 1987.



EXPLANATION

APPROXIMATE AREA OF CONE OF DEPRESSION BASED ON THE 950-FOOT CONTOUR

—920— — POTENTIOMETRIC CONTOUR--Dashed where approximate. Interval 10 and 20 feet. Datum is sea level.

GROUND-WATER DIVIDE

DIRECTION OF GROUND-WATER FLOW

• OBSERVATION WELL

Figure 7.--Potentiometric surface of the St. Peter-Prairie du Chien-Jordan aquifer near Rochester, Minnesota, August 1987.

The potentiometric surfaces for January and August 1988 are very similar to that for August 1987 except near downtown Rochester (fig. 9). Ground-water withdrawals from the St. Peter-Prairie du Chien-Jordan aquifer near downtown Rochester cause a seasonal decline in the potentiometric surface, called a cone of depression. Increased summer pumping in Rochester produces a cone of depression that is much larger and deeper (fig. 7 and fig. 9b) than that during the winter months (fig. 9a). Ground-water flow that would normally discharge to the South Fork Zumbro River from the St. Peter-Prairie du Chien-Jordan aquifer is diverted to high-capacity wells in the city during the summer. High-capacity wells are herein defined as wells that pump greater than about 200 gallons per minute. This diversion of flow is less during the winter.

The effects of increased pumping during the drought of 1988 can be recognized in a comparison of figures 9a and 9b. The cone of depression during August 1988 (fig. 9b) is both deeper and larger than the cone identified during August 1987 (fig. 7). The area within the 950 foot potentiometric-surface contour in Rochester, for example, increased from about 1.2 mi^2 in August 1987 to about 2.3 mi^2 in August 1988 (fig. 7 and fig. 9b). By comparison, this area was only about 0.4 mi^2 in January 1988 (fig. 9a). Seasonal pumping during 1987 and 1988 did not affect the contributing area shown in figure 8.

Although horizontal flow predominates in the St. Peter-Prairie du Chien-Jordan aquifer, a slight downward gradient caused by recharge and pumping is evident. The vertical head differences across the 500-foot-thick aquifer are generally less than 5 ft. Localized confining units within the aquifer can produce large vertical gradients. The downward vertical gradient probably reverses periodically because of changes in recharge to and discharge from the aquifer.

Head generally increases with depth near streams in the area, and flow is upward as near Cascade Creek (fig. 6). Hydraulic head in the St. Peter-Prairie du Chien-Jordan aquifer for well 106N14W24BAB, for example, was about 3 ft higher than the stage of Willow Creek on June 24, 1987. Ground-water withdrawals within the cone of depression in downtown Rochester (fig. 9) have resulted in a lowering of the potentiometric surface of the aquifer so that flow is locally downward beneath the South Fork Zumbro River (fig. 6).

Recharge

Recharge to the St. Peter-Prairie du Chien-Jordan aquifer occurs in five general zones in the area (fig. 10). In the probable order of increasing rates of recharge, the zones are (1) the Decorah-Platteville-Glenwood confining unit (where present); (2) the bedrock valley west of Rochester where glacial drift is greater than about 100 ft thick; (3) the city of Rochester where storm runoff (potential recharge water) is diverted to sewers; (4) where the St. Peter Sandstone or Prairie du Chien Group is the uppermost bedrock unit, that is, where the Decorah-Platteville-Glenwood confining unit is absent; and (5) along the edge of the Decorah-Platteville-Glenwood where recharge has increased because of the influx of water from springs at the base of the overlying upper carbonate aquifer. The conceptual distribution of these recharge zones and the most likely distribution of recharge based on water-level data and model results are shown in figure 10.

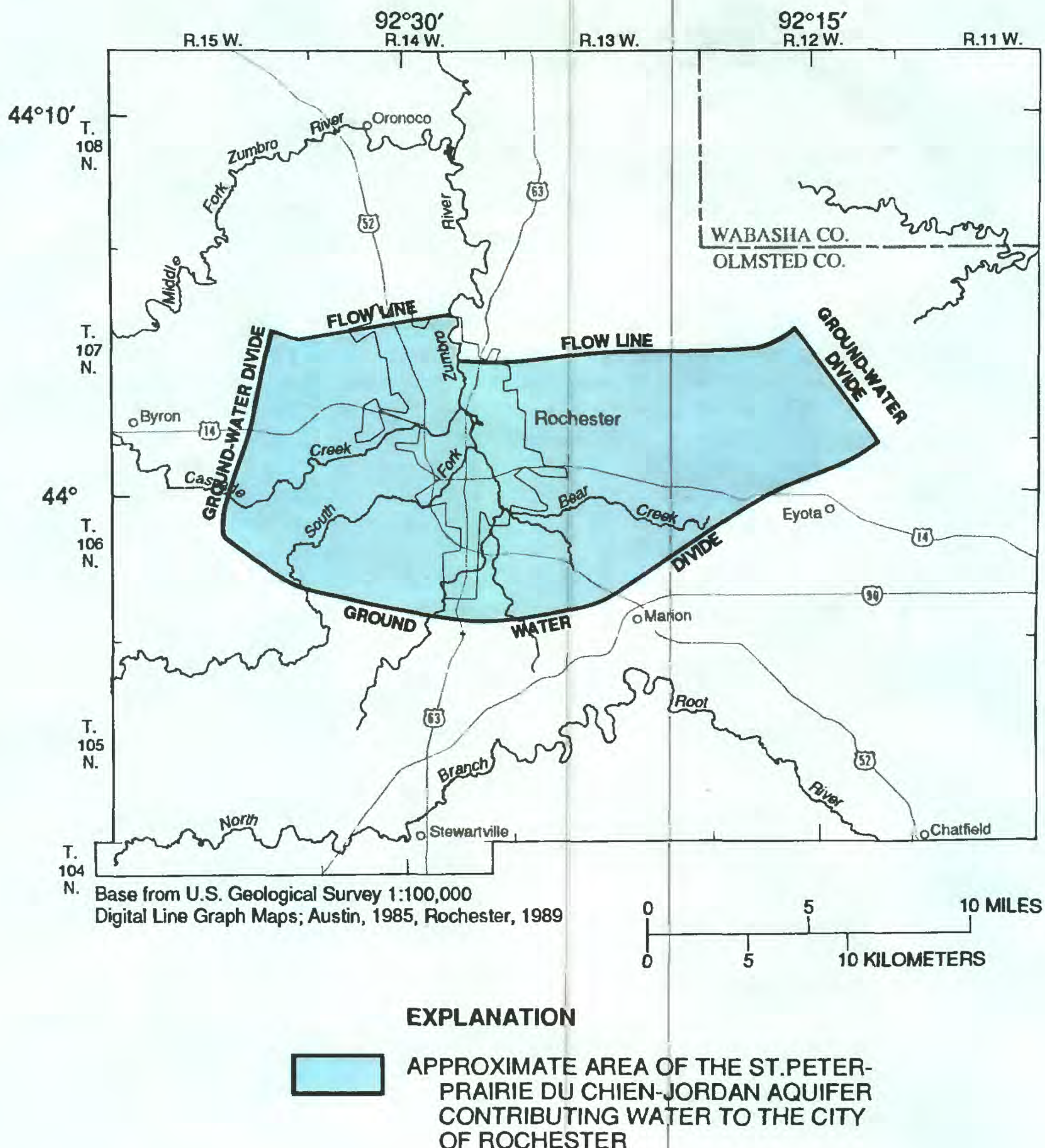


Figure 8.--Approximate area of the St. Peter-Prairie du Chien-Jordan aquifer contributing water to the city of Rochester, Minnesota, August 1987.

Recharge to the St. Peter-Prairie du Chien-Jordan aquifer occurs as leakage from the upper carbonate aquifer through the Decorah-Platteville-Glenwood confining unit, where it is present. Rates of recharge to these aquifers based on ground-water-flow model analyses in the Minneapolis-St. Paul area (Stark and Hult, 1985) are as much as 2 in/yr (inches per year).

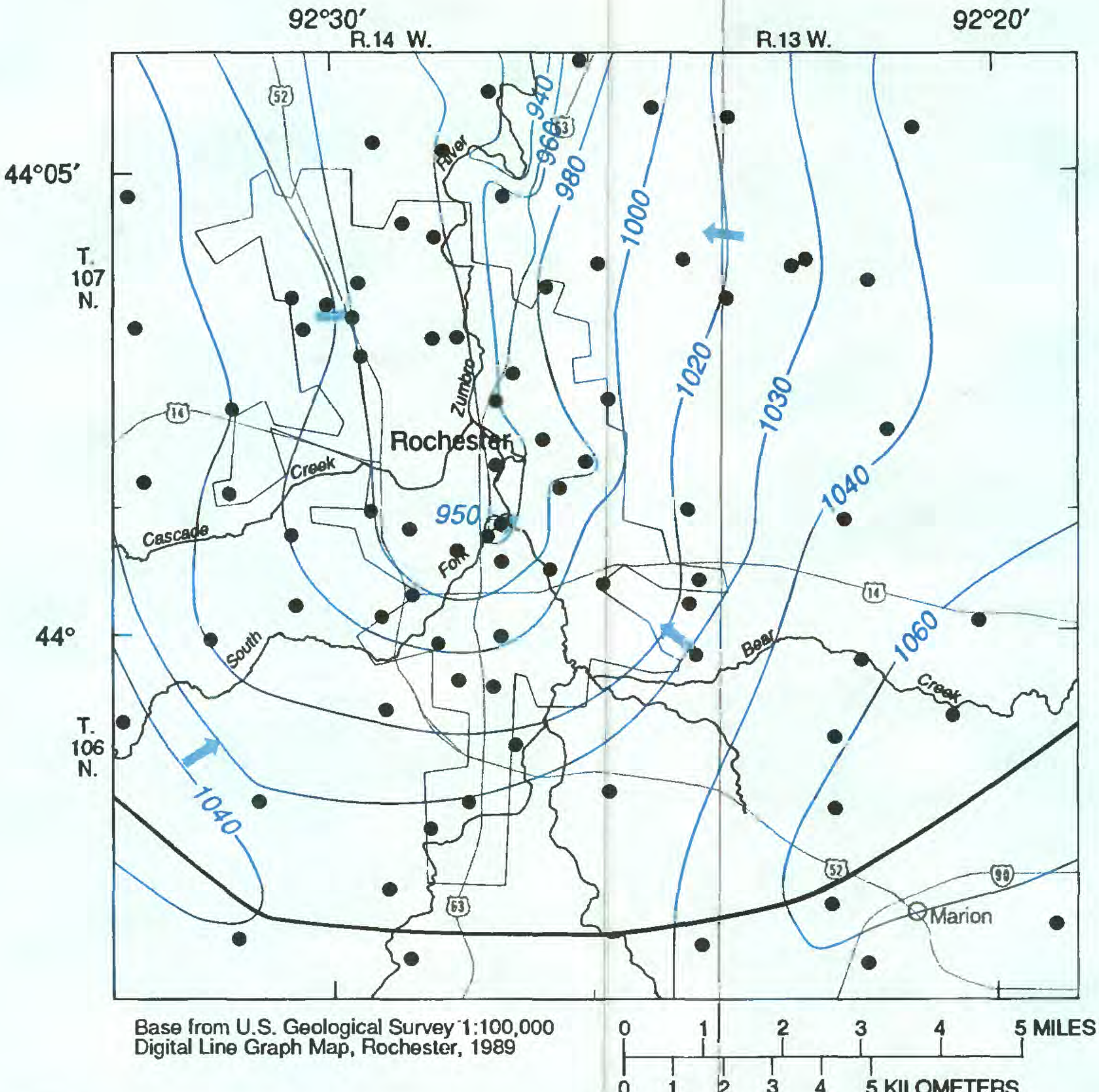
Recharge to the St. Peter-Prairie du Chien-Jordan aquifer is infiltration from precipitation where the Decorah-Platteville-Glenwood confining unit is absent, as in the north part of Olmsted County. Recharge in this zone is likely greatest during the spring because of snowmelt, spring rain, and scant evapotranspiration. This recharge results in rising ground-water levels.

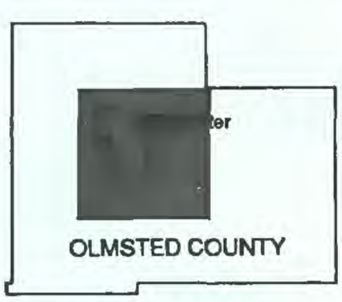
Recharge to the St. Peter-Prairie du Chien-Jordan aquifer occurs as leakage where glacial drift overlies the aquifer. Recharge is variable in this zone, and rates are likely less than those in areas where drift does not overlie the aquifer. The decrease in recharge is primarily caused by low-permeability beds of clay or till in the drift that effectively reduce vertical leakage to underlying formations. The greatest likelihood for a lower recharge rate in this zone occurs where the thickness of the glacial material is more than about 100 ft (fig. 10). On the basis of water-level-hydrograph and ground-water-flow model analyses for glacial drift in western Minnesota, Delin (1987 and 1988) suggests that recharge through drift likely ranges from 3 to 6 in/yr.

The St. Peter-Prairie du Chien-Jordan aquifer is not confined by the Decorah-Platteville-Glenwood unit throughout much of Rochester, and glacial drift is generally thin (less than 20 ft thick) or is absent. Consequently, rates of recharge to the aquifer in the city may be similar to those in the north part of Olmsted County. Storm runoff is diverted to sewers in certain sections of Rochester (fig. 10). Although some water undoubtedly leaks from sewers into the underlying aquifer, net recharge to the aquifer is probably less in the city than in other areas where the Decorah-Platteville-Glenwood confining unit overlies the aquifer. Because of a lack of data, leakage from the sewers, and resultant recharge to the St. Peter-Prairie du Chien-Jordan aquifer in Rochester, could not be determined.

Highs in the potentiometric surface of the St. Peter-Prairie du Chien-Jordan aquifer are probably caused by greater rates of recharge along the edge of the Decorah-Platteville-Glenwood confining unit (fig. 10) than elsewhere. The source of water for this increase in recharge is the overlying upper carbonate aquifer. This zone of increase in recharge was first identified by Delin and Woodward (1984).

The increase in recharge along the edge of the confining unit can be explained by the assumption that recharge to the overlying upper carbonate aquifer is at a rate similar to the rate where the Prairie du Chien is the uppermost bedrock unit. Because the vertical hydraulic conductivity of the Decorah-Platteville-Glenwood confining unit is much less than that for aquifers, ground water flows horizontally to the edge of the upper carbonate aquifer rather than through the confining unit. Here the water discharges from springs and seeps into the underlying St. Peter-Prairie du Chien-Jordan aquifer.





AREA OF DETAIL

EXPLANATION

APPROXIMATE AREA OF CONE OF DEPRESSION CAUSED BY PUMPING, JANUARY 1988

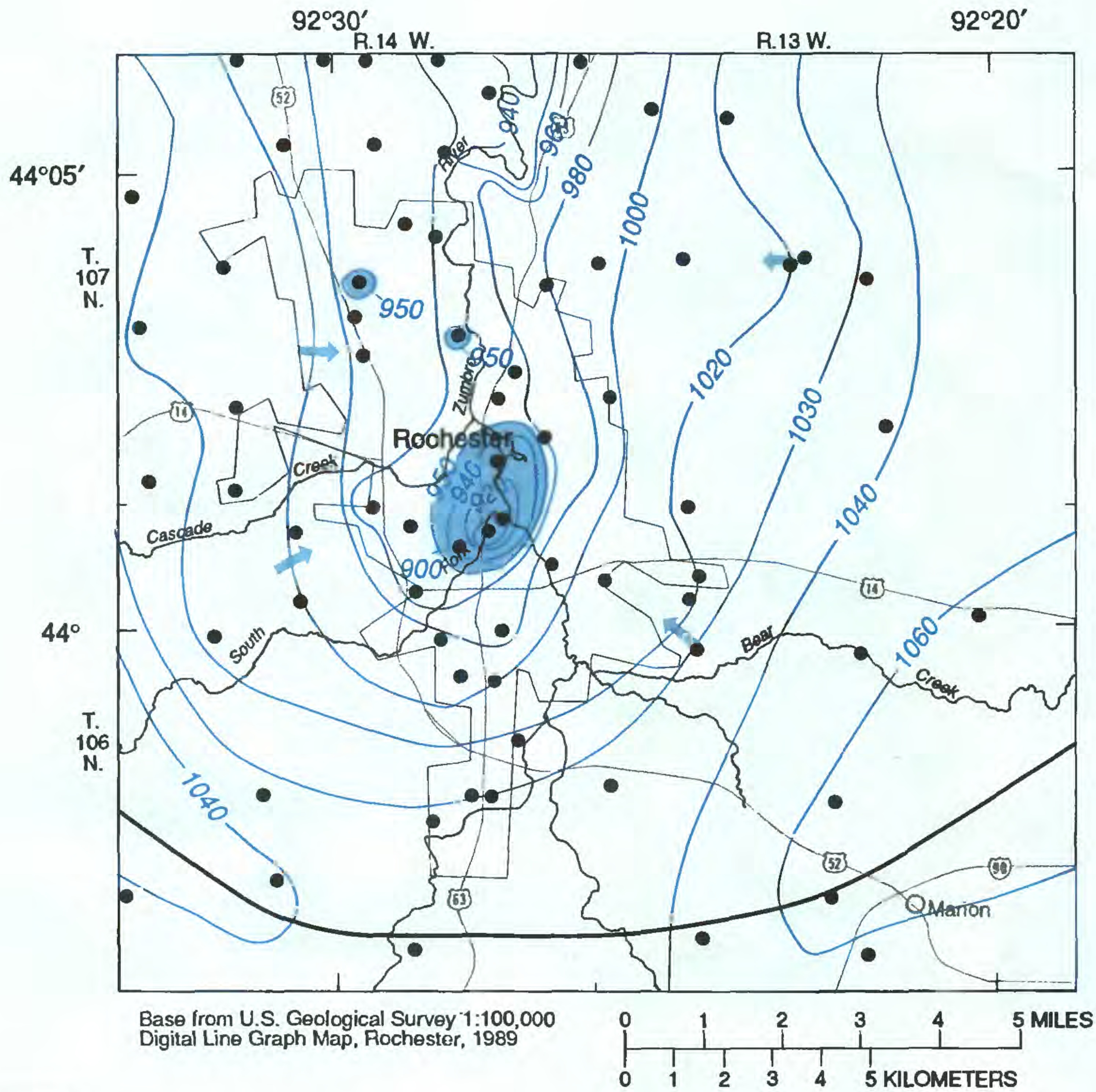
—960— POTENTIOMETRIC CONTOUR. Interval 10 and 20 feet. Datum is sea level.

GROUND-WATER DIVIDE

DIRECTION OF GROUND-WATER FLOW

● OBSERVATION WELL

Figure 9a.--Cones of depression caused by pumping in the St. Peter-Prairie du Chien-Jordan aquifer, Rochester, Minnesota, during January 1988.



AREA OF DETAIL

EXPLANATION

APPROXIMATE AREA OF CONE OF DEPRESSION CAUSED BY PUMPING, AUGUST 1988

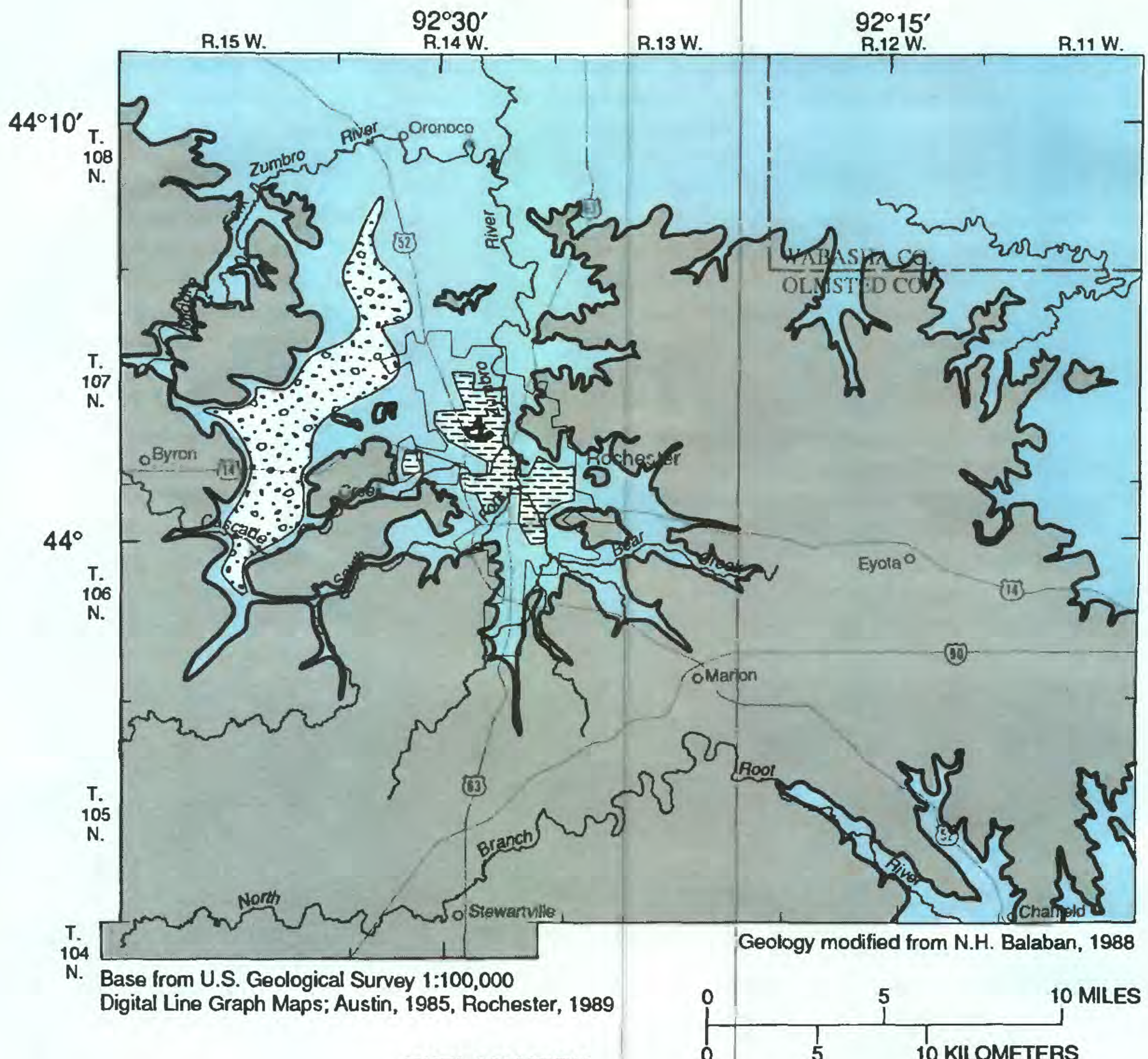
—980— POTENTIOMETRIC CONTOUR. Interval 10 and 20 feet. Datum is sea level.

GROUND-WATER DIVIDE

DIRECTION OF GROUND-WATER FLOW

● OBSERVATION WELL

Figure 9b.--Cones of depression caused by pumping in the St. Peter-Prairie du Chien-Jordan aquifer, Rochester, Minnesota, during August 1988.



EXPLANATION

RECHARGE ZONES:

- Decorah-Platteville-Glenwood confining unit
- Thick glacial drift
- Sewered area of Rochester
- Prairie du Chien Group uppermost unit
- Edge of Decorah-Platteville-Glenwood confining unit

Figure 10.--General locations of recharge zones near Rochester, Minnesota.

The inability of the Decorah-Platteville-Glenwood confining unit to transmit water vertically can be demonstrated with Darcy's Law--

$$Q = K \frac{(h_1 - h_2)}{m}, \qquad (3)$$

where

Q is the unit flux of water through the confining unit per unit area [L/t],
K is the hydraulic conductivity of the confining unit [L/t],
h_1 is the hydraulic head in the upper carbonate aquifer [L],
h_2 is the hydraulic head in the St. Peter-Prairie du Chien-Jordan aquifer [L], and
m is the thickness of the confining unit [L].

Example calculation: Assume a drop in hydraulic head of 200 ft through a confining unit that has a vertical hydraulic conductivity of 10^{-5} ft/d and a thickness of 70 ft. Based on these assumptions, the rate of recharge is about 0.1 in/yr. If the rate of recharge for the upper carbonate aquifer is about 5 in/yr and the confining unit can transmit only about 0.1 in/yr, most of the remaining 4.9 in/yr likely flows to the edge of the upper carbonate aquifer.

The zone of increased recharge along the edge of the Decorah-Platteville-Glenwood confining unit, represented by a thick line in figure 10, is probably a zone of variable width. Variations in width would result from varying degrees of fracturing in the Decorah-Platteville-Glenwood confining unit. Rates of recharge within this zone are probably variable. The degree of variability depends largely on local ground-water flow rates in the upper carbonate aquifer. A steeper potentiometric-surface gradient locally than elsewhere in the upper carbonate aquifer will potentially supply greater amounts of water to the zone than a less steep surface would. Areas in the upper carbonate aquifer with higher permeability than elsewhere in the aquifer may have gentle gradients but have higher flow rates than some areas with lower permeability and steeper gradients.

Rates of recharge to the St. Peter-Prairie du Chien-Jordan aquifer vary seasonally at a given location. Rates along the edge of the Decorah-Platteville-Glenwood confining unit, for example, vary in response to seasonal and long-term variations in recharge to the upper carbonate aquifer. Consequently, there is a delayed response, of some unknown length of time, between precipitation reaching the upper carbonate aquifer and subsequent flow of that same water to the St. Peter-Prairie du Chien-Jordan aquifer, through the zone along the edge of the confining unit. A longer delay occurs between recharge to the upper carbonate aquifer and subsequent leakage of that same water through the confining unit to the St. Peter-Prairie du Chien-Jordan. Similar unknowns occur for temporal variation of recharge in the sewered area of Rochester and where drift is thick (fig. 10). Data for documenting the seasonal and the long-term variations in recharge are unavailable.

Ground-Water Withdrawals

Approximately 4.3 billion gallons of ground water was withdrawn from high-capacity wells in the Rochester area during 1986 (Rochester Public Utilities, written commun., 1987; Minnesota Water-Use Database). About 3.5 billion gallons of the total was for municipal use. The St. Peter-Prairie du Chien-Jordan, Franconia-Ironton-Galesville, and Mount Simon aquifers are the sources of about 87, 12, and 1 percent, respectively, of the ground water pumped by high-capacity wells in the area. Ground water is pumped for three major uses: (1) municipal (83 percent), (2) industrial (15 percent), and (3) irrigation of golf courses and commercial use in hospitals (2 percent).

Many of Rochester's municipal wells are multi-aquifer wells open from the St. Peter-Prairie du Chien-Jordan aquifer to the Franconia-Ironton-Galesville aquifer. Two municipal wells also extend to the underlying Mount Simon aquifer. Withdrawals from the Franconia-Ironton-Galesville and Mount Simon aquifers in the Rochester area come from these multi-aquifer wells. The approximate percentage of water contributed by each aquifer penetrated was computed for the Rochester multi-aquifer wells (table 1). Included in this table is the estimate of ground water pumped from the Prairie du Chien Group and Jordan Sandstone for wells completed in both formations.

Discharge from aquifers to a multi-aquifer well is dependent primarily on the transmissivity and the hydraulic head in the aquifers that are penetrated. Heads for most of the multi-aquifer wells are indistinguishable from heads in the St. Peter-Prairie du Chien-Jordan aquifer. Therefore, heads in the St. Peter-Prairie du Chien-Jordan and the Franconia-Ironton-Galesville aquifers were assumed to be identical. Consequently, the percentages shown in table 1 were computed by dividing the transmissivity of one aquifer or formation by the total transmissivity of all aquifers or formations penetrated by the well. If data on the hydraulic head in the Franconia-Ironton-Galesville aquifer should become available, more reliable estimates of the contributions of ground water from each formation penetrated could be calculated. Transmissivities of aquifers used in these calculations were generally based on regional averages. Roughly 8 percent of ground-water pumped by Rochester municipal wells in 1986 was from the Prairie du Chien; 76 percent, from the Jordan; 15 percent, from the Franconia-Ironton-Galesville; and 1 percent from the Mount Simon. These percentages are based on the analysis described above in this paragraph.

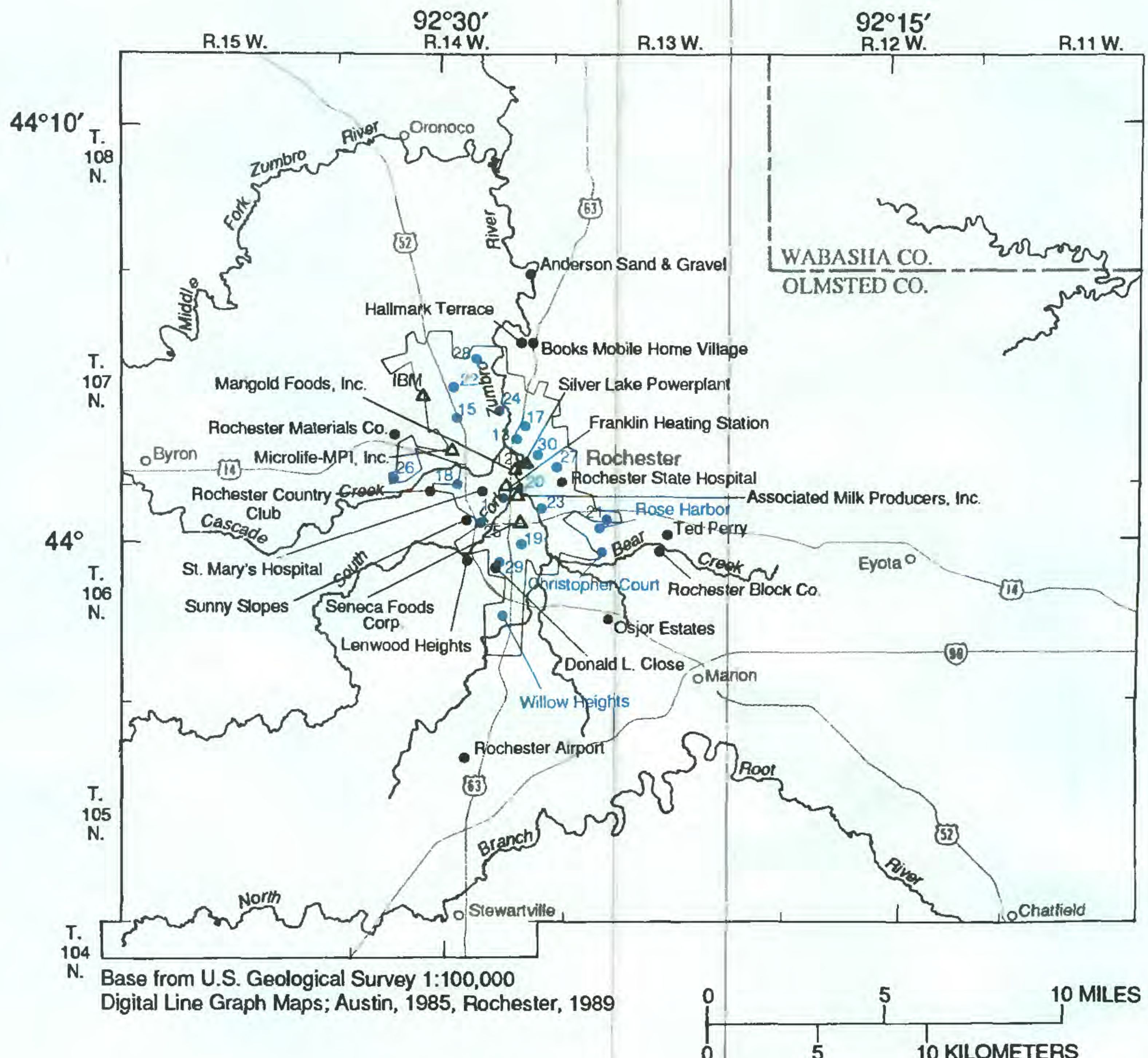
Information on ground-water withdrawal for 1986 was compiled from records of RPU and from the Minnesota Water-Use Database at the MDNR for 42 high-capacity wells in and around Rochester (fig. 11). Use of municipal water was also tabulated for 1977 to 1988.

Ground-water withdrawals have increased steadily through the 1980's, in part because of below-normal precipitation (fig. 12). Precipitation during 1976, 1980, 1985, 1987, and 1988 was below the normal of 28.25 in/yr (table 2), according to records of the National Weather Service at the Rochester municipal airport (U.S. Department of Commerce, 1976-88). The below-normal years of precipitation likely resulted in increases in pumping rates for these years. Although ground-water withdrawals fluctuate seasonally in a given year, withdrawal rates in winter months have remained virtually constant from 1977-88, except for a slight increase from about 1984-88 (fig. 12).

Table 1.--*Estimates of percentages of ground-water pumped from aquifers by the Rochester municipal wells*

[--, well not completed in this formation]

Well	Estimates of withdrawal from aquifers, in percent			
	St. Peter-Prairie du Chien-Jordan			
	Prairie du Chien	Jordan	Franconia-Ironton-Galesville	Mount Simon
11	42	58	--	--
12	--	64	36	--
13	60	40	--	--
15	71	29	--	--
16	--	--	26	74
17	--	54	46	--
18	--	56	44	--
19	--	55	45	--
20	--	52	30	18
21	--	60	40	--
22	--	59	41	--
23	--	100	--	--
24	--	58	42	--
25	--	57	43	--
26	56	44	--	--
27	--	100	--	--
28	--	100	--	--
29	--	100	--	--
30	--	100	--	--
31	--	100	--	--



EXPLANATION

HIGH-CAPACITY WELLS (pumped greater than 200 gallons per minute):

- 28● Rochester municipal well and identifier
- ● Industrial well
- △ Other high-capacity well

Figure 11.--Location of high-capacity supply wells near Rochester, Minnesota.

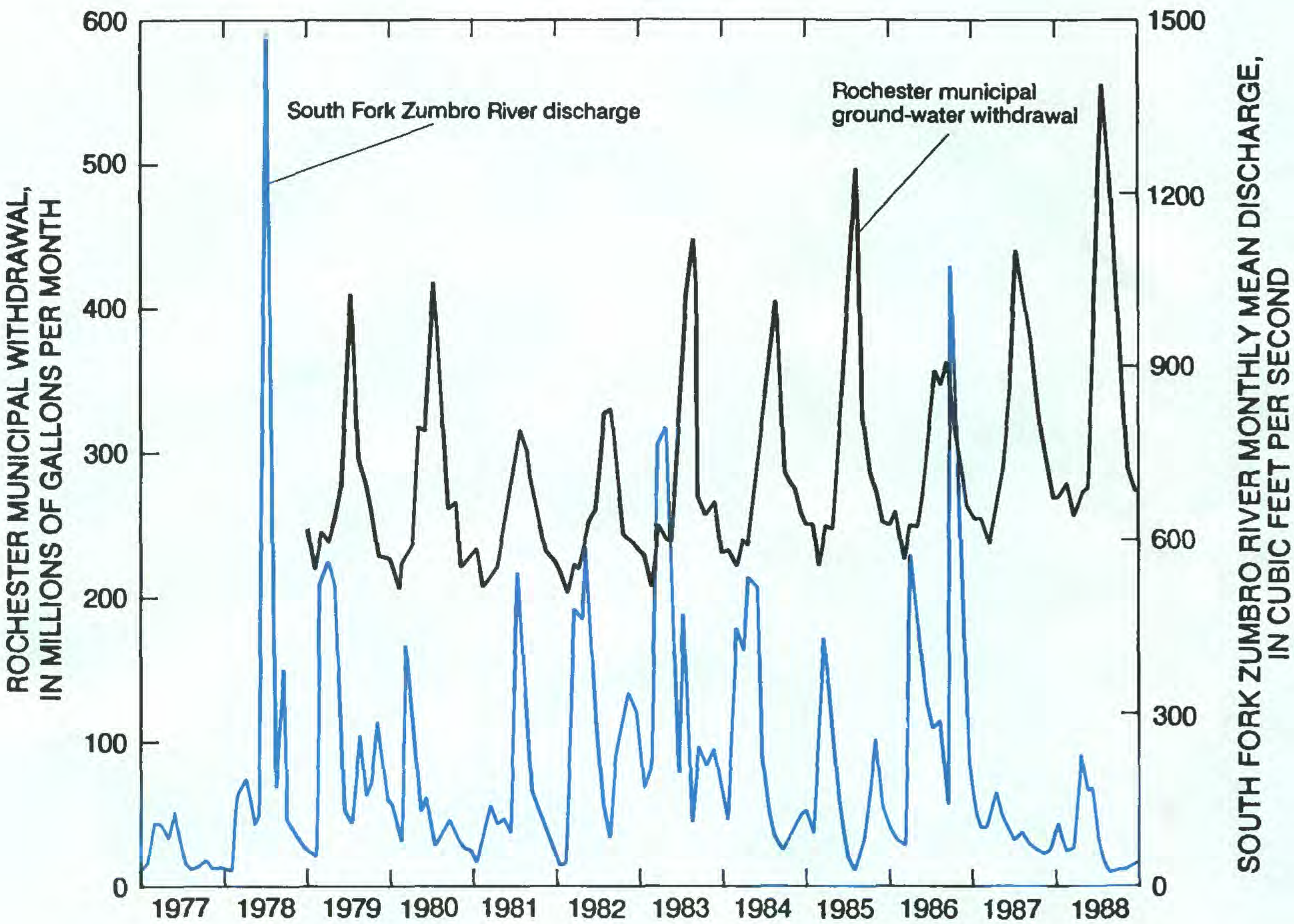


Figure 12.--Municipal ground-water withdrawals and discharge of South Fork Zumbro River, Rochester, Minnesota, 1977-88.

Table 2.--*Precipitation measured at the municipal airport, Rochester, Minnesota, 1976-88*

Data from U.S. Department of Commerce, National Oceanic and Atmospheric Administration Climatological Data, Minnesota annual summary reports for 1976-88. Normal precipitation (1951-80) is 28.25 inches per year.

Year	Precipitation (inches)	Year	Precipitation (inches)	Year	Precipitation (inches)
1976	15.44	1981	33.00	1985	27.25
1977	29.25	1982	36.83	1986	39.99
1978	39.26	1983	35.34	1987	27.37
1979	33.04	1984	28.61	1988	21.39
1980	25.32				

Seasonal fluctuations of municipal ground-water withdrawals in response to changes in precipitation are shown in figure 13. Precipitation measured in July 1987 was about 3.4 inches above the normal monthly rate (fig. 13). During the period of record (1977-88), average municipal withdrawals from June to October were 1.3 times the average withdrawals from November to May (Rochester Public Utilities, written commun., 1987).

Water-Level Changes in the St. Peter-Prairie du Chien-Jordan Aquifer

Water levels fluctuate in response to seasonal variations in recharge to and discharge from the ground-water system. Variations in ground-water withdrawal from and recharge to the aquifer are the major factors affecting water-level fluctuations.

A continuous water-level hydrograph (for part of 1987) for observation well 106.14.24BAB completed in the Jordan member of the St. Peter-Prairie du Chien-Jordan aquifer is shown in figure 13. The well is on the south side of Rochester about 1 mile from Rochester municipal well 29 and the Willow Heights well (fig. 11). In this area, the Decorah-Platteville-Glenwood confining unit is absent, and the Prairie du Chien part of the aquifer is overlain by about 15 ft of sandy clay and 23 ft of silty gravel.

Daily water-level fluctuations in observation well 106.14.24BAB (fig. 13) were caused by withdrawals from the nearby municipal wells. These fluctuations illustrate the difficulties involved in interpreting water-level data collected infrequently. A significantly different trend could be suggested on the basis of water levels measured in the observation well only a few days apart. (See miscellaneous water-level measuring points, fig. 13.) Measurments of water levels in a high-capacity pumping well results in further uncertainties in the precision of estimating the water-level trends.

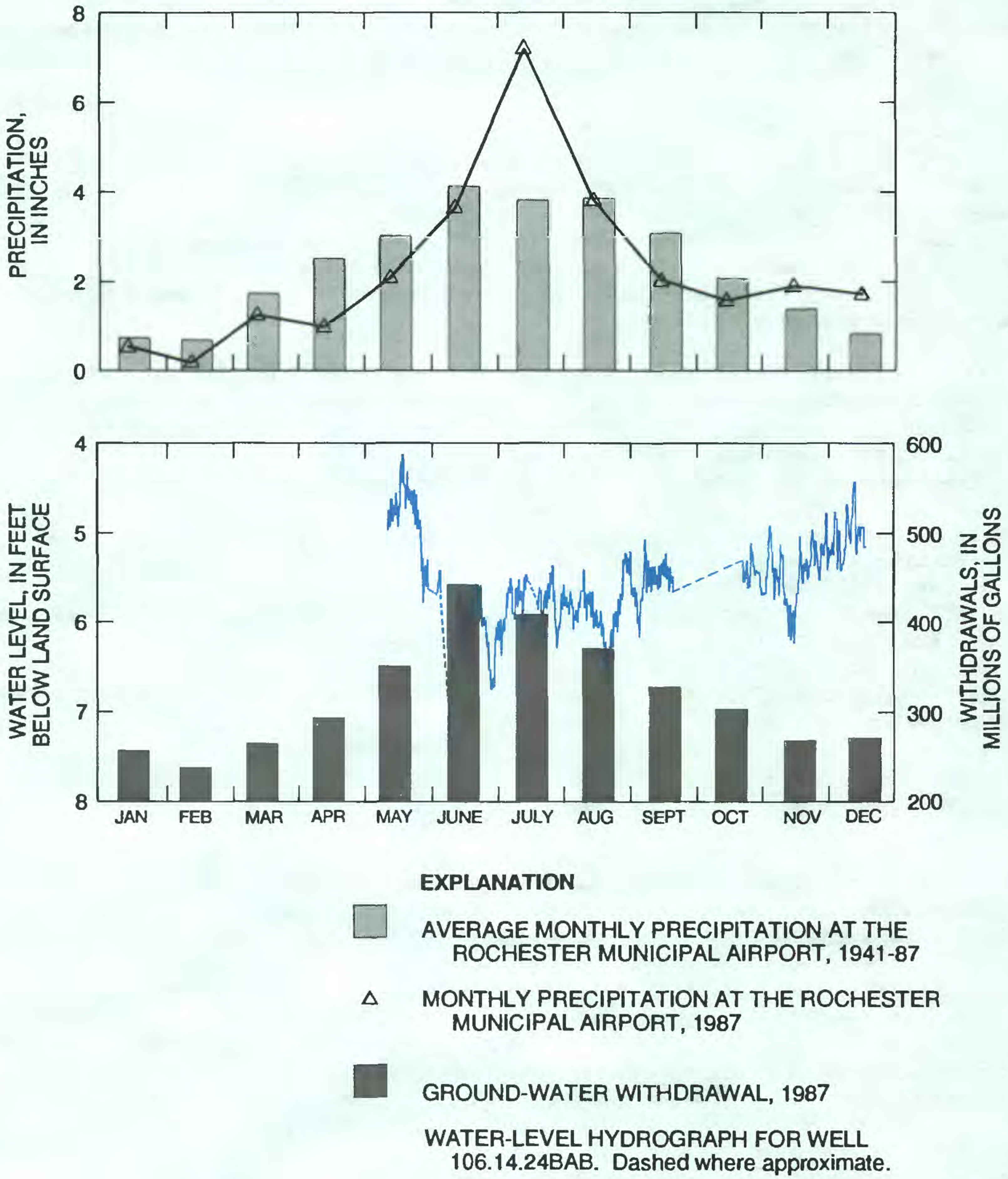


Figure 13.--Seasonal variation in municipal ground-water withdrawals, ground-water levels, and precipitation, Rochester, Minnesota, 1987.

Water-level and precipitation data collected at the Rochester airport (fig. 13) probably mean that the water-level rise measured in May resulted from increases in recharge from the melting winter snowpack and in precipitation. The water level declined sharply from May to June and remained seasonally low through August because of an increase in ground-water withdrawal. The water level gradually rose throughout the remainder of the year. The lack of water-level rise during July in response to above-normal precipitation was likely the result of an increase in ground-water withdrawal and the effects of evapotranspiration.

The water level in the Golden Hill School well was measured quarterly and (or) monthly from 1977 through 1988 (fig. 14). The levels, which rose during the late 1970's and the early 1980's, reached a maximum during spring 1983. The seasonal water-level fluctuations are caused by the pumping of nearby Rochester wells 19 and 29 (fig. 11). The large water-level declines during the summers of 1985 to 1988 resulted primarily from the pumping of well 29 in 1984. Although summer water-level declines have been greater in recent years than in the past, water levels in the winter were similar to water levels during the previous winters.

Maps of water-level changes were used to evaluate the effects of seasonal changes in recharge to and discharge from the St. Peter-Prairie du Chien-Jordan aquifer. Water levels outside of Rochester generally declined 1 to 4 ft (fig. 15) from August 1987 through January 1988. The greatest water-level declines outside the city were in areas to the north, where the aquifer is unconfined. During a period of normal precipitation, water levels would typically rise in these areas. Below-normal precipitation during 1987 probably resulted in a reduction of recharge to the St. Peter-Prairie du Chien-Jordan aquifer. Consequently, water levels in the aquifer did not rise during the fall and the winter months as they would have risen in an average climatic year. Recharge to the aquifer is virtually constant in areas where the aquifer is confined by the Decorah-Platteville-Glenwood confining unit. Consequently, water-level fluctuations are slight in these areas. The effects of ground-water withdrawals in Rochester during the fall and the winter months were superimposed on the regional effects of recharge. Water-level recovery within Rochester was generally 1 to 20 ft, but in the AMPI (Associated Milk Producers, Inc.) well (fig. 15) was 45 ft.

Maps of water-level changes were also used to evaluate areas affected by ground-water pumping. Areas affected by pumping are difficult to differentiate from areas affected only by changes in recharge. The limit of the area affected by pumping in the city is probably between the 1- and 2-foot contours, because a water-level decline of less than 1 ft was common outside Rochester from August 1987 through January 1988 (fig. 15). The area affected by pumping cannot be delineated more precisely because of the effects of below-normal recharge during 1987. The area affected by pumping was centered around Rochester well 20 and the nearby AMPI wells in the south part of the city. More than 2 ft of water-level recovery was measured in Rochester wells 11, 12, 18, 19, 23, 22, 24, 25, 28, and 29. Less than 2 ft of water-level recovery was computed for each of the remaining municipal wells, and the water levels in Rochester wells 17 and 26 declined from August through January. Although pumping from these wells undoubtedly affects water levels nearby, the effects cannot be distinguished from changes in water level resulting from changes in recharge. Pumping in the Rochester area, from August 1987 through January 1988 probably did not affect water levels near the ground-water divide (fig. 7).

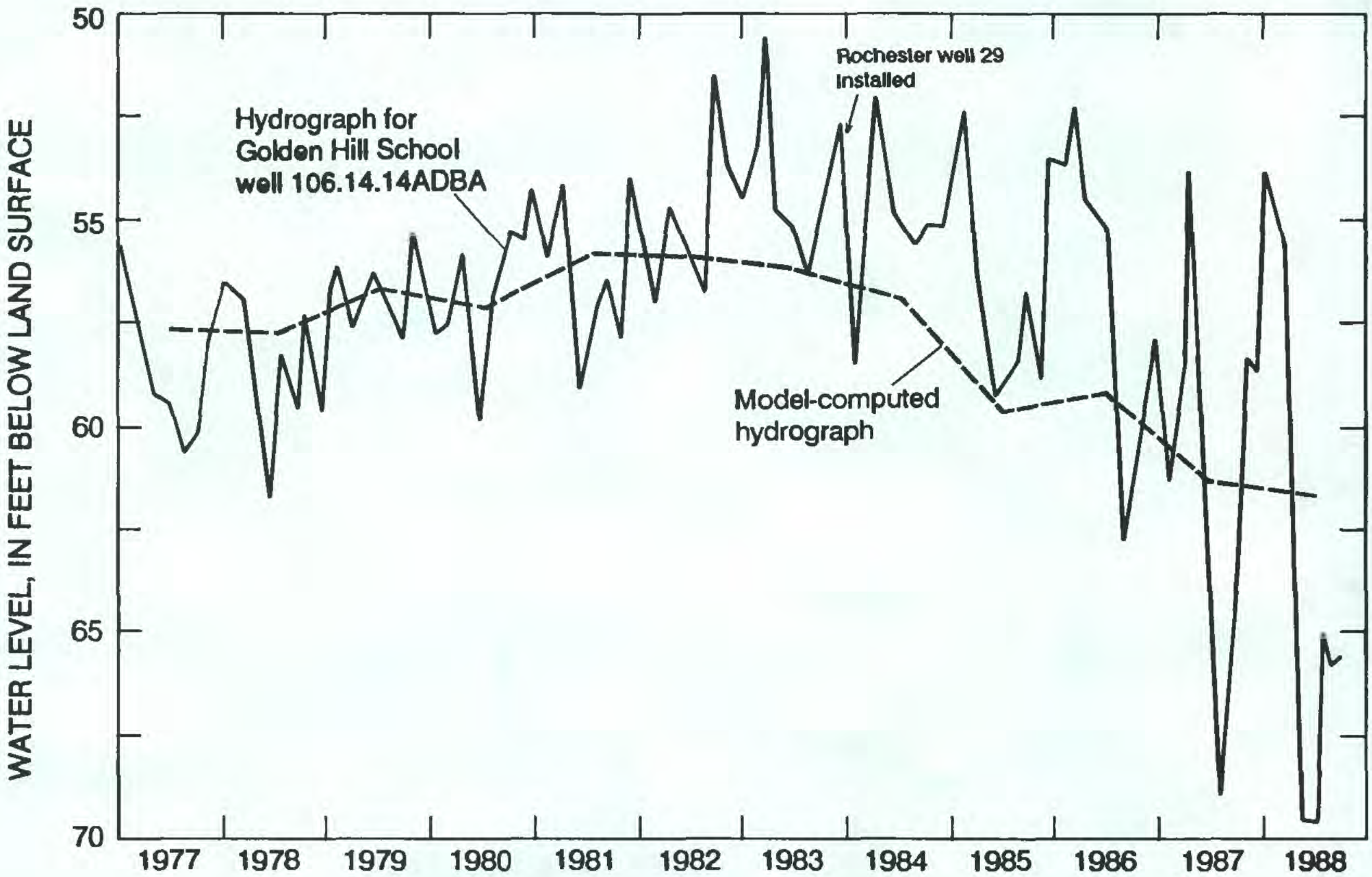
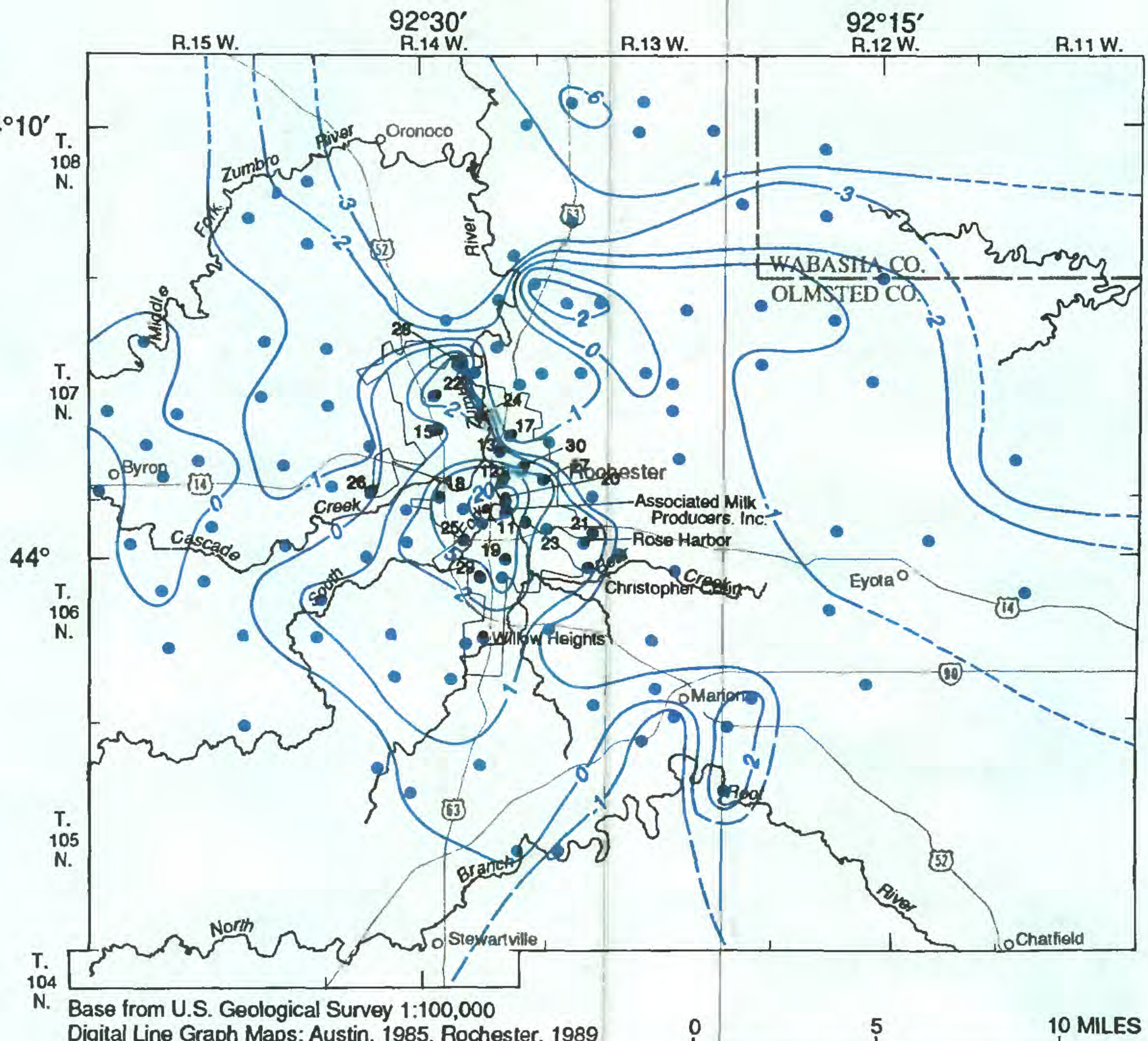


Figure 14.--Simulated and recorded hydrographs for the Golden Hill School well, Rochester, Minnesota, 1977-88.



EXPLANATION

—6— — LINE OF EQUAL WATER-LEVEL CHANGE, IN FEET--Dashed where approximate. Interval variable.

Positive number indicates water level rise

Negative number indicates water level decline

22● HIGH-CAPACITY WELL, WELL NUMBER OR OWNER (pumping greater than 200 gallons per minute)

● DATA POINT

Figure 15.--Water level change in the St. Peter-Prairie du Chien-Jordan aquifer near Rochester, Minnesota, August 1987 through January 1988.

Water-level changes in the St. Peter-Prairie du Chien-Jordan aquifer during the drought of 1988 generally were 10 to 15 ft greater in the Rochester municipal wells than the changes measured in those wells during 1987. The drought began in 1987 and extended into 1988. Water levels outside the city generally declined 1 to 5 ft (fig. 16) from January through August 1988. The greatest water-level decline outside the city, 8 ft, was about 3 miles north of Rochester. Water levels rose less than 1 ft in the western part of Olmsted County near Byron (fig. 16). Water-level decline and recovery outside the city results primarily from variations in recharge. Recharge to the aquifer during the drought was virtually stable in areas overlain by the Decorah-Platteville-Glenwood confining unit. Conversely, recharge to the aquifer during the drought was likely below normal in unconfined areas.

The extent of the area affected by pumping in the Rochester area is more difficult to estimate for January through August 1988 because the variation in water-level decline throughout the area was greater than during 1987 (fig. 15). Water-level decline caused by pumping in the city is likely located between the 2- and 4-foot contours because a water-level decline of less than about 2 ft was common outside Rochester from January through August 1988 (fig. 16). The area affected by pumping cannot be delineated more precisely because of the effects of below-normal recharge during 1987 and 1988. For comparison, the 20-foot change in water-level contour for January through August 1988 encompasses an area of about 4.3 mi^2 compared to an area of about 0.9 mi^2 for August 1987 through January 1988. The area affected by pumping was centered around the AMPI wells, where the decline was greater than 60 ft. This water level was about 15 ft below the level in 1987.

Interaction of Ground-Water and Surface-Water

Streamflow fluctuates seasonally with variations in precipitation, evapotranspiration, runoff, water use, and leakage to or seepage from the ground-water system. The fluctuation of South Fork Zumbro River streamflow from 1977 through 1988 in response to these factors is illustrated in figure 12. Although streamflow typically fluctuates over a range of several thousand cubic feet per second during a given year, discharge rates generally fluctuate over a range of 100 to 200 ft^3/s (cubic feet per second) during fall and winter months.

Ground-water seepage to or leakage from a stream depends on (1) thickness of the streambed material, (2) vertical hydraulic conductivity of the streambed material, (3) permeability of the aquifer near the stream, and (4) head differences between the aquifer and the stream. Stream reaches that receive ground water are called gaining reaches. Those that lose water by infiltration through the streambed are called losing reaches.

The amount of ground-water seepage to streams was estimated for selected reaches of South Fork Zumbro River, Bear Creek, and Cascade Creek (fig. 17; table 3) from streamflow measurements during March and August 1987. Long-term (1977-88) streamflow measurements on the South Fork Zumbro River at Rochester (fig. 12) are an indication that the March and August 1987 periods were representative of low streamflow. Periods of low streamflow were selected because ground water represents most of streamflow then. Streamflow during March, which often is high because of overland runoff from early snowmelt, was low in March 1987.

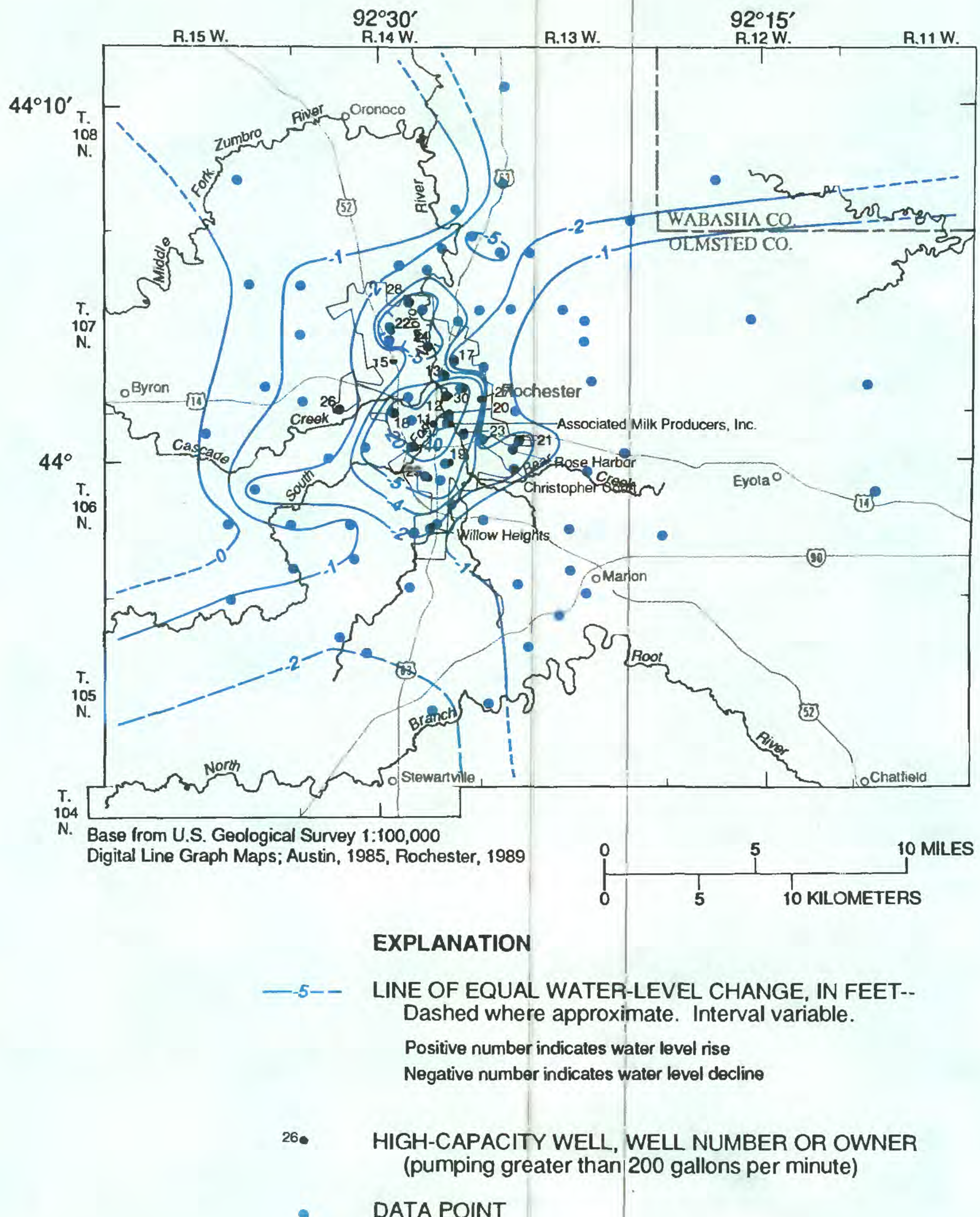


Figure 16.--Water level change in the St. Peter-Prairie du Chien-Jordan aquifer near Rochester, Minnesota, January through August 1988.

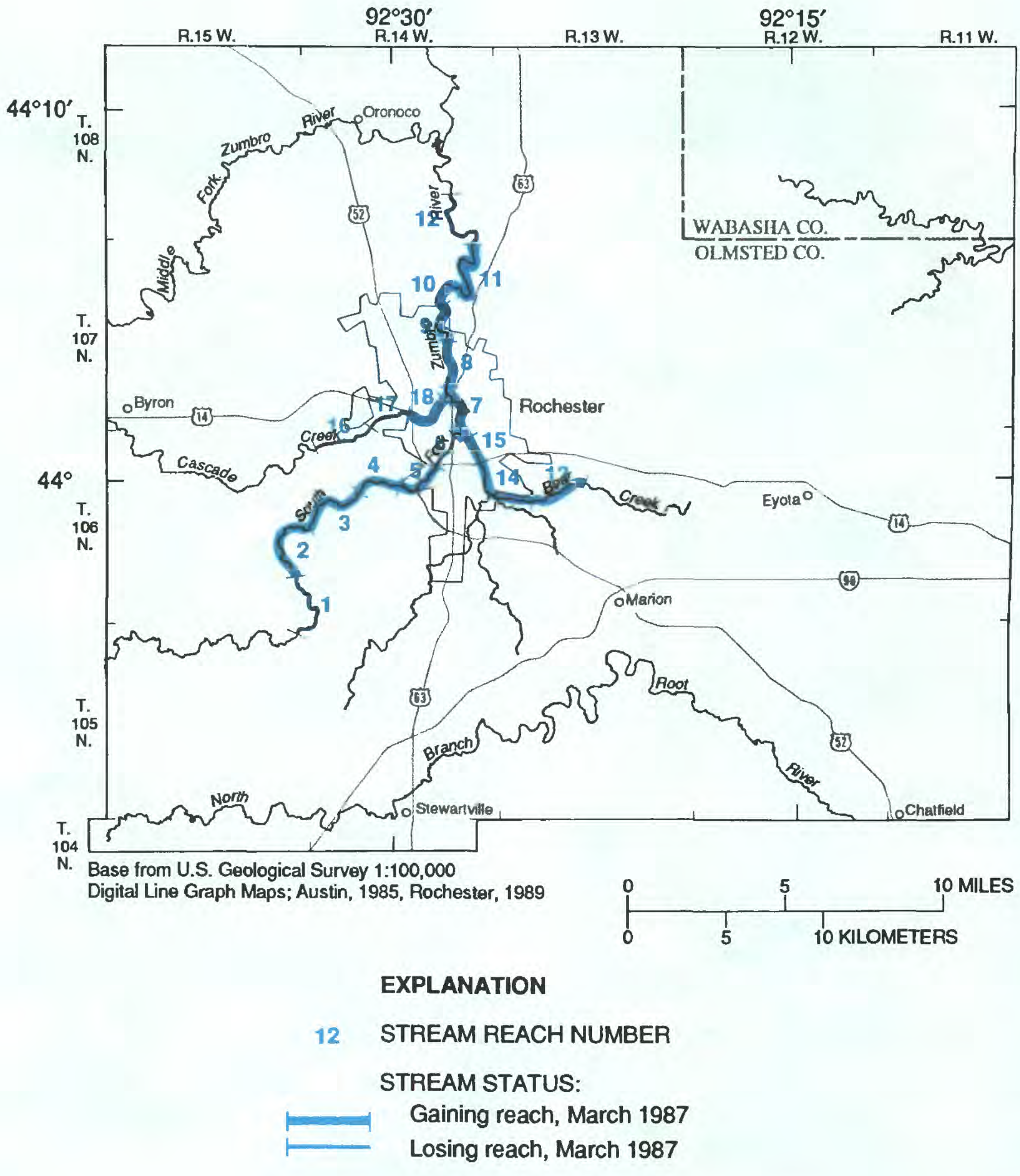


Figure 17.--Steream reaches near Rochester, Minnesota, where rates of ground-water seepage were estimated, March and August, 1987.

Table 3.--*Estimated ground-water seepage to the South Fork Zumbro River, Bear Creek, and Cascade Creek*

[--, ground-water seepage could not be made for this reach because gaging error is less than ground-water seepage estimate; ft^3/s, cubic feet per second; $(ft^3/s)/mi$, cubic feet per second per stream mile]

Stream reach	March 1987: Estimated ground-water seepage to stream (ft^3/s)	March 1987: Seepage per stream mile ($(ft^3/s)/mi$)	August 1987: Estimated ground-water seepage to stream (ft^3/s)	August 1987: Seepage per stream mile ($(ft^3/s)/mi$)	Difference in seepage between March and August
			South Fork Zumbro River		
1	--	--	-3	-1	--
2	--	--	2	1	--
3	5	2	6	2	1
4	7	5	-4	-3	-11
5	--	--	4	2	--
6	--	--	-1	-1	--
7	19	9	10	5	-9
8	--	--	4	3	--
9	--	--	-7	-4	--
10	20	15	--	--	--
11	28	9	14	5	-12
12	--	--	7	3	--
Total	77	--	32	--	--
			Bear Creek		
13	--	--	--	--	--
14	--	--	4	2	--
15	8	3	5	2	-1
Total	8	--	9	--	--
			Cascade Creek		
18	--	--	-2	-1	--
17	--	--	4	2	--
18	4	3	1	1	-3
Total	4	--	3	--	--

When evaluating streamflow measurements, one should be aware that current-meter measurements are typically accurate to plus or minus 5 percent, possibly a conservative estimate (Pelletier, 1988). Thus, an error of plus or minus 10 ft^3/s would apply to a streamflow of 200 ft^3/s (the approximate discharge of the South Fork Zumbro River at reach 12, March 11th, 1987). Because the calculated ground-water seepage for reach 12 (about -2 ft^3/s) is less than this inherent error, for example, ground-water seepage cannot be estimated for reach 12. Calculated ground-water seepage rates that are less than the stream-measurement error for that reach are not shown in table 3. A greater number of measurements are within the gaging error during March 1987 than during August 1987 because streamflow was greater during March than during August.

Ground-water seepage to streams in the Rochester area is generally greater than leakage from streams into the ground-water system. Streamflow increased in about three-fourths of the stream reaches during the two gaging periods (table 3). Ground-water seepage to streams was greater during March than during August for most reaches. Estimated ground-water seepage rates were generally less than 5 $(ft^3/s)/mi$ (cubic feet per second per stream mile) during the two gaging periods. Seepage rates per stream mile, however, exceeded this value for reaches 7, 10, and 11 during March. These values are likely greater than 5 (ft^3/s)/mi because of local effects of bank storage of ground water discharging to the stream. The difference in ground-water seepage to streams between the March and the August measurements was greatest at reach 4. This difference could also be related to the effects of bank storage or to the effects of the storage of water in ponds near the stream.

Streamflow in reach 6 of the South Fork Zumbro River, immediately north of US Highway 14 (fig. 17), decreased during the March and the August 1987, gaging periods. The decreases could be significant because of the proximity of this reach to the center of the cone of depression in the St. Peter-Prairie du Chien-Jordan potentiometric surface. Rochester well 11 and the AMPI wells are nearby. Loss of stream water to the St. Peter-Prairie du Chien-Jordan aquifer in reach 6 could be virtually continuous because ground-water withdrawals lower the head in the aquifer. Movement of stream water into the aquifer could be of concern if the South Fork Zumbro River becomes contaminated by an accidental spill of hazardous waste.

Although estimates of ground-water seepage to streams in the area were made during 1987, data on seasonal variations in ground-water discharge to streams are lacking. As can be seen in figure 12, streamflow for the South Fork Zumbro River can fluctuate seasonally from about 50 to 1,500 ft^3/s. Because ground-water seepage to streams is a function of streamflow (or stage), ground-water seepage can fluctuate in response to seasonal variations in streamflow.

The location and the magnitude of ground-water seepage to streams can be estimated by measuring the changes in the activity of radon (^{222}Rn) gas in streams (Lee and Hollyday, 1987). Radon activity in ground water is typically several orders of magnitude greater than in surface water. Thus, the result of ground-water seepage to a stream is usually an increase in radon activity in stream water. Radon activity in stream water decreases as radon escapes slowly to the atmosphere along calm stream reaches and rapidly along turbulent reaches. Therefore, a reduction in ground-water seepage to a stream results in a reduction of radon activity in the stream water.

A relation between ground-water seepage, stream discharge, and radon activity (Lee and Hollyday, 1987) can be computed as a mass balance as follows:

$$Q_{gw} = \frac{A_m - A_s}{A_{gw} - A_s} Q_m, \qquad (4)$$

where

Q_{gw} is the rate of ground-water seepage $[L^3/t]$,
Q_m is the stream discharge $[L^3/t]$,
A_m is the activity of ^{222}Rn in stream water at a downstream point [disintegrations/t],
A_s is the activity of ^{222}Rn in stream water at an upstream point [disintegrations/t], and
A_{gw} is the activity of ^{222}Rn in ground water [disintegrations/t].

The assumption that the sole source of radon in stream water is from the ground-water system applies to equation 4.

A detailed survey of radon activity in the South Fork Zumbro River and Bear Creek in Rochester was completed during July 1988 as part of another Geological Survey investigation (J.F. Ruhl, U.S. Geological Survey, written commun., 1988). Water samples were collected for measurement of radon activity at 11 sites on the South Fork Zumbro River (reach 6, fig. 17) and 6 sites on Bear Creek (reach 15, fig. 17). Discharge was also measured on both streams during the sampling period. The South Fork Zumbro River seems to lose water into the ground-water system along at least one 600-ft-long reach of calm water in reach 6. Infiltration from the South Fork Zumbro River to the underlying aquifer along this 600-ft-long reach was calculated to be about 1.2 ft^3/s by use of equation 3. The reach is about midway between Rochester well 11 and the AMPI wells (fig. 11). Pumping of these wells could be the cause of induced infiltration from the river to the underlying aquifer. On the basis of radon data, the author concluded that two other reaches of the South Fork Zumbro River and at least one reach of Bear Creek may also have been losing streamflow to the ground-water system, but data for these reaches were less conclusive than data for reach 6. Also on the basis of radon data, the author concluded that ground-water interaction with Bear Creek is variable. Gaining and losing reaches alternate over distances of 50 to 100 ft.

SIMULATION OF GROUND-WATER FLOW

A ground-water-flow model was developed to simulate movement of ground water in the St. Peter-Prairie du Chien-Jordan aquifer in the Rochester area. The model was used to estimate the hydrologic effects of (1) current ground-water development on water levels, direction of ground-water movement, and streamflow; (2) projected future ground-water withdrawals; and (3) a hypothetical long-term drought. Listings of model input values for the model are shown in appendix C.

Model Description

The computer-model program by McDonald and Harbaugh (1988) was used to simulate ground-water flow in the St. Peter-Prairie du Chien-Jordan aquifer with the model. A finite-difference method is used to obtain a solution to the partial-differential equation of ground-water flow in three dimensions, which is as follows:

$$\frac{\partial}{\partial x}K_{xx}\frac{\partial h}{\partial x} + \frac{\partial}{\partial y}K_{yy}\frac{\partial h}{\partial y} + \frac{\partial}{\partial z}K_{zz}\frac{\partial h}{\partial z} - W = S_s\frac{\partial h}{\partial t}, \qquad (5)$$

where

x, y, and z are Cartesian coordinates aligned along the major axes of hydraulic conductivity K_{xx}, K_{yy}, K_{zz}, [L/t],

h is the head [L],

W is a volumetric flux per unit volume and represents sources and/or sinks of water $[t^{-1}]$,

S_s is the specific storage of the porous material $[L^{-1}]$, and

t is time [t].

A conceptual model of the ground-water system was formulated before the numerical model was constructed. The conceptual model consists of assumptions used for simplifying the geometry, the boundary conditions, the hydraulic stresses, and the hydrologic properties used to simulate ground-water flow with the model. These assumptions are necessary because the ground-water system is too complex to be simulated in detail. The major simplifying assumptions for the conceptual model are--

1. The hydrogeologic units are considered to be homogeneous and horizontally isotropic.

2. The St. Peter Sandstone, Prairie du Chien Group, and Jordan Sandstone are hydraulically connected and are a single aquifer, the St. Peter-Prairie du Chien-Jordan.

3. Recharge to the St. Peter-Prairie du Chien-Jordan aquifer is by leakage through the overlying Decorah-Platteville-Glenwood confining unit and through drift, where these units are present; rates of recharge are greatest along the edge of the Decorah-Platteville-Glenwood confining unit.

4. Water is discharged from the aquifer into the South Fork Zumbro River and into smaller streams through alluvium in the stream valleys. Water also leaks from the stream to the ground-water system through the alluvium.

5. The volume of water that moves vertically across the base of the Jordan Sandstone is small compared to lateral flow in the St. Peter-Prairie du Chien-Jordan aquifer, and the base can be treated as a no-flow boundary.

6. Vertical flow between the St. Peter-Prairie du Chien-Jordan and the underlying aquifers in the multi-aquifer city wells is negligible during non-pumping periods. Pumpage from each aquifer penetrated in these wells is proportional to the ratio of the aquifer transmissivity to the total transmissivity of all aquifers penetrated. A similar relation applies to municipal wells completed in the Prairie du Chien Group the and Jordan Sandstone; and

7. Ground water flows laterally across the model's boundaries toward streams outside the modeled area.

The model was designed to simulate ground-water flow in the immediate vicinity of Rochester. The modeled area is larger than the study area so that the effects of regional boundaries on the position of the ground-water divide west, south, and east of Rochester may be included. The modeled area was subdivided into discrete blocks by a variably spaced grid of 64 rows and 52 columns (fig. 18). The center of each cell (grid block) is called a node. The outermost rows and the columns of cells are illustrated in figure 18. Location of a specific cell in the interior of the model can be obtained by projecting the cell boundaries into the model's area. Grid spacings range from 1,000 ft in Rochester, where the most detail is required, to 11,100 ft on the periphery of the model, where less detail is needed.

Horizontal ground-water flow in the St. Peter-Prairie du Chien-Jordan aquifer was simulated with three model layers that represent, in descending order, the (1) sandstone in the St. Peter part, (2) limestone and dolomite in the Prairie du Chien part, and (3) sandstone in the Jordan part (fig 6). Some cells in model-layer 1 also represent the effects of glacial drift, primarily in bedrock valleys west of Rochester. Vertical flow in the ground-water system was simulated in the model by allowing leakage between layers.

Geologic data from maps prepared by the Minnesota Geological Survey (Minnesota Geological survey, written commun., 1987) were used to define the extent and the thickness of the hydrogeologic units simulated in the model. The thickness of each unit was determined by overlaying the model's grid on the appropriate map and averaging the thickness within each cell. Because the dimensions of cells increase toward the edges of the model's area, hydrologic properties assigned to these cells are averaged over larger areas, compared to cells in the middle of the model.

Hydraulic conductivities within each layer of the model were based primarily on calculations from aquifer tests. Calculations from specific-capacity tests also were used but were considered to be less accurate than aquifer-test results. Initial horizontal hydraulic conductivity for the layers ranged from 3 to 10 ft/d. Initial vertical hydraulic conductivity for each layer (1 ft/d) was based on data by Norvitch and others (1974).

Ground-water seepage from the aquifer to streams was simulated by head-dependent-flux cells in model layers 1 and 2 (fig. 18). Leakage between the aquifer and the stream cells is approximated by Darcy's law as--

$$Q_{riv} = (H_{riv} - H_{aq})\ C\ A, \tag{6}$$

where

- Q_{riv} is the leakage through a reach of the riverbed $[L^3/t]$,
- H_{riv} is the specified head on the river side of the streambed [L],
- H_{aq} is the model-computed head on the aquifer side of the streambed [L],
- C is the specified streambed leakage coefficient, equal to the vertical hydraulic conductivity of the streambed divided by its thickness [L/t-L], and
- A is the area of the streambed in the model cell $[L^2]$.

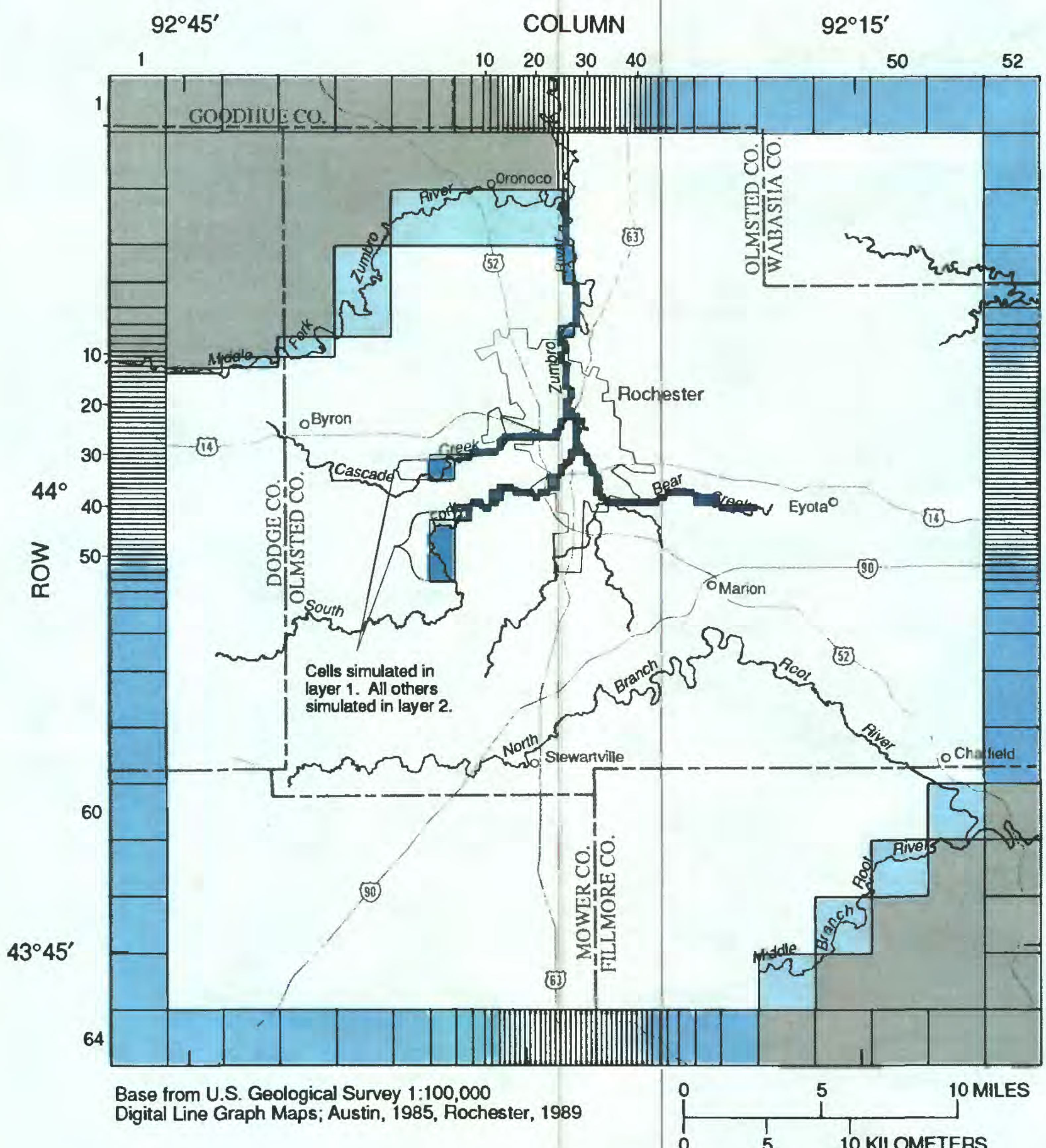
A streambed-leakage coefficient was calculated for each stream cell and was multiplied by the streambed area of that cell. An initial value of 0.1 (ft/d)/ft (foot per day per foot) was specified for C. This value is close to those used in previous investigations in western Minnesota by Lindholm (1980), Soukup and others (1984), Delin (1987), and Delin (1988).

Ground-water pumpage was based on MDNR records for 1986 and on average pumpages from RPU records (1977-88). MDNR records were incomplete for 1977 to 1988. About 4,000 Mgal/yr (million gallons per year) was simulated for 20 of Rochester's municipal wells and 22 other high-capacity wells near Rochester (fig. 11). Locations and pumping rates of the wells are given in appendix B. Withdrawals from more than one well owned by the same company, and within the area of the same model cell, were simulated by a single cell in the model. Rochester well 16 was not simulated because it is not completed in the St. Peter-Prairie du Chien-Jordan aquifer. Discharge rates simulated for the Prairie du Chien and the Jordan parts of the St. Peter-Prairie du Chien-Jordan aquifer (layers 2 and 3) were computed as the product of the ratios shown in table 1 and the average discharge rates from 1977 to 1988.

Recharge simulated by the model represents the net amount of water reaching the ground-water system after losses to evapotranspiration. Recharge occurs as leakage through the Decorah-Platteville-Glenwood confining unit and glacial drift. The model was not used to simulate ground-water losses to evapotranspiration because these losses occur in only a small percentage of the modeled area, primarily in the immediate vicinity of major streams, where the water table is within about 5 ft of land surface.

Recharge rates were assigned to five zones (fig. 19): (1) where the Decorah-Platteville-Glenwood confining unit occurs; (2) where glacial drift is more than about 100 ft thick in the bedrock valley west of Rochester; (3) where storm runoff (potential recharge water) is diverted to sewers, in the city of Rochester; (4) where the St. Peter Sandstone or Prairie du Chien Group are the uppermost bedrock units (that is, where the Decorah-Platteville-Glenwood confining unit is absent); and (5) where recharge is greatest (along the edge of the Decorah-Platteville-Glenwood confining unit because of springs and seeps at the base of the overlying upper carbonate aquifer). The model's representation of the recharge zones is shown in figure 9.

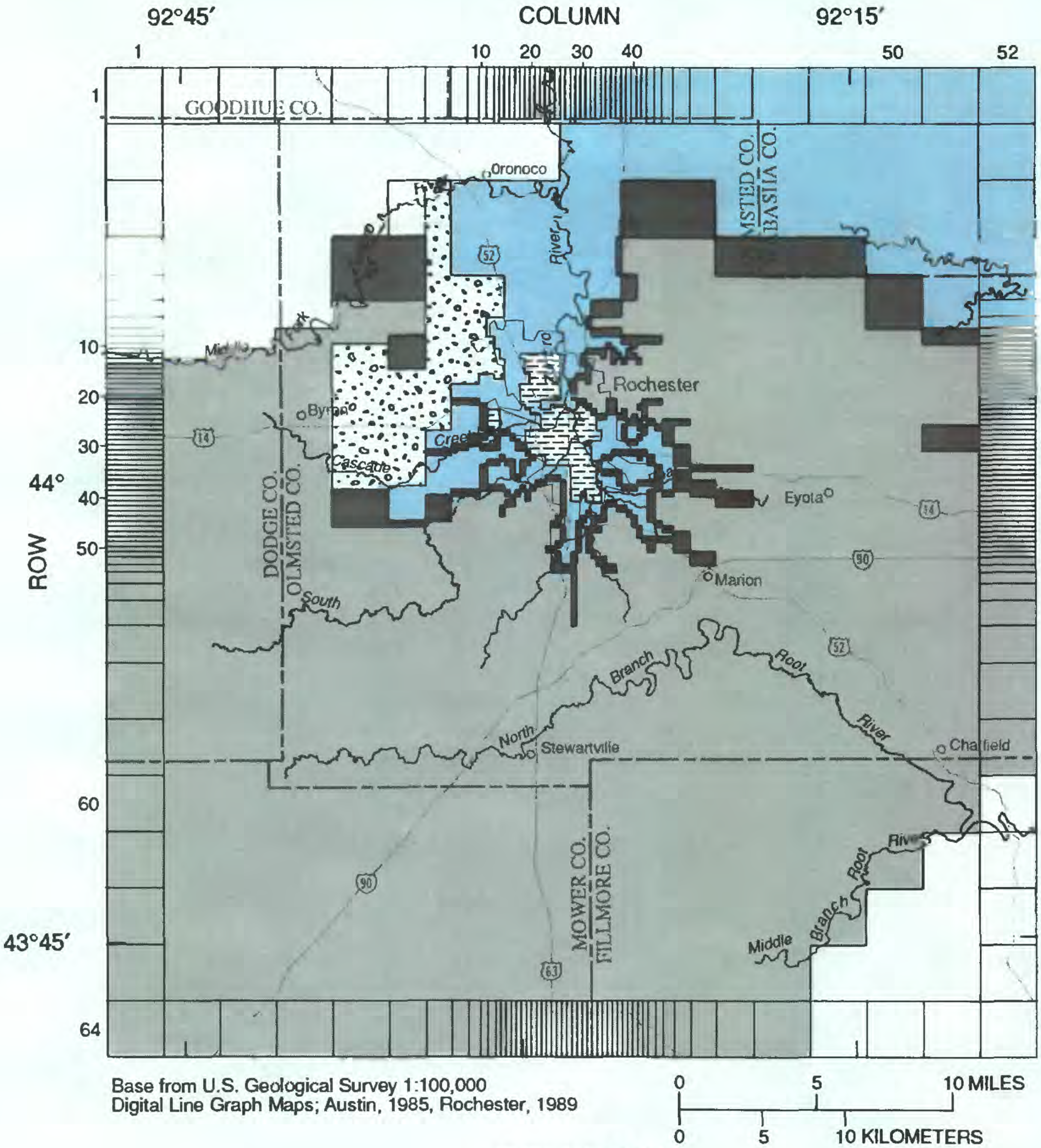
Specification of boundary conditions that accurately simulate actual conditions is critical to constructing an accurate model. Where possible, the natural hydrologic boundaries of the ground-water system were selected as model boundaries. Selection of boundary conditions, however, involves simplification of the hydrogeology.



EXPLANATION

- CONSTANT-HEAD CELL REPRESENTING A RIVER IN LAYER 2
- CONSTANT-HEAD CELL REPRESENTING REGIONAL POTENTIOMETRIC SURFACE
- HEAD-DEPENDENT FLUX CELL REPRESENTING A STREAM
- GROUND-WATER FLOW NOT SIMULATED IN THE MODEL

Figure 18.--Finite-difference grid and model boundaries used to simulate ground-water flow in the Prairie du Chien Group and the Jordan Sandstone (layers 2 and 3) for the steady-state model.



EXPLANATION

DECORAH-PLATTEVILLE-GLENWOOD CONFINING UNIT--0-1.5 inches per year recharge.

THICK GLACIAL DRIFT--1.5-3.0 inches per year recharge.

SEWERED AREA OF ROCHESTER--3-5 inches per year recharge.

EDGE OF DECORAH-PLATTEVILLE-GLENWOOD CONFINING UNIT--6-15 inches per year recharge.

PRAIRIE DU CHIEN GROUP UPPERMOST UNIT-- 3-6 inches per year recharge.

GROUND-WATER FLOW NOT SIMULATED IN THE MODEL

Figure 19.--Recharge zones and rates of recharge specified in the steady-state model.

The ground-water divide in the potentiometric surface of the St. Peter-Prairie du Chien-Jordan aquifer (fig. 7) controls horizontal flow within the model's area. Accurate simulation of the area contributing ground-water to Rochester, bounded by the ground-water divide and flow lines to the north, was critical to simulating the ground-water system. The ground-water divide was not simulated explicitly as a boundary in the model. Instead, the model was extended beyond this no-flow boundary so that the model could be used to estimate the location of the ground-water divide and the contributing area, for simulated pumpage and climate scenarios. The northwest part of the model's boundary in layer 2 represents the Middle Fork Zumbro River (fig. 18). Ground-water flow was not simulated north of this river. Part of the south side of the model's boundary in layer 2 represents the Middle Branch Root River (fig. 18). These rivers were simulated as constant-head boundaries in layer 2 and as no-flow boundaries in layer 3 (fig. 18). These perennial streams, whose flow remains virtually constant, are distant from the pumping centers in Rochester. Because the St. Peter (layer 1) is not in the north and the southeastern parts of the modeled area (fig. 20), ground-water flow was not simulated in these areas in layer 1. The remaining boundaries in all three layers of the model were simulated by use of constant-head cells representing regional hydraulic head in the aquifers. Water-level fluctuations near these boundaries are insignificant in all three layers, and the boundaries are distant from the pumping centers in Rochester. Because the hydraulic heads at all boundaries are lower than the heads at the ground-water divide, the other model boundary conditions (recharge, river leakage, and pumping) control positioning of the ground-water divide and the contributing area. In addition, the effects of stresses simulated in the Rochester area for the experiments with the model did not extend to these boundaries.

Calibration of Model

The model was calibrated to define hydrologic properties that would result in a good fit between model-computed and measured hydraulic heads and to assure that the boundaries selected were reasonable for simulation of flow in the ground-water system. The model was calibrated to steady state by comparing measurements of hydraulic head in the St. Peter-Prairie du Chien-Jordan aquifer and ground-water seepage to streams with corresponding model-computed data. The model was also calibrated for transient conditions by comparing model-computed hydraulic heads to ground-water levels measured from 1976 to 1988.

Steady State

Calibration consisted of comparing model-computed hydraulic heads and ground-water seepages to streams to water levels measured in wells and estimates of ground-water seepage during January 1988. From a study of long-term (1977-88) water-level data (fig. 14) in the area, one can understand that winter water levels approach and probably attain equilibrium (steady state) in the ground-water system. Thus, changes in recharge to and discharge from the aquifer during winter are close to zero, and recharge and discharge are in equilibrium. Although ground-water withdrawals increased during the period 1983 to 1988, most of this increase can be attributed to increases in summer pumping; winter pumping remained virtually constant (fig. 12). Although ground-water discharge to streams fluctuates as a function of stream stage, discharge of the South Fork Zumbro River generally returns to baseflow (steady state) during the winter months (fig. 12).

Steady-state calibration of the model centered on adjustment of recharge, horizontal and vertical hydraulic conductivity of the aquifers, and streambed conductance because these inputs to the model are least known. Calibration of the model was achieved when hydraulic heads in each layer calculated by use of the model matched measured water levels to within about 5 ft. Comparison of estimated and model-computed ground-water seepage to streams was also an important part of the calibration process. Estimating the approximate location of the ground-water divide and the area contributing ground water to Rochester were of principal concern.

Distribution of water-level and hydraulic-conductivity data was insufficient within each layer of the model to calibrate each layer separately to steady state. Instead, the model was calibrated for all three layers of the model on the basis of available data. This procedure is acceptable because the water levels are close and the hydraulic conductivities are also close in the St. Peter Sandstone, the Prairie du Chien Group, and the Jordan Sandstone.

During the initial stage of model calibration, recharge was simulated with two zones: where the Decorah-Platteville-Glenwood confining unit occurs and elsewhere in the model. On the basis of the model results, the author concluded that this was an unreasonable representation of recharge distribution. The model strongly supports the theory of a zone where recharge increases at the edge of the Decorah-Platteville-Glenwood confining unit. Without this zone, the correct location of the ground-water divide and the area contributing ground water to Rochester could not be simulated with the model. Results supported dividing the area into five zones of varying recharge. Therefore, recharge rates were varied within each of the recharge zones during the remainder of the calibration process.

In areas where the Decorah-Platteville-Glenwood confining unit occurs (fig. 19), recharge was adjusted in the range from 0 to 2 in/yr; model simulation of heads was best with a rate of 0.4 in/yr. Leakage through the Decorah-Platteville-Glenwood confining unit is least in the southwest part of the modeled area, where the thickness of the upper carbonate aquifer is greater than about 200 ft. Simulated leakage in this part of the modeled area is near zero.

Recharge was adjusted from 2 to 6 in/yr in areas where the Decorah-Platteville-Glenwood confining unit is absent, such as the north-central part of Olmsted County. Model simulation of heads in these areas was best with a recharge rate of 5 in/yr. Recharge was also adjusted in the range from 2 to 6 in/yr in the city of Rochester. A recharge rate of about 4.5 in/yr may occur there. This low rate, compared with other areas where the Decorah-Platteville-Glenwood is absent, is likely the result of urban runoff diverted to sewers. Because of this diversion, less water is available for recharge to the ground-water system.

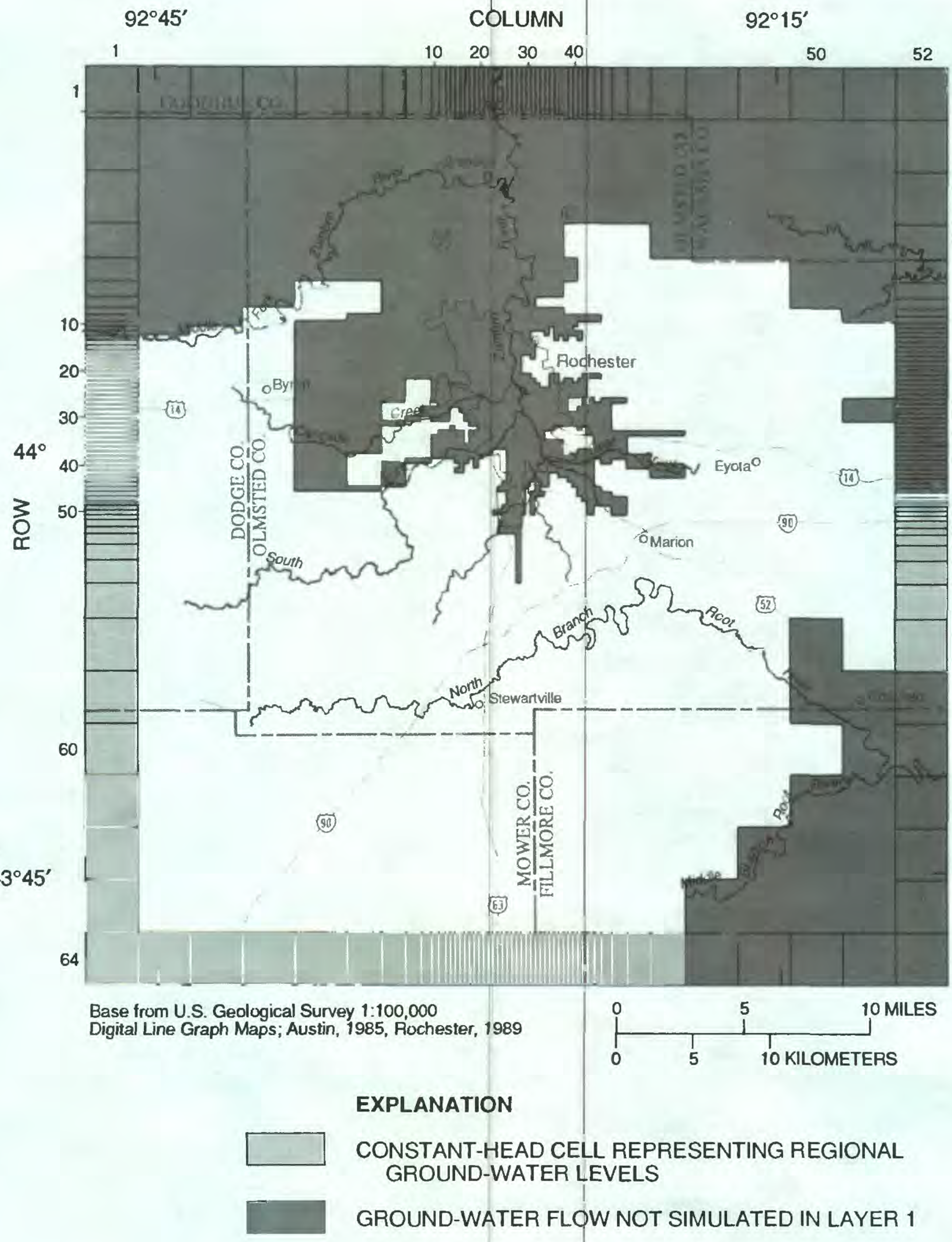


Figure 20.--Model boundaries for the St. Peter Sandstone (layer 1) for the steady-state model.

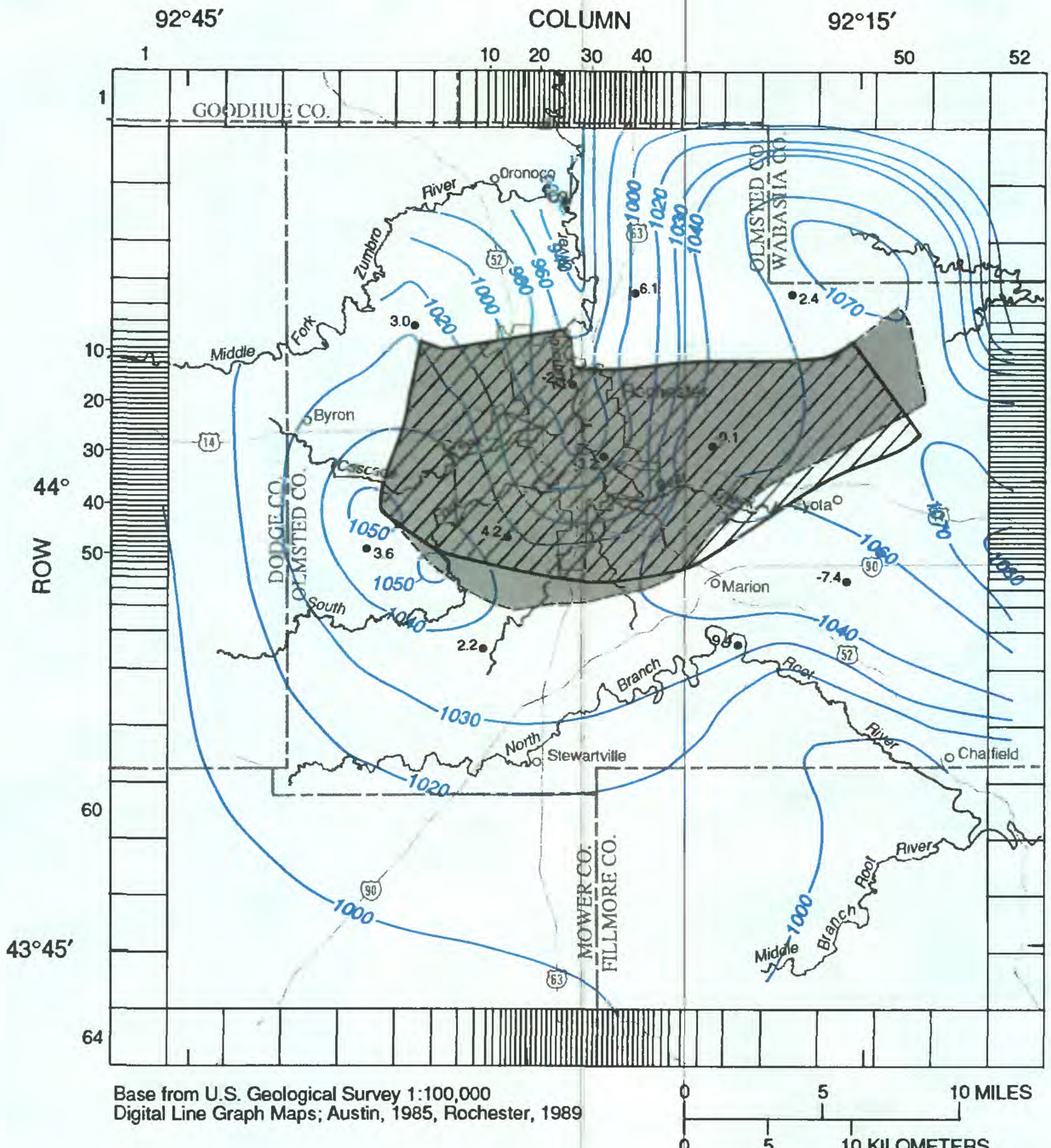
Recharge to the aquifer system is less in areas where thickness of glacial drift is greater than about 100 ft, such as in the bedrock valley west of Rochester (fig. 19). Recharge was adjusted from 0 to 2.5 in/yr in that area. Model simulation of heads in the bedrock valley was best with a recharge rate of 1 in/yr.

Recharge was adjusted in the range from 5 to 17 in/yr along the edge of the Decorah-Platteville-Glenwood confining unit. Model simulation of heads in this area was best with a recharge rate of 13 in/yr. Near Rochester, cell dimensions for this zone are 1,000 ft on a side, which may be a reasonable approximation for the width of the zone of increased recharge. In areas north of Rochester, however, such as near the Olmsted-Wabasha County line (model rows 3 and 4, fig. 19), the model cells for this zone are larger than those in Rochester. Thus, it was necessary to adjust the simulated recharge rate for this zone to 3.6 in/yr to obtain the best simulation of the recharge rate relative to the zone width.

The horizontal hydraulic conductivity for each layer was adjusted within each layer during calibration in the range from 0.1 to 10.0 times the best estimates of hydraulic conductivity based on available data. The hydraulic conductivity for each layer in the steady-state model ranges from 1 to 35 ft/d. On the basis of the model results, the author concludes that the horizontal hydraulic conductivities of the St. Peter Sandstone, the Prairie du Chien Group, and the Jordan Sandstone are close but highly variable near downtown Rochester. Highly variable hydraulic conductivity for limestone and dolomite, such as the Prairie du Chien, is common because of fractures and solution crevices. Aquifer hydraulic conductivity may increase with distance from the downtown area to the southeast. These potentially higher conductivities, however, are not supported by aquifer-test data from municipal wells. Because data were not available to justify changing the hydraulic conductivity in the model for these local areas, model-computed heads in three cells were about 10 ft more than, and in three cells about 10 ft less than, measured heads in Rochester municipal wells.

The vertical hydraulic conductivity between each model layer of the St. Peter-Prairie du Chien-Jordan aquifer was adjusted in the range from 0.001 to 10 times the initial value of 1 ft/d. The best model simulation of heads was with a vertical hydraulic conductivity of 1 ft/d.

The steady-state potentiometric surface for the Prairie du Chien (layer 2) computed by use of the model is illustrated in figure 21. The potentiometric surfaces computed for the St. Peter (layer 1) and Jordan (layer 3) parts of the aquifer are similar to the surface shown in figure 21. Shown also in figure 21 is the ground-water divide computed by use of the model and the divide based on measured data. The accuracy of the model-computed potentiometric surface and the area contributing ground water to Rochester is illustrated in figures 7 and 21. The mean of the absolute value of the difference between the measured and the model-computed heads was 0.6 ft for the St. Peter (layer 1), 1.5 ft for the Prairie du Chien (layer 2), and 0.5 ft for the Jordan. Corresponding values for only the high-capacity wells within Rochester are 0.8 ft for the Prairie du Chien and 2.8 ft for the Jordan. Greater model-computed differences for the high-capacity wells, compared to non-high-capacity wells, is not surprising because the ground-water-flow model computes the average hydraulic head in a



EXPLANATION

AREA CONTRIBUTING GROUND-WATER TO ROCHESTER BASED ON MEASURED WATER-LEVEL DATA

MODEL-COMPUTED AREA CONTRIBUTING GROUND-WATER TO ROCHESTER

MODEL-COMPUTED POTENTIOMETRIC CONTOUR-- Interval 10 and 20 feet. Datum is sea level.

4.2• SELECTED DATA POINT AND DEVIATION OF SIMULATED WATER LEVEL FROM MEASURED WATER LEVEL, IN FEET

Figure 21.--Model-computed potentiometric surface of the Prairie du Chien Group (layer 2) for steady state conditions, near Rochester, Minnesota, 1988.

cell containing a well and does not simulate drawdown in the well bore. An analytical technique developed by Thiem (1906) was used to estimate the hydraulic head in each municipal well. By use of these calculations, the model was shown to have computed steady-state heads to within about 1 to 5 ft in most high-capacity pumped wells.

Water levels measured in eight single-aquifer municipal wells during 1951 in Rochester were compared to simulated heads by removing pumping from the steady-state model. Earlier water-level data were unavailable. The author expected model-computed heads to be higher than measured values because 11 municipal wells were in use during 1951. Water levels measured in 1951, therefore, represent a stressed potentiometric surface. The average model-computed hydraulic head was about 5 ft higher than water levels measured in 1951. This is an acceptable figure, particularly as pre-development water-level data are unavailable.

Comparison of estimates of model-computed ground-water seepage to rivers was also used to evaluate how well the model simulates the ground-water-flow system. Accuracy of stream-discharge measurements is plus or minus 5 percent. Estimates of ground-water seepage rates are likely less than the gaging error for reaches 1, 2, 5, 6, 8, 9, 12, 13, 14, 16, and 17 (table 3). In addition, estimates of ground-water seepage for reach 4 (table 3) are postive in March 1987 and negative in August 1987, an indication that ground-water seepage is highly variable locally. Consequently, accurate simulation of ground-water seepage rates is impossible.

Model-computed seepage to river cells representing various reaches of the South Fork Zumbro River, Bear Creek, and Cascade Creek (fig. 17) was compared to estimates of seepage for those reaches in January 1988. Thus, water-level and stream-seepage rates used in model calibration were for the same time. Seepage in January were estimated by computing the ratio of streamflow measured on the South Fork Zumbro River at Rochester for March or August 1987 with January 1988 measurements (Geological Survey streamflow records, St. Paul, Minn.). This ratio was multiplied by the ground-water seepage rates computed for each reach during March or August 1987 to obtain an estimate of the January 1988 values.

The streambed-conductance coefficient (C) was adjusted in the range from 0.001 to 10 (ft/d)/ft for all reaches of streams where hydrologic data were obtained. The best match (final steady state) of C for most river cells was 0.1 (ft/d)/ft. Lowering the value of C, however, to 0.01 (ft/d)/ft for reaches 4, 7, and 9 improved model calibration. According to grain-size information obtained during test-drilling along the river, streambed conductances for these reaches are lower than for most other reaches.

The model was used to duplicate the correct order of magnitude of ground-water seepage to streams for all reaches. Estimates and model-computations of ground-water seepage to the South Fork Zumbro River, Bear Creek, and Cascade Creek for steady state are shown in table 4. Most of the estimates and the model-computations of seepage rates for the simulated streams agree or are close to agreement. Agreement, however, is variable between estimates and model-computations of seepage rates for individual reaches. Lack of agreement between the two sets of data for most reaches is likely because of inherent

Table 4.--*Estimates of and model-computed ground-water seepage to the South Fork Zumbro River, Bear Creek, and Cascade Creek*

[Seepage is in cubic feet per second]

River reach	Ground-water seepage for steady state: Estimates of	Model-computed
	South Fork Zumbo River	
1	-2	-2
2	1	0
3	3	0
4	-2	0
5	2	2
6	-1	0
7	6	0
8	2	3
9	-6	1
10	1	3
11	8	7
12	4	3
Total seepage	16	17
	Bear Creek	
13	3	1
14	2	2
15	0	1
Total seepage	5	4
	Cascade Creek	
16	-1	0
17	3	2
18	0	0
Total seepage	2	2

inaccuracies in (1) stream-discharge measurements, (2) estimates of ground-water seepage, and (3) model-simulation of ground-water seepage. Improvements in the estimating and the measuring of seepage and refinement of the model grid are required for an accurate calibration of the model with these types of data.

A water budget is an accounting of inflow to, outflow from, and storage in the aquifer system. For steady state, which is based on a constant storage, inflow (sources) to the system equals outflow (discharges) from the system. A general equation of the steady-state water budget for the St. Peter-Prairie du Chien-Jordan aquifer in the modeled area is as follows:

Recharge to the top of the aquifer +
horizontal ground-water flow into the modeled area +
leakage from streams =
ground-water seepage to streams + ground-water pumpage +
horizontal ground-water flow out of the modeled area. (7)

The steady-state water budget for the approximate area contributing water to Rochester (fig. 8) is likely of greatest interest to ground-water managers in the Rochester area. The model-computed water budget for the approximate area coinciding with the area shown in figure 8 is shown in tabel 5. Recharge accounts for about 91 percent of inflow to the area according to results obtained by use of the model. Streams account for the remaining 9 percent. Ground-water pumpage and ground-water seepage to streams account for 55 and 45 percent of the discharges from the area contributing water to Rochester.

The steady-state water budget for the calibrated model is shown in table 6. Recharge from precipitation is the major source of inflow to the modeled area according to results obtained by use of the model. Discharge from the model, however, differs significantly from the budget for the area contributing water to Rochester; ground-water flow across model boundaries is the source of about 61 percent of discharge from the model. This ground-water discharge is the result of flow from the ground-water divide to model boundaries (fig. 21). The elevation of these model boundaries are lower than that of the ground-water divide.

The model was used to define the sources of recharge contributing water to the city of Rochester. About 55 percent of recharge to the aquifer in this 140-square-mile area is from the zone along the edge of the Decorah-Platteville-Glenwood confining unit. This recharge represents a rate of about 3,500 Mgal/yr. About 25 percent of the recharge within the area enters the aquifer where the Prairie du Chien Group is the uppermost bedrock unit, about 10 percent enters the sewered area of Rochester, about 10 percent enters as leakage through the Decorah-Platteville-Glenwood confining unit, and less than about 5 percent enters through thick drift west of Rochester.

About 40 percent of the recharge to the St. Peter-Prairie du Chien-Jordan aquifer in the entire modeled area is from the zone along the edge of the Decorah-Platteville-Glenwood confining unit. This recharge is reasonable if one assumes that the rate of recharge to the upper carbonate aquifer is about 5 in/yr and that most of the water reaches the St. Peter-Prairie du Chien-Jordan aquifer through this zone. About 40 percent of recharge to the aquifer enters where the Prairie du Chien Group is the uppermost bedrock unit, about 15 percent enters as leakage through the Decorah-Platteville-Glenwood confining unit, and less than 5 percent enters the sewered area of Rochester and as leakage through thick drift west of Rochester.

Sensitivity Analysis

A sensitivity analysis was completed to determine the response of the model to changes in aquifer properties, recharge, and streambed conductance. The sensitivity analysis consisted of uniformly increasing or decreasing selected model variables separately and noting the change in simulated hydraulic head. Sensitivity of the model is an indication of the degree to which additional information could improve knowledge of the ground-water-flow system and improve calibration of the model.

Table 5.--*Water budget for the approximate area contributing water to Rochester computed by the steady-state model*

[Mgal/yr, million gallons per year]

Sources	Rate (Mgal/yr)	Percent
Recharge to top of aquifer layers	6,500	90.9
Leakage from stream cells to aquifer layers	650	9.1
Inflow	7,150	100.0

Discharges	Rate (Mgal/yr)	Percent
Ground-water withdrawal	3,950	54.9
Ground-water seepage to stream cells	3,250	45.1
Outflow	7,200	100.0

Table 6.--*Water budget for the modeled area computed by the steady-state model*

[Mgal/yr, million gallons per year]

Sources	Rate (Mgal/yr)	Percent
Recharge to top of aquifer layers	23,350	90.0
Ground-water flow into the modeled area (constant-head cells)	1,600	6.2
Leakage from stream cells to aquifer layers	1,000	3.8
Inflow	25,950	100.0

Discharges	Rate (Mgal/yr)	Percent
Ground-water flow out of the modeled area (constant-head cells)	15,650	61.0
Ground-water seepage to stream cells	6,150	23.6
Ground-water withdrawal	4,000	15.4
Outflow	26,000	100.0

During the sensitivity analysis, values of horizontal hydraulic conductivity for each hydrogeologic unit and recharge were varied by a factor of 2 (table 7). Vertical hydraulic conductivity of the hydrogeologic units and streambed conductance were varied by a factor of 10. The model is most sensitive to changes in recharge, particularly to recharge along the edge of the Decorah- Platteville-Glenwood confining unit. Variation of this variable of the model resulted in a mean deviation which ranged from -12 to +33.1 ft between model-computed heads and measured water levels in all layers (table 7). The model is sensitive also to variations in the horizontal hydraulic conductivity. The model is more sensitive to variations in conductivity for the Prairie du Chien part than for the St. Peter and Jordan parts of the St. Peter-Prairie du Chien-Jordan aquifer (table 7). Variation of the horizontal hydraulic conductivity for the Prairie du Chien resulted in a mean deviation which ranged from -11.8 to +14.8 ft between model-computed heads and measured water levels in all layers. The model is also sensitive to variations in streambed conductance. Variation of streambed conductance resulted in a mean deviation which ranged from -3.6 to +15.6 ft between model-computed heads and measured water levels in all layers. Differences in model-computed heads are greatest near the streams. The model is virtually insensitive to variations in the vertical hydraulic conductivity (table 7).

Table 7.--*Sensitivity of the model to changes in values of hydrologic properties of the steady-state model*

[L1 = model layer 1; L2 = model layer 2; L3 = model layer 3. Mean deviation from values calculated by best-match simulation. Deviations calculated for 16 cells in layer 1 of model, 53 cells in layer 2 of model, and 51 cells in layer 3 of model. A positive deviation indicates calculated heads greater than best-matched simulation. A negative deviation indicates calculated heads less than best-matched simulation]

Property varied	Multiplication factor	Hydrogeologic unit and model layer	Mean deviation of water level (in feet)		
			L1	L2	L3
Recharge	2.0	Uppermost unit (L1 & L2)	+25.7	+26.2	+33.1
	.5	Uppermost unit (L1 & L2)	-12.0	-11.1	-12.0
Streambed leakance	10.0	All reaches (L1 & L2)	+ .2	+ .2	-3.6
	.1	All reaches (L1 & L2)	+5.4	+10.3	+15.6
Horizontal hydraulic conductivity	2.0	St. Peter (L1)	-1.4	+ .4	-1.0
	.5	St. Peter (L1)	+1.8	+2.1	- .3
	2.0	Prairie du Chien (L2)	-9.1	-7.1	-11.8
	.5	Prairie du Chien (L2)	+12.6	+12.3	+14.8
	2.0	Jordan (L3)	-3.5	-2.3	-6.1
	.5	Jordan (L3)	+3.3	+4.0	+3.3
Vertical hydraulic conductivity	10.0	All units (L1, L2, & L3)	+ .6	+1.5	- .5
	.1	All units (L1, L2, & L3)	+ .6	+1.5	- .9

Transient Conditions

Because long-term water-level data and information on seasonal variations in recharge are lacking, the model could not be calibrated to transient conditions. Transient simulations were completed, therefore, to learn more about how the ground-water flow system responds to seasonal changes in pumping and climatic stresses. The transient simulations were used to identify additional hydrologic data needs and to test concepts of recharge to and discharge from the ground-water flow system.

The model was used to simulate the effects of pumping and climatic stresses on the ground-water system for the years of 1976 and 1986. As shown in table 2, precipitation at the Rochester airport was below normal (drought) for 1976 and above normal for 1986 (U.S. Department of Commerce, 1976-88). Thus, the model was used to simulate extremes in climatic conditions. Storage coefficients were based on results of nine aquifer tests run on Rochester municipal wells (Bruce Liesch & Assoc., written commun., 1987). An initial storage coefficient of 10^{-2} was assigned to the St. Peter and the Jordan sandstones and 10^{-3} to the Prairie du Chien limestone. Initial specific yield values of 0.2 and 0.05 were assigned to the St. Peter and the Prairie du Chien where they are unconfined (Morris and Johnson, 1967). Heads from a steady-state simulation of the hydrologic variables in January 1976 were used as starting heads for the transient simulations. Ground-water withdrawals were adjusted monthly on the basis of data provided by RPU and the MDNR. Thus, the values represent withdrawal totals for each well during each month of the simulation.

Recharge rates were estimated for each month of the transient simulations on the basis of a comparison of the recharge rates used during the steady-state simulations with precipitation at the Rochester airport. Thus, the simulated recharge rates are related to seasonal changes in precipitation. In areas where the Prairie du Chien Group is the uppermost bedrock unit (fig. 10), recharge to the aquifer likely is rapid after precipitation, and the above concept is probably valid. This concept probably is incorrect for other parts of the ground-water system. Water recharging the St. Peter-Prairie du Chien-Jordan aquifer along the edge of the Decorah-Platteville-Glenwood confining unit is from the overlying upper carbonate aquifer. Consequently, there is a delayed response, of some unknown length of time, between precipitation reaching the upper carbonate aquifer and subsequent flow of that same water to the St. Peter-Prairie du Chien-Jordan aquifer through the zone along the edge of the confining unit. Unknowns are similar for temporal variation of recharge in the sewered area of Rochester and where drift is thick (fig. 10). Lack of data on the seasonal variation in recharge in these areas is the primary reason why the model could not be calibrated to transient conditions.

Ground-water discharge rates to streams were simulated as constant throughout the transient simulations. Ground-water-discharge rates, however, vary as a function of stream stage. The lack of data on seasonal variations in ground-water discharge to streams imposes further uncertainty on transient simulation.

The general trend of most model-computed and measured well hydrographs are in agreement; however, the magnitude and the frequency of the fluctuations are not in agreement. The model-computed and the measured hydrographs for Rochester well 11 and 30 during 1986 are presented in figures 22a and 22b. The primary reason for the lack of agreement in the two hydrographs is that water levels measured in high-capacity wells were used. A representative static water level is not easily obtained from such a well when the demand for public water supplies must be maintained. In addition, there is the possibility of water-level interference from nearby high-capacity wells. Water-level data for nonhigh-capacity wells were unavailable for 1976 and 1986.

To avoid the problems associated with calibrating to water levels measured in high-capacity wells, the author compared water levels in several domestic wells in areas throughout the area to model-computed water levels for 1988. Model-computed and measured hydrographs for one of these domestic wells is shown in figure 22c. Again, the model simulated the general downward trend of the measured hydrograph; however, the seasonal water-level fluctuations were not in agreement. This lack of match in hydrographs in the nonhigh-capacity wells likely results from inaccurate representation of seasonal variations in recharge. Because data for documenting seasonal variations in recharge in southeast Minnesota are unavailable, an acceptable match between model-computed and measured hydrographs is not possible.

A separate transient simulation was made to simulate the effects of historical pumping and climatic stresses on the ground-water system from 1977 to 1988. This long-term simulation was designed to avoid the effects of seasonal variations in recharge. The simulation was designed to approximate the long-term trend of the hydrograph and was not expected to duplicate seasonal water-level fluctuations. Each year was simulated as a separate stress period. The storage terms from the previous simulations were used for initial conditions in the simulation. Precipitation measured for each of the years simulated was first computed as a percentage of average precipitation. Model-simulated recharge rates were then multiplied by these percentages to obtain an estimate of recharge for each year of the simulation. A separate simulation for 1974-76 was used to generate starting heads for this simulation.

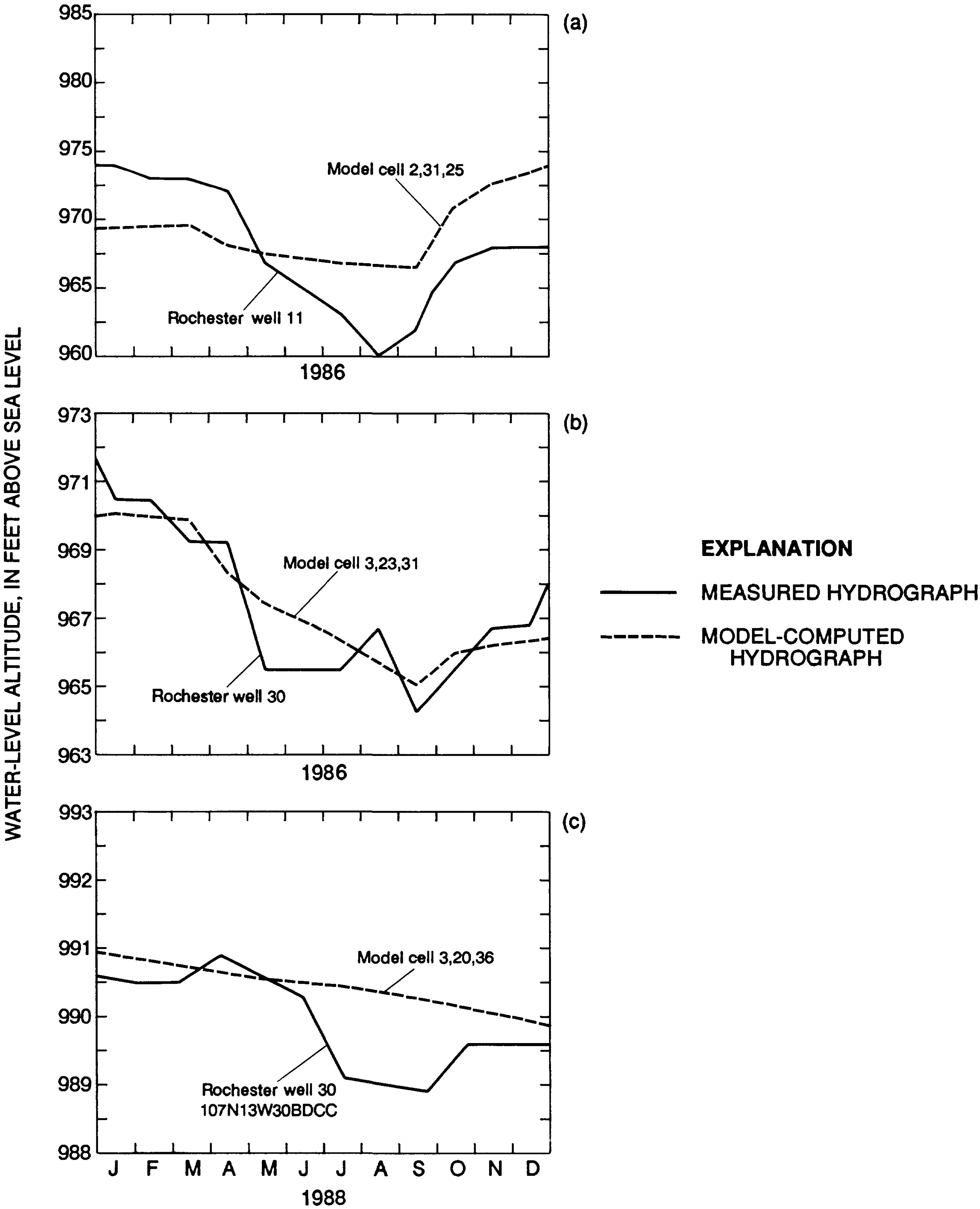


Figure 22.--Model-computed and measured water levels for selected wells in the St. Peter-Prairie du Chien-Jordan aquifer.

Model results were compared to water-level fluctuations measured in the Golden Hill School well for 1977-88 (fig. 14). This is the only nonhigh-capacity well in the modeled area for which long-term water-level records were available. The storage coefficients were adjusted in the range from 10^{-5} to 10^{-1}, and the specific yield was adjusted in the range 0.0005 to 0.1 for the transient simulations. An increase in storage coefficient for the St. Peter and the Jordan to 10^{-1} and for the Prairie du Chien to 10^{-2} improved the match between measured and computed water-levels. A decrease in the specific yield for the St. Peter and Prairie du Chien to 0.005 also improved the match. The model approximated the general water-level trend reasonably well namely, a general rise in water level during the late 1970's and the early 1980's and a general decline in water level from about 1983 to 1988 (fig. 14).

The short-term transient simulations demonstrate that calibration of the model for one year is not possible without information on seasonal variations in recharge. The calibration of the model could be enhanced and the transient experiments could be run if data on seasonal variations in recharge were gathered during future ground-water investigations in southeast Minnesota. Transient calibration and verification of the model also would require that water levels be measured over several years in nonhigh-capacity observation wells. These wells should be located both inside and outside the influence of pumping from high-capacity wells in the city as well as in each of the zones of recharge.

Model Experiments

The calibrated steady-state model was used to assess ground-water availability by simulating the effects of hypothetical conditions on ground-water levels and streamflow. The effects of (1) historical withdrawals, (2) an extended drought, (3) installing of six municipal wells on the perimeter of the city, (4) discontinuance of withdrawals from six municipal wells in downtown Rochester, and (5) discontinuance of withdrawals from eight nonmunicipal wells were simulated.

The hypothetical simulations described in this section were at steady state. Transient experiments were not made because data were insufficient to calibrate the model to transient conditions. The steady-state simulations are indicative of the long-term effects of the hypothetical conditions simulated because, unlike transient simulations, no water is derived from storage. The steady-state heads for January 1988 were used as the initial condition for each steady-state simulation. Hypothetical model simulations and corresponding aquifer responses are summarized in table 8, and the water budget is summarized for each simulation in table 9. A water-level-change map is presented for each hypothetical simulation. Model-computed water-level changes in the Prairie du Chien Group (layer 2) are illustrated in figures 23, 24, 26, 27, and 28. Model-computed water-level changes in the St. Peter and the Jordan Sandstones (layers 1 and 3) are similar to those in layer 2.

Table 8.--*Results for model experiments A, B, C, D, and E, Rochester, Minnesota, 1988*

[ft, feet; mi, miles]

Simulation	Conditions of simulation	Results
A	Predevelopment: average pumping removed to determine effects of historical withdrawals Recharge: 0 to 13 inches per year	Water levels declined generally from 4 to 15 ft within the city limits. Water levels declined more than 20 ft near Rochester wells 12, 13, 17, 27, 30, the Franklin Heating Station, and the Rochester State Hospital. The decline (about 48 ft) was greatest near Franklin Heating Station. Ground-water discharge to streams decreased by about 39 percent since predevelopment.
B	Current well development (42 wells) Pumping stress: average X 1.5 Drought: 30 percent less recharge for about 3-year duration	Water levels declined from 5 to 10 ft regionally and from 5 to 20 ft within the the city limits. Declines were greater than 20 ft near Rochester wells 12, 20, 27, 30, and the Franklin Heating Station. The greatest decline, about 32 ft, was near the Franklin Heating Station. Ground-water discharge to streams were reduced by about 86 percent of steady state.
C	Current + hypothetical well development: 6 planned wells (48 wells total) Pumping stress: average + estimated[a] Recharge: 0 to 13 inches per year	Water levels declined from 1 to 5 ft regionally and more than 20 ft near the hypothetical wells. The greatest decline, about 33 ft, was near well 32, northeast of downtown Rochester. The ground-water divide shifted about 1 mile south as a result of the expanded development. Water-level declines of as much as 2 ft extended south into Mower and Fillmore Counties. Ground-water discharge to streams were reduced by about 39 percent of steady state.
D	Pumping from wells 11, 12, 13, 20, 23, and 30 discontinued; (36 wells total) Pumping stress: average Recharge: 0 to 13 inches per year	Water levels recovered from 1 to 10 ft regionally and more than 10 ft near Rochester wells 12, 13, 20, and 30. Water-level recoveries of more than 1 foot extended to roughly 7 mi northeast of downtown Rochester. Ground-water discharge to streams increased by about 19 percent of steady state. By discontinuing pumpage from these municipal wells, the South Fork Zumbro River north of US Highway 14 would gain instead of lose water from the ground-water system.
E	Pumping from 8 nonmunicipal wells discontinued; (34 wells total) Pumping stress: average Recharge: 0 to 13 inches per year	Water levels recovered from 1 to 3 ft regionally and more than 10 ft near the AMPI and Franklin Heating Station wells. Recovery was the greatest (about 43 ft) near the Franklin Heating Station. Ground-water discharge to streams increased by about 12 percent of steady state. By removing pumpage from these nonmunicipal wells, ground-water discharge to the South Fork Zumbro River in Soldiers Field Park would be reduced to zero.

[a] Pumping rate for each hypothetical well was approximately 423 Mgal/yr.

Table 9.--*Model-computed water budget for steady state calibration and model experiments A, B, C, D, and E, Rochester, Minnesota*

Simulation	Well-development year (number of wells)	Pumping stress	Average recharge rate (inches per year)	Inflow (million gallons per year)			Outflow (million gallons per year)		
				Areal recharge	River leakage	Across model's boundary	River leakage	Ground-water pumpage	Across model boundaries
Steady-state	1988 (42)	Average (1977-88)	6.5	24,000	950	1,550	6,450	3,750	16,300
A	Predevelopment (Pumping removed)	None	6.5	24,000	700	1,550	9,800	0	16,500
B	1988 (42)	Average X 1.5	5.25 (Drought)	16,800	2,200	1,850	3,000	5,650	12,250
C	1988 + hypothetical: 6 planned wells (48)	Average + estimated[a]	6.5	24,000	1,550	1,600	4,900	6,300	15,950
D	1988 with wells 11, 12, 13, 20, 23, & 30 removed; (36)	Average	6.5	24,000	850	1,550	7,400	2,650	16,350
E	1988 with 8 nonmunicipal wells removed; (34)	Average	6.5	24,000	900	1,550	7,050	3,100	16,300

[a] Pumping rate for each hypothetical well is approximately 423 Mgal/yr.

The probable effects resulting from simulation of two or more of the hypothetical situations presented in this section of the report can be estimated by the principle of superposition (Reilly and others, 1987). According to this principle, the solutions to individual parts of a problem can be added to solve a larger problem composed of the individual parts. For example, model-computed water-level declines for simulations C and E could be added at a given point of interest. Thus, the effects of installing six municipal wells on the perimeter of the city and discontinuing withdrawals from eight nonmunicipal wells could be estimated at any point.

Historical Pumping

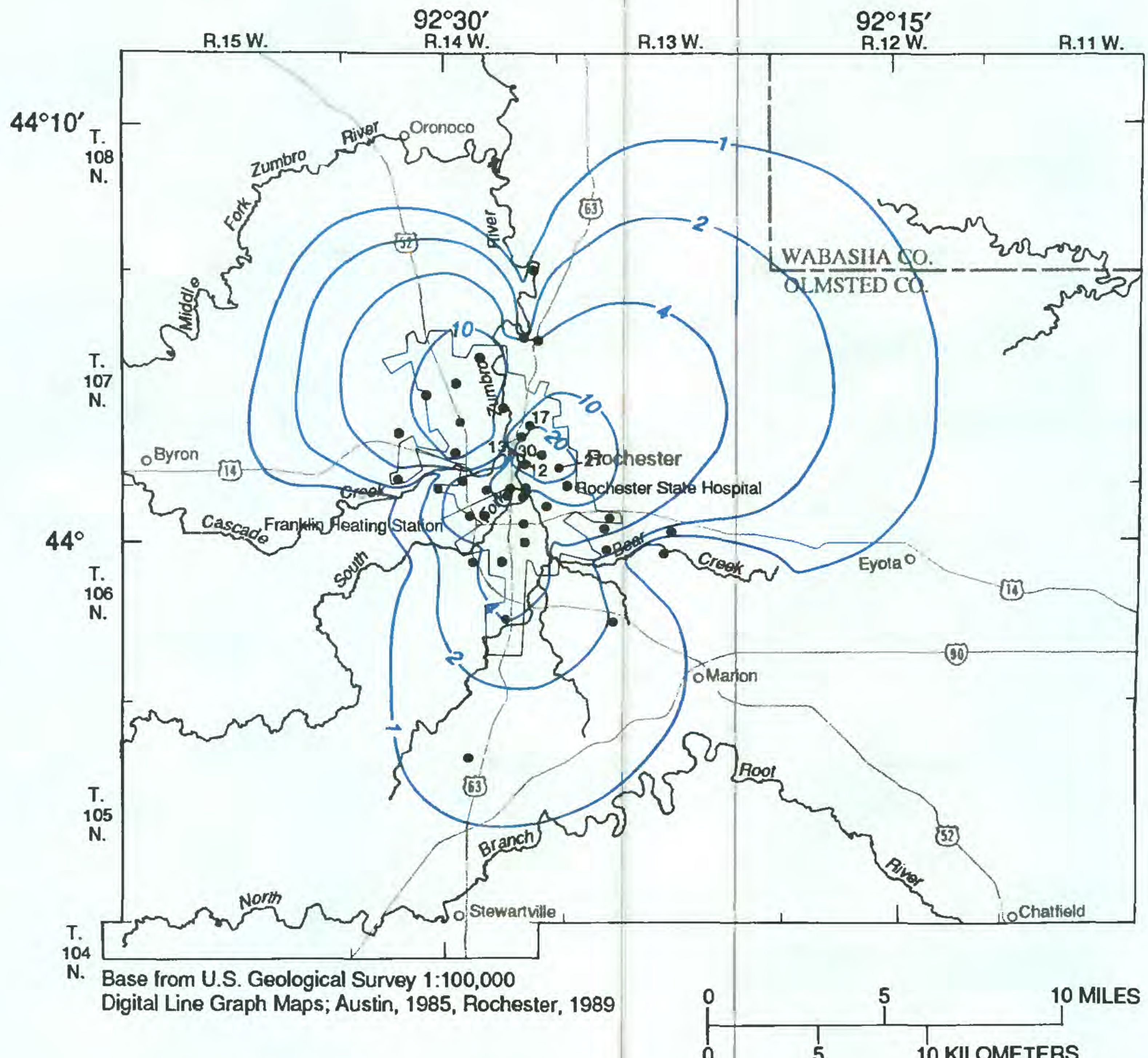
Simulation A (table 7) was designed to evaluate the effect of historical and 1988 pumping on water-level changes in the ground-water system. This was achieved by removing pumping from the steady-state model and simulating average recharge. Recharge was assumed to have remained constant throughout the period of historical ground-water development. The model's results are assumed to be an estimate of predevelopment equilibrium conditions. By comparing results of simulation A with the steady-state calibration, one can evaluate the effects of historical withdrawals of ground water on the ground-water system.

According to model computations, withdrawals of ground water have lowered water levels generally from 4 to 15 ft within the city limits of Rochester (fig. 23). The cloverleaf pattern of the water-level decline contours results from the effects of streams in the area. The St. Peter-Prairie du Chien-Jordan aquifer is hydraulically connected to major streams, and water-level declines caused by pumping or other stresses are reduced near the streams. In addition, water levels have declined more than 20 ft near Rochester wells 12, 13, 17, 27, and 30; the Franklin Heating Station wells; and Rochester State Hospital wells (fig. 23). Water-level decline was greatest (about 48 ft) near the Franklin Heating Station wells. Model-computed water-level declines of 1 ft extend to within about 2 mi of the towns of Oronoco, Eyota, Stewartville, and Byron and extend northeast into Wabasha County. According to the model's computations, ground-water development reduced ground-water discharge to South Fork Zumbro River, Bear Creek, and Cascade Creek by about 39 percent (table 9).

Hypothetical Drought

Simulation B was designed to investigate the effect of an extended drought. The experiment was a steady-state simulation in which recharge was reduced by 30 percent throughout the model. Because pumping for municipal supply and other uses is greater during a drought, pumpage rates were increased also by 50 percent for all wells.

According to the model's computations, water levels may decline 5 to 10 ft regionally in the aquifer and 5 to 20 ft within Rochester (fig. 24). Also, water-level declines would be more than 20 ft near Franklin Heating Station wells and Rochester wells 12, 20, 27, and 30. Water-level decline was greatest (about 32 ft) near the Franklin Heating Station wells. Model-computed water-level declines generally decrease toward streams. Ground-water discharge to South Fork Zumbro River, Bear Creek, and Cascade Creek would be reduced by about 86 percent (table 9). In conformity with the computations, stream reaches 13, 14, 15, and 16 (fig. 17), which were gaining under steady state, would become losing reaches because of the simulated drought; and some reaches in the upper parts of the watersheds could go dry.

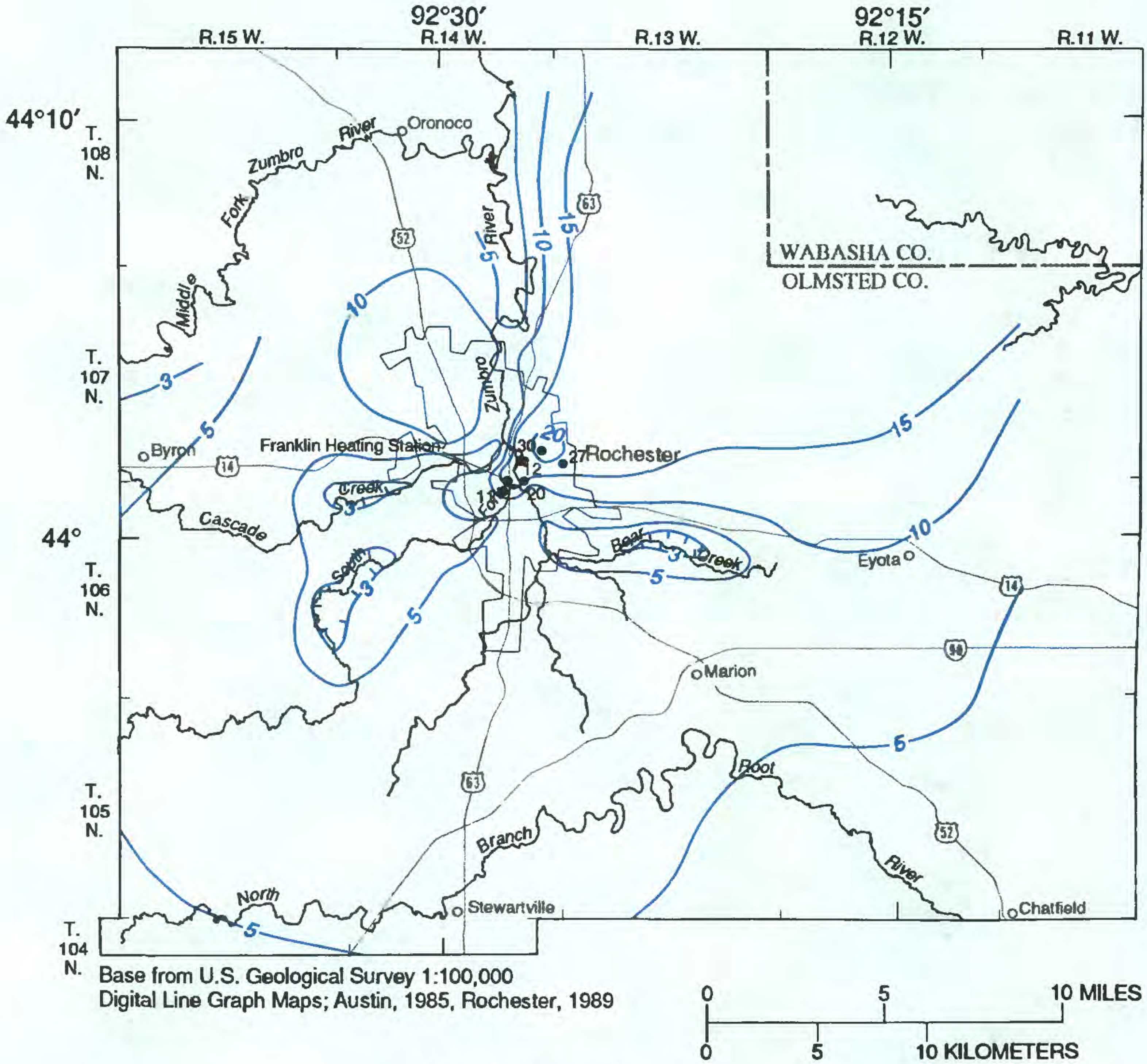


EXPLANATION

—10— WATER-LEVEL-DECLINE CONTOUR, IN FEET--Shows model-computed water-level declines. Interval variable.

27• HIGH-CAPACITY WELL, WELL NUMBER OR OWNER MENTIONED IN TEXT (pumped greater than 200 gallons per minute)

Figure 23.--Model-computed water-level declines caused by pumping from the St. Peter-Prairie du Chien-Jordan aquifer under steady state conditions from predevelopment to 1988 (simulation A).



EXPLANATION

—5— WATER-LEVEL-DECLINE CONTOUR, IN FEET--Shows model-computed water-level declines. Hachures indicate depression. Interval 2 and 5 feet.

11• HIGH-CAPACITY WELL, WELL NUMBER OR OWNER MENTIONED IN TEXT (pumped greater than 200 gallons per minute)

Figure 24.--Model-computed water-level declines in the St. Peter-Prairie du Chien-Jordan aquifer after an extended drought (simulation B).

A transient simulation was run to estimate the length of time of the simulated drought. Storage coefficients determined from transient calibration were used for this simulation. Transient storage effects for the Decorah-Platteville-Glenwood confining unit were not simulated. The transient conditions of the drought were simulated for 10 consecutive years. Model-computed water-level declines during the simulation are illustrated in figure 25 for three locations in Olmsted County. The Golden Hill School well and Rochester well 11 are within the city limits of Rochester, but the third location is that of a domestic well about 4 mi north of downtown Rochester. According to the model's computations, most of the water-level declines would occur during the first 3 years of the simulated drought, particularly near Rochester. Outside of Rochester, however, water-level declines resulting from the drought would probably be more prolonged at increasing distances from the city (fig. 25). Because most of the model-computed water-level declines were for the first 3 years of the hypothetical drought, the steady-state simulation could be considered to represent a drought of roughly 3-year duration.

Hypothetical Ground-Water Development

Simulation C was designed for studying the steady-state effects resulting from a hypothetical increase in the number of Rochester municipal wells. Withdrawals from 6 wells (31 through 36) completed in the Jordan Sandstone, each pumping approximately 423 Mgal/yr, were simulated (fig. 26). Locations of the wells, were in areas where future increases in water use will likely require installation of wells. Although these wells are henceforth termed hypothetical wells, well 31 had been drilled and construction plans for well 32 had begun at the time this report was written.

According to model computations, water levels may decline 1 to 5 ft regionally in the St. Peter-Prairie du Chien-Jordan aquifer under steady-state conditions. The most significant declines would be on the perimeter of the city (fig. 26). In addition, water-level decline would be greatest (about 33 ft) near well 32. The location of each hypothetical well and the model-computed water-level decline for the model cell in which the declines were simulated are listed in table 10. The ground-water divide south of Rochester would probably shift about 1 mi south (fig. 26) because of the hypothetical withdrawals from wells 31, 33, 34, and 36. Also, water-level declines of about 2 ft would extend south of Olmsted County (fig. 26). Pumping from the hypothetical wells would reduce ground-water discharge to South Fork Zumbro River, Bear Creek, and Cascade Creek by about 39 percent (table 8).

Discontinuance of Pumping from Selected Municipal Wells

Simulation D was designed to study steady-state effects resulting from discontinuance of pumping from selected municipal wells in downtown Rochester. Future ground-water development plans for the city may include eliminating the older wells in the downtown area and adding new wells near the city limits. Pumping for Rochester wells 11, 12, 13, 20, 23, and 30 was discontinued in the steady-state model so that the magnitude of water-level recovery could be estimated.

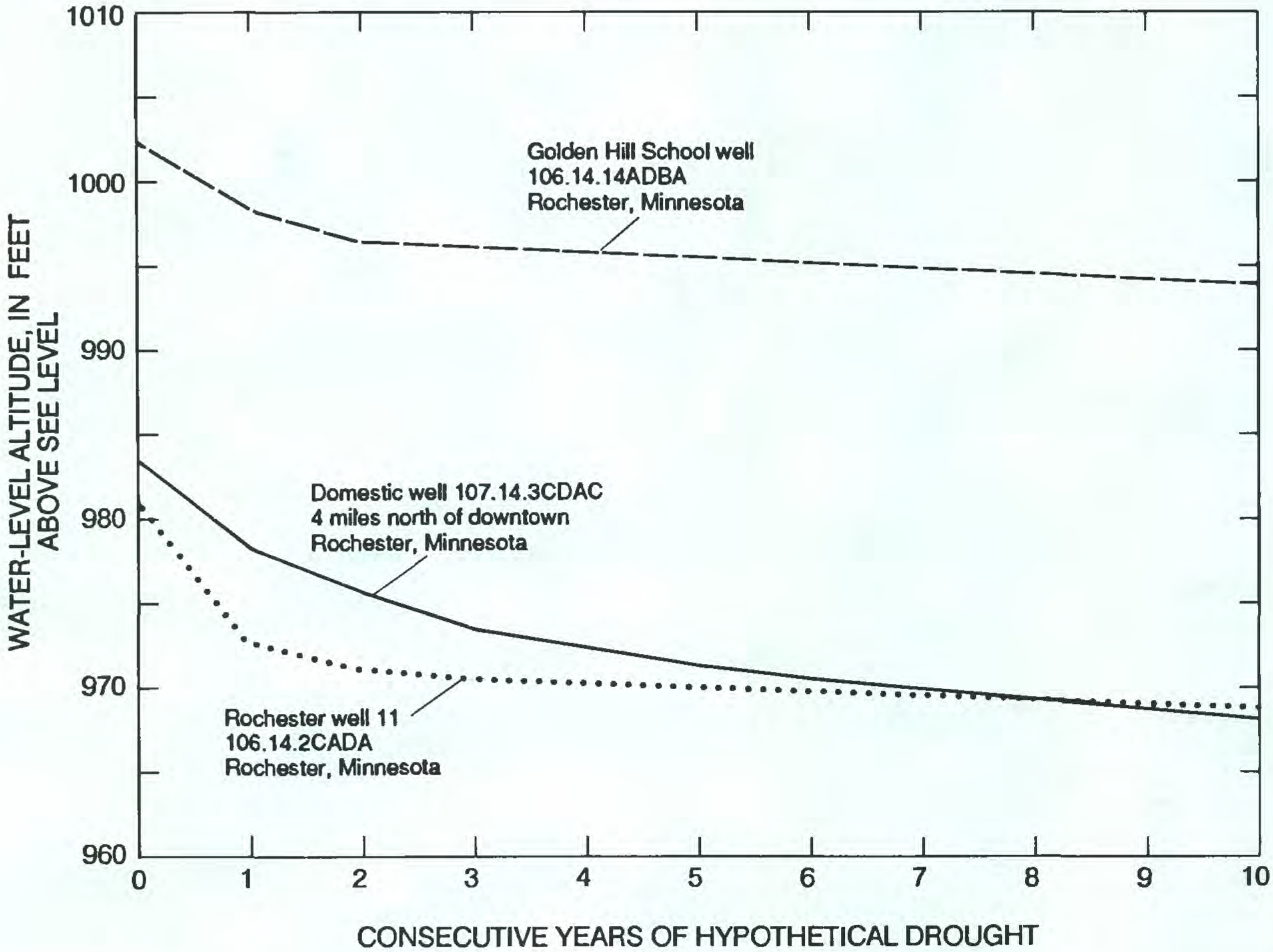
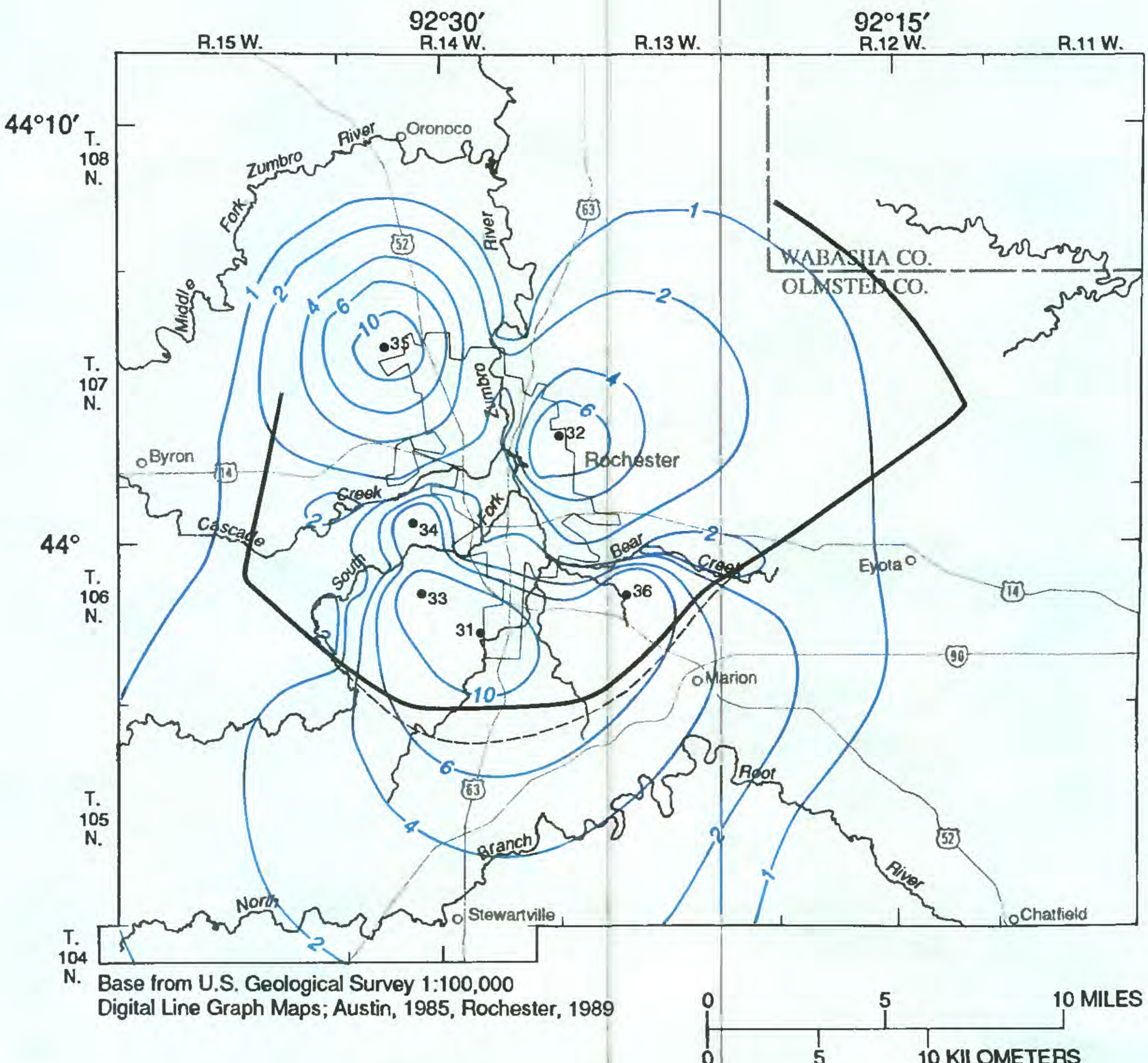


Figure 25.--Model-computed water-level declines during 10 years of a hypothetical drought.



EXPLANATION

—6— MODEL-COMPUTED WATER-LEVEL-DECLINE CONTOUR, IN FEET--Shows model-computed water-level declines. Interval 1, 2 and 4 feet.

MODEL-COMPUTED GROUND-WATER DIVIDE

MODEL-COMPUTED GROUND-WATER DIVIDE AFTER EXPANDED DEVELOPMENT

36• PLANNED MUNICIPAL WELL

Figure 26.--Model-computed water-level declines in the St. Peter-Prairie du Chien-Jordan aquifer after hypothetical ground-water development (simulation C).

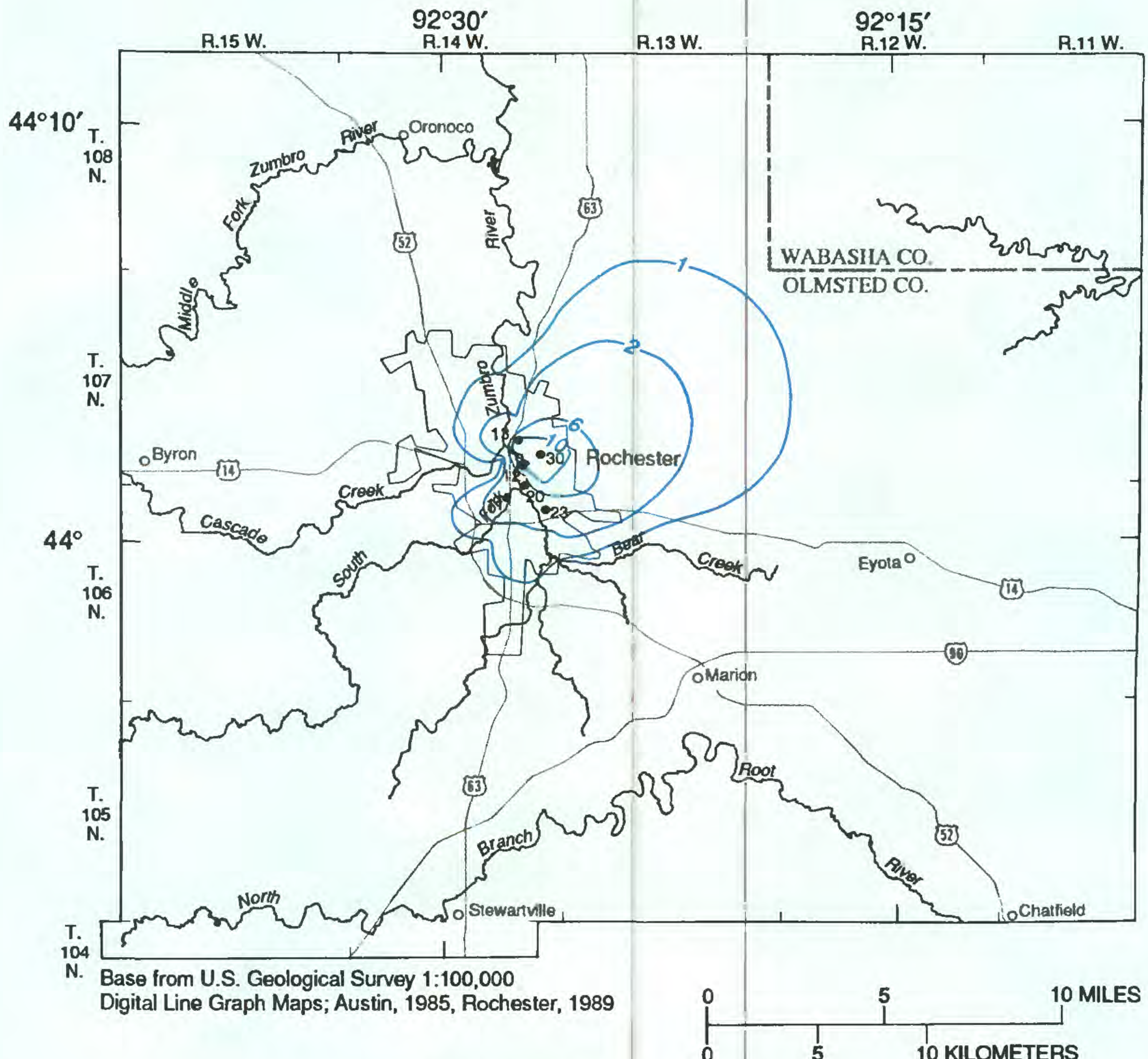
Table 10.--*Locations of hypothetical wells and water-level declines for the model cell in which the declines were simulated, Rochester, Minnesota*

Well	Location	Model cell (layer, row, column)	Model-computed water-level decline (feet)
31	106.14.23CC	3,49,23	32
32	107.13.30CA	3,21,35	33
33	106.14.16CD	3,43,13	28
34	106.14.04CD	3,33,13	24
35	107.14.08DC	3,8,10	30
36	106.13.16CC	3,43,43	26

Water levels may recover 1 to 10 ft in Rochester (fig. 27). Water-level recovery was greatest (about 18 ft) at well 30. The approximate model-computed water-level recoveries for the model cells containing wells 13, 20, 12, 11, and 23 are 14, 12, 11, 9, and 5 ft. A water-level recovery of about 1 ft would extend northeast about 7 mi from downtown Rochester. Discontinuance of pumping from the six municipal wells would increase ground-water discharge to South Fork Zumbro River, Bear Creek, and Cascade Creek by about 19 percent (table 9). By discontinuance of pumping from these municipal wells, river reach 6 (fig. 17) may gain instead of lose water.

Discontinuance of Pumping from Selected Nonmunicipal Wells

Simulation E was designed to study the steady-state effects resulting from discontinuance of pumping at selected nonmunicipal wells in Rochester. Future ground-water development plans in the area may require that some nonmunicipal well owners abandon their own well(s) and use municipal water supplies. Thus, pumpages from wells of the Franklin Heating Station, AMPI, Microlife-MPI Inc. (formerly Stauffer Chemical Company), Marigold Foods, St. Mary's Hospital, Seneca Foods, Rochester State Hospital, and IBM (International Business Machines Corp.) were removed from the steady-state model so that the magnitude of water-level recovery could be estimated. These wells were selected because their total pumpage represents about 90 percent of nonmunicipal pumpage in the Rochester area. Other than the effects of the pumping of municipal wells, pumping of these wells has the greatest effect on water levels in the area.



EXPLANATION

—6— MODEL-COMPUTED WATER-LEVEL RECOVERY CONTOUR--Shows model-computed water-level recovery. Interval 1 and 4 feet.

20• MUNICIPAL WELL WHERE PUMPING WAS DISCONTINUED

Figure 27.--Model-computed water-level recovery in the St. Peter-Prairie du Chien-Jordan aquifer after discontinuance of pumping from selected municipal wells (simulation D).

Water levels might recover 1 to 3 ft in Rochester (fig. 28) if pumping from the selected wells were discontinued. The approximate model-computed water-level recoveries for the model cells containing the Franklin Heating Station, AMPI, Microlife-MPI Inc., Marigold Foods, St. Mary's Hospital, Seneca Foods, Rochester State Hospital, and IBM wells are 43, 16, 12, 7, 5, 2, 2, and 2 ft. Discontinuance of pumping from the eight wells would increase ground-water discharge to the South Fork Zumbro River, Bear Creek, and Cascade Creek by about 12 percent (table 9). Discontinuance of pumping from these industrial and commercial wells may result in river reach 6 (fig. 17) changing from a losing reach to a near equilibrium one.

Model Limitations

A ground-water-flow model is a practical tool for simulating response of the ground-water system to projected recharge and stresses (pumping) on the system. A model is a simplification of a complex flow system. The accuracy of the simulations is limited by the accuracy of the data used to describe the properties of the aquifer and the confining unit, recharge rates, pumpages, streambed-leakage coefficients, and boundary conditions. In addition, a combination of input to the computer different from that used in a simulation could produce the same result.

Improvements in the accuracy of the various inputs to the model would enhance accuracy of the model. The model does not duplicate seasonal water-level fluctuations. More detailed information than are currently available on variations in recharge rates, in space and in time, are necessary for accurately simulating transient ground-water fluctuations in the Rochester area. As additional data become available, the model could be modified and recalibrated to improve its accuracy.

The model was designed to simulate ground-water flow in and near Rochester. Thus, ground-water-management decisions based on model results in areas simulated outside the roughly 140-square-mile area contributing ground-water to Rochester would not be appropriate. Detailed models of local areas are needed for site-specific analyses. Fluctuations in the potentiometric surface computed for hypothetical simulations A through E represent average declines computed for grid blocks of about 0.04 to 4.41 mi^2. Each well was simulated in the center of a cell, but the well may be near the edge of the cell. In these cases, water-level declines measured in wells will differ from model-computed declines, and computed declines in or near individual high-capacity pumped wells will always be greater than measured declines. Because simulations A through E are steady-state simulations, results do not reflect the seasonal effects of climatic and pumping stresses. Rather, the results represent long-term effects of the stresses applied. Steady-state simulations do not include water from storage, which may appreciably affect short-term changes in water levels.

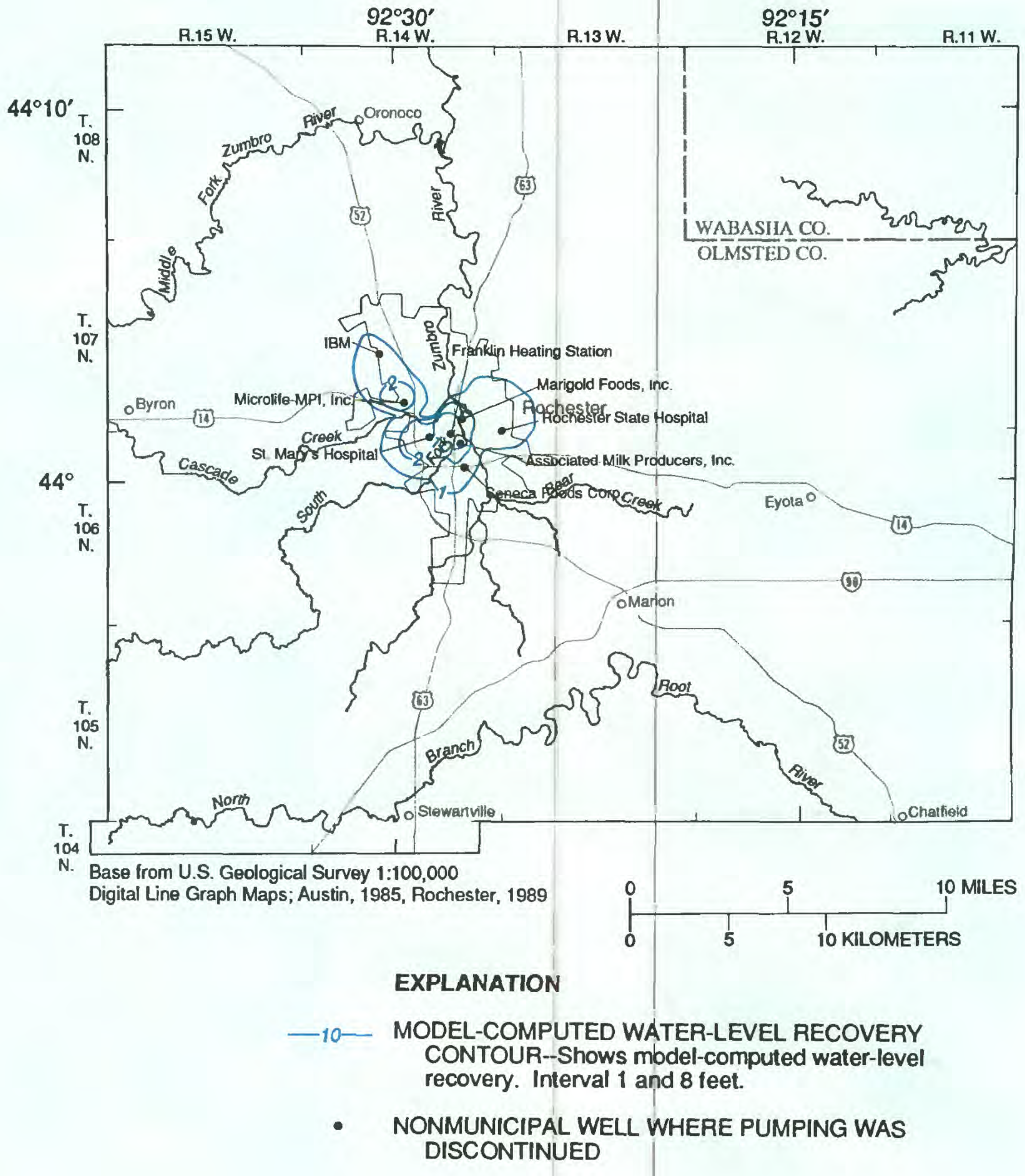


Figure 28.--Model-computed water-level recovery in the St. Peter-Prairie du Chien-Jordan aquifer after discontinuance of pumping from selected nonmunicipal wells (simulation E).

SUMMARY AND CONCLUSIONS

A study was done to describe the hydrogeology and the ground-water flow in the Rochester area as an aid to efficient management of the current ground-water supply and future development. The city of Rochester obtains most of its water supply from ground water pumped from the St. Peter-Prairie du Chien-Jordan aquifer. Part of this aquifer is a karstic dolomite that is exposed or is near land surface and, thus,is readily susceptible to contamination. Local officials are concerned that a combination of ground-water withdrawals, disposal of wastes, and use of agricultural, industrial, and household chemicals may adversely affect the quantity and the quality of ground water. A network of 129 domestic, municipal, commerical, industrial, and observation wells was established to monitor water levels and water quality.

The St. Peter-Prairie du Chien-Jordan aquifer is part of a sequence of nine hydrogeologic units of regional aquifers and confining units defined in the area. The aquifer consists of sandstone, limestone, and dolomite and is generally 400 to 500 ft thick. Hydraulic conductivities generally range from 1 to 40 ft/d. Transmissivity of the St. Peter-Prairie du Chien-Jordan aquifer generally ranges from 1,000 to 6,000 ft^2/d. The Decorah-Platteville-Glenwood confining unit, consisting of shale and limestone, confines the aquifer locally. The confining unit is approximately 70 ft thick but is absent throughout much of Rochester and regions to the north. West of Rochester, the aquifer is locally confined by drift and generally ranges in thickness from zero to 200 ft.

Ground-water flow in the St. Peter-Prairie du Chien-Jordan aquifer is generally horizontal, from highs in the potentiometric surface toward major streams in the area. Horizontal hydraulic gradients in the aquifer are 10 to 20 ft/mi. Vertical head gradients are generally downward and are less than 5 ft through the entire aquifer thickness, except near streams where flow is upward. A roughly 140 mi^2 area of the aquifer contributes water to the Rochester area.

A cone of depression in the potentiometric surface of the aquifer is caused by pumping from high-capacity wells. The 950-foot contour roughly defines the area of the cone. This contour encompassed an area of about 1.2 mi^2 during August 1987 compared to an area of about 0.4 mi^2 during January 1988 and 2.3 mi^2 during August 1988. The area influenced by pumping near Rochester may be as large as 11 mi^2.

Recharge enters the aquifer system through five general zones. Although no data on actual recharge are available, recharge rates can be inferred from analysis of ground-water-flow-model simulations. Areal recharge is greatest (about 13 in/yr) along the edge of the Decorah-Platteville-Glenwood confining unit. The source of this recharge water is the overlying upper carbonate aquifer. Recharge rates are lower (about 5 in/yr) where the Decorah-Platteville-Glenwood confining unit is absent. Areal recharge is likely reduced to about 4.5 in/yr in Rochester because of diversion of storm-water runoff to sewers. Where glacial drift overlies the Prairie du Chien formation, recharge rates are about 1 in/yr. Recharge is lowest (about 0.4 in/yr) where the Decorah-Platteville-Glenwood confining unit is present.

Most stream reaches in the area gain water from the ground-water reservoir. However, two separate observation of stream discharge indicated that a reach of the South Fork Zumbro River north of US Highway 14 in Rochester was losing flow. Concentrations of dissolved radon gas in stream water are evidence that a 600-ft section of this same reach lost about 1.2 ft^3/s to the ground-water system during July 1988. Ground-water withdrawals through nearby high-capacity wells is the likely cause of this loss.

A ground-water-flow model was constructed to improve understanding of the regional behavior of the ground-water system. Steady-state calibration of the model resulted in simulated water levels generally within 2 ft of measured levels. Model-computed steady-state ground-water discharge to streams in the area compare favorably with independent estimates of discharge. In the 140-square-mile area contributing water to Rochester, 91 percent of the inflow is from areal recharge; and the remaining 9 percent is seepage from streams. Fifty-five percent of the ground-water outflow from the area is by pumping and 45 percent is by discharge to streams.

In transient simulations, the magnitude and the frequency of seasonal water-level fluctuations are not duplicated accurately by the model. Long-term simulations adequately duplicated water-level hydrographs. Data on seasonal variations in recharge are needed for adequate calibration of the model to transient conditions.

In the area contributing water to Rochester, about 54 percent of recharge to the St. Peter-Prairie du Chien-Jordan aquifer is from a zone along the edge of the Decorah-Platteville-Glenwood confining unit. Approximately 26 percent of recharge in the Rochester contributing area enters the aquifer where the Prairie du Chien Group is the uppermost bedrock unit, 10 percent enters in the sewered area of Rochester, 8 percent enters as leakage through the Decorah-Platteville-Glenwood confining unit, and about 2 percent enters the aquifer through thick drift west of Rochester.

The effects of historical and 1988 pumping has lowered water levels from 4 to 15 ft within the city limits of Rochester. Declines have exceeded 20 ft near several wells. Ground-water discharge to streams has decreased by about 39 percent because of historical pumping.

Decreases in recharge and increases in pumping during a 3-year hypothetical drought may lower water levels an additional 5 to 10 ft regionally and as much as 32 ft in the city, according to model simulations. Ground-water discharge to streams in the model area during the simulated drought was reduced by 86 percent.

Simulations of hypothetical ground-water development by use of the model indicate that the addition of six municipal wells outside downtown Rochester would lower water levels 1 to 5 ft regionally. The ground-water divide south of Rochester would shift about 1 mi south as a result of such expanded development.

Water levels would probably recover 1 to 18 ft if pumping from six municipal wells in downtown Rochester were discontinued. Water-level recoveries of greater than 1 ft would extend roughly 7 mi northeast of downtown Rochester, and ground-water discharge to streams would increase by about 19 percent. By discontinuance of pumping from these municipal wells, a reach of the South Fork Zumbro River north of US Highway 14 would probably gain, instead of lose, water from the ground-water reservoir.

Water levels would recover from 1 to 43 ft if pumping from eight nonmunicipal wells in and near Rochester were discontinued. Ground-water discharge to streams would increase by about 12 percent. Ground-water discharge to the reach of the South Fork Zumbro River north of US Highway 14 may change from a losing reach to a near equilibrium one because of discontinuance of pumping from nonmunicipal wells.

The ground-water-flow model is a practical tool for understanding operation of the ground-water system. However, the accuracy of results obtained by use of the model is limited by the accuracy of the data that describe aquifer and confining-unit properties, recharge rates, streambed conductance, and boundary conditions. Actual water-level declines in wells likely differ from model-computed levels, and declines in or near individual high-capacity pumping wells likely will be greater than the actual declines. As additional data become available, particularly for recharge rates, the model could be modified and recalibrated to improve its accuracy.

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APPENDIX A

Established observation-well network

[Unique number, Minnesota Geological Survey Unique Well Number; Explanation of "Location," is given in the section, "Numbering System for wells and test holes"; obs.-well, observation well; O.C., Olmsted County; AMPI, Associated Milk Producers, Inc.; --, unknown or nonexistent unique number; IBM, International Business Machines Corp.]

Owner's name	Unique number	Location	Aquifer
		Wells Measured Monthly	
Jay Deanas	220941	108.15.26BCAC	Jordan
Charles Till	148359	107.15.11DBCC	St. Peter
Abandoned Factory	220825	107.14.29CAAA	Prairie Du Chien
Phill Hukom	220873	107.15.36BBAB	Prairie Du Chien
Mat Puffer	411279	106.15.3CBAC	Prairie Du Chien
B'Ann Marvin	217516	106.15.22DAADD	St. Peter
Yvonne Nubmayr	105002	106.14.30CCCC	Prairie Du Chien
Rochester Airport	241968	105.14.9CDDD	St. Peter - Prairie Du Chien
Silverstein	150282	106.14.34DCAA	St. Peter
Robert Sheehan	192592	105.13.4CAAB	Prairie Du Chien
Robert Sheehan	W00711or12	105.13.4CAAB	Galena
Burr Oak School	220615	106.13.22CCBC	Jordan
Dick Brackin	411264	106.13.10DCDD	Prairie Du Chien
Steve Winter	220612	106.12.30BBABB	St. Peter
Donald Fenske	192541	106.11.17CBAB	Jordan
Bernard Loftus	148355	107.11.31AAAA	Prairie Du Chien
Yoder Feed	119824	107.12.15CCDC	Jordan
Golden Hill School	220679	106.14.14ADBA	Jordan
Loomis obs. well	--	106.14.24BABBB01	Jordan
Shallow obs. well	--	106.14.24BABBB02	Drift
Robert Barclay	220644	106.13.19CBAB	Praire Du Chien
O.C. Historical	227831	106.14.9BADA	Jordan
USGS obs. well	--	106.14.1DBDC	Drift
USGS obs. well	--	106.14.10AAAB	Drift
AMPI	--	106.14.2BCBADA	Jordan
Frank Bigelow	218843	108.12.29ADADD	Prairie Du Chien
Roger Dozois	220884	108.13.36CBAD	Jordan
Gene Sennick	401607	107.13.15DCCD	Prairie Du Chien
Earl Stephan	101443	107.13.27DDCC	Prairie Du Chien
M.E. Carter	107664	107.12.31CDDC	St. Peter
M.E. Carter	W00264	107.12.31CDDC	Galena
H.C. Hoaglen	119849	107.13.30BDCC	Prairie Du Chien
Leon Larson	228569	107.14.23DDBD	Prairie Du Chien
Nancy Parnow	187623	107.13.18CBAD	Jordan
USGS Obs. Well	--	107.14.14BACBB	Drift
Thomas Pike & Thede	228624	107.14.10ABCB	Jordan
Julie O'Marro	135640	108.13.29BCCB	Jordan
C. Schultz	411291	108.13.10CBCBB	Jordan

APPENDIX A

***Established observation-well network*--Continued**

Owner's Name	Unique number	Location	Aquifer
	Wells Measured Periodically (synoptic)		
Ron Hovda	156962	105.13.1BBCB	St. Peter
St. Bridget Church	219537	105.13.6CCBD	St. Peter
B. Kaldenberg	192520	105.13.8DBBC	St. Peter
(unkown owner)	150215	105.13.11DDDD	St. Peter
Paul Gerber	219551	105.13.19BDDA	Prairie Du Chien
Mike Edge	139142	105.14.8ACBC	St. Peter
Herman Ristau	227661	105.14.11BACC	St. Peter
Allen Doty	227659	105.14.11BDAA	Galena
Frank D. Quam	227663	105.14.15DDDB	Galena
Charles Pearson	119819	105.14.23DBCC	St. Peter
David Yennie	141010	105.15.3AAAA	St. Peter
Mulford	219588	105.15.12ADDC	St. Peter
Norman Moe	227388	106.11.9CABA	Prairie Du Chien
Robert Randall	104971	106.12.4CCCC	Prairie Du Chien
John Fuchs	W00088	106.12.11ABCB	Galena
Tim Riley	220607	106.12.20AAAA	Prairie Du Chien
David Higgins	220613	106.12.33AABA	Prairie Du Chien
Erwin Palmer	220621	106.13.3BABC	St. Peter
Midwest Off. Rd.	228143	106.13.6CCAC	Prairie Du Chien
Harley Davidson	227486	106.13.11ADAA	Prairie Du Chien
James Hebl	107688	106.13.14DBBC	Prairie Du Chien
J. & B. White	228187	106.13.15CCCC	Prairie Du Chien
Don Frish	179207	106.13.32CAAD	Prairie Du Chien
Jerry Sample	179132	106.13.34BBBC	St. Peter
Buckbesch,	132672	106.13.34DCDC	St. Peter
David Jones	W00628	106.13.36ACDD	Galena
St. Mary's Hosp.	220786	106.14.3AADBD	Jordan
Rochester Country Club	227828	106.14.4BDAB	Prairie Du Chien
Paul Anderson	228156	106.14.8CABB	Prairie Du Chien
E.G. Turlington	228607	106.14.10BDAB	Prairie Du Chien
Bergler, Arnold	--	106.14.11CACCB	Jordon
Richard Martin	--	106.14.11CBDDB	Prairie Du Chien
Smithson	120023	106.14.15DBBC	Prairie Du Chien
(unkown owner)	120008	106.14.18CBCA	Prairie Du Chien
Dr. H.O. Perry	220697	106.14.20DADA	Prairie Du Chien
Ideal Vans	220702	106.14.23DACB	Prairie Du Chien
Willow Cr. Golf	220710	106.14.27DCCA	Jordan
David Stutz & Penney Pries	220706	106.14.28CCBB	St. Peter
Gordan Bishop	W00191	106.15.7AAAD	St. Peter
John Wallin	227820	106.15.12BBDC	Prairie Du Chien
Paul Koperski	220731	106.15.14ADCD	Prairie Du Chien
G. & B. Beech	105033	106.15.16AACC	St. Peter
Bernard Donovan	220736	106.15.17ACCD	St. Peter

APPENDIX A

Established observation-well network--Continued

Owner's Name	Unique number	Location	Aquifer
Wells Measured Periodically--Continued			
Duane Quam, Sr.	192511	106.15.20DDDD	Prairie Du Chien
John Donovan	220742	106.15.24DADD	Prairie Du Chien
J. & R. Evans	411278	106.15.26AABC	Prairie Du Chien
John Leitzen	139110	106.15.32AABB	St. Peter
David Booker	156954	107.11.20ADBD	Jordan
Warren Phipps	220751	107.12.3BAAD	Jordan
P. Westbrook	W00243	107.12.6CCBB	Prairie Du Chien
Richard Eagan	235540	107.12.9BBDC	Jordan
Donald Lee	147088	107.12.10AACC	Jordan
Schumacher	132653	107.12.13AACD	Prairie Du Chien
L. Melvin	227475	107.12.18BCCD	Galena
N. Bernhardt	W00263	107.12.30BBBB	Prairie Du Chien
Warren Beighley	105493	107.13.2CCCC	Prairie Du Chien
Larry K. Plank	415365	107.13.5DACA	Jordan
Mike Waara	W00350	107.13.6DBDC	Jordan
Guest House	220771	107.13.16DACB	Jordan
Marvin Rose	220769	107.13.16DAAA	St. Peter
Ronald Hunter	220772	107.13.17CBAA	Prairie Du Chien
M. Maronde	150350	107.13.20AABC	Jordan
C. O. Siewert	--	107.13.22DBCC	St. Peter
Haver Hill Sub	130612	107.13.29ACBD	Jordan
K. Kappauf	220789	107.13.32CDDC	Prairie Du Chien
Terry Risley	220792	107.14.1AADA	Jordan
Gary Dix	220795	107.14.2DADA	Jordan
J & J Ashenmacher	120019	107.14.7CDCC	Prairie Du Chien
C. & J. Benike	147657	107.14.11BDAD	Jordan
Wayne Boelter	150329	107.14.13CODACC	Jordan
Scott Stevens	147652	107.14.14CABB	Jordan
Bob Chappius	--	107.14.19BDCCC	Prairie Du Chien
IBM 804W	--	107.14.21BDABB	Jordan
808W	--	107.14.21ADDBB	Jordan
811W	--	107.14.21CADAA	Jordan
Tracy Blanshan	--	107.14.22CBADD	Prairie Du Chien
Vern Bushlack	227781	107.14.31CAACD	Jordan
Greenway	--	107.14.34DABBB	Drift
Walter Newell	--	107.14.36DBDCB	Prairie Du Chien
Ox Bow Park	220841	107.15.8CACD	Jordan
Byron Price	220850	107.15.19CABB	St. Peter
Stephen Fenske	220861	107.15.21CBDC	Prairie Du Chien
Larry Bucker	220863	107.15.23BADD	Prairie Du Chien
P. & H. Smars	220867	107.15.28DDCC	Prairie Du Chien
Byron Garage	227526	107.15.29BDDC	Prairie Du Chien
Lloyd Caulfield	235521	107.15.30 ACCD	Galena
Robert Brekke	160831	107.15.31CBCC	Prairie Du Chien
(unknown owner)	220870	107.15.32ADBD	Jordan

APPENDIX A

Established observation-well network--Continued

Owner's Name	Unique number	Location	Aquifer
Wells Measured Periodically--Continued			
Steve Milde	120032	107.15.35DCDC	Prairie Du Chien
G. & J Timm	192534	108.12.17DAACC	Jordan
James Walker	156999	108.13.1CCCB	Jordan
Edgar Siem	--	108.13.8BCBCD	Jordan
Virgil Pugh	178850	108.13.14AAAAB	Jordan
Paul Culbertson	227530	108.13.16AAAA	Prairie Du Chien
Kachelski	--	108.13.21DADD	Prairie Du Chien
Lester Benike	W00423	108.13.25ABAB	Prairie Du Chien
Frank Ohm	218847	108.13.33ADDD	Jordan
W. C. Hoeft	148366	108.14.12DDCC	Jordan
Bob Gray	132998	108.14.36BDDB	Jordan
R. W. King	220937	108.15.23DAAD	Jordan
Lyle Mathison	220938	108.15.24ADBD	Jordan
R. & P. Breid	412436	108.15.35BADA	Prairie Du Chien
Allen Walker	132660	108.15.36 AABB	Prairie Du Chien
Ron Utley	120001	109.13.33AAA	Jordan
Jack Landrum	218817	109.14.36CDCD	Jordan

APPENDIX B

High-capacity wells simulated in the steady-state ground-water-flow model

[Pumpage in millions of gallons per year. PDCN, Pumpage simulated in the Prairie du Chien part of the St. Peter-Prairie du Chien-Jordan aquifer. All other pumpage simulated in the Jordan part of the aquifer]

Well name (or owner)	Location	Model layer, row, column	Simulated pumpage
	Rochester Municipal Wells		
Well 11 (PDCN)	106.14.02CADA	2,31,25	91.6
Well 11		3,31,25	126.5
Well 12	107.14.35ADDA	3,25,28	24.1
Well 13 (PDCN)	107.14.26DADA	2,21,27	125.1
Well 13		3,21,27	83.4
Well 15 (PDCN)	107.14.27BABB	2,18,18	152.3
Well 15		3,18,18	62.2
Well 17	107.14.25BCAA	3,19,29	35.9
Well 18	107.14.34CDCC	3,28,19	127.4
Well 19	106.14.12CBBC	3,37,28	136.8
Well 20	106.14.01BBBC	3,29,28	103.8
Well 21	106.13.05CDDD	3,33,41	4.8[a]
Well 22	107.14.22BBDA	3,13,18	93.9
Well 23	106.14.01DBDC	3,31,31	187.0
Well 24	107.14.23CDAD	3,17,25	53.8
Well 25	106.14.10AAAB	3,34,22	169.3
Well 26 (PDCN)	107.14.32CDAA	2,27,10	27.2
Well 26		3,37,10	21.4
Well 27	107.13.31BCCD	3,25,33	438.5
Well 28	107.14.14BCBC	3,9,21	466.0
Well 29	106.14.14BAAD	3,39,25	178.3
Well 30	106.14.36ABBC	3,23,31	371.9
Christopher Court	106.13.08CCDA	3,38,40	5.9
Rose Harbor	106.13.08BBDD	3,34,39	23.5
Willow Heights	106.14.23DBCB	3,47,25	20.9

High-capacity wells simulated in the steady-state ground-water-flow model--Continued

Well name (or owner)	Location	Model layer, row, column	Simulated pumpage
	Non-municipal Wells		
Anderson Sand and Gravel	108.14.36CD	2,5,29	23.4[a]
Associated Milk Producers	106.14.02ADAC	3,30,27	257.4[a]
Books Mobile Home Park	107.14.12CD	3,9,28	9.6[a]
Donald L. Close	106.14.14BBDD	3,40,24	5.4[a]
Franklin Heating Station	107.14.02ABAB	2,28,25	193.3[a]
IBM (PDCN)	107.14.21CABB	2,15,13	12.6[a]
IBM		3,15,13	3.8[a]
Hallmark Terrace	107.14.12CCC	3,8,28	0.5[a]
Lenwood Heights	106.14.15BAAD	3,39,19	1.5[a]
Marigold Foods	107.13.35DABD	3,26,27	5.3[a]
Microlife-MPI Inc.	107.14.34BBBC	2,23,17	53.4[a]
Osjor Estates	107.13.20CDAA	3,48,41	5.7[a]
Ted Perry	106.13.10BCDB	3,36,45	2.9[a]
Rochester Airport (PDCN)	105.14.10CADB	2,57,19	6.5[a]
Rochester Airport		3,57,19	1.4[a]
Rochester Block	106.13.09DDAC	2,38,45	4.5[a]
Rochester Country Club	106.14.04BDAB	3,29,14	5.2[a]
Rochester Materials Company	107.14.29DBDA	3,21,10	5.8[a]
Rochester State Hospital	107.13.31CACC	3,26,35	51.5[a]
Saint Mary's Hospital (PDCN)	106.14.03AADB	2,29,22	58.2[a]
Saint Mary's Hospital		3,29,22	34.2[a]
Seneca Foods (PDCN)	106.14.11AAAD	2,34,27	14.8[a]
Seneca Foods		3,34,27	21.3[a]
Silver Lake Power Company	107.14.35ADDB	2,25,28	85.8[a]
Sunny Slopes	106.14.03DCCC	2,33,20	0.7[a]

[a]Estimate of average pumpage (1977-88) is based on incomplete data.

APPENDIX C

Listings of model input values for the modular, three-dimensional, finite-difference, ground-water-flow model of the St. Peter-Prairie du Chien-Jordan aquifer in the Rochester, Minnesota area

Appendix C lists input values for the three-dimensional, finite-difference, ground-water-flow model of the St. Peter-Prairie du Chien-Jordan aquifer in the Rochester area. Each listing contains values for a particular modular-model package, or part of a package, as defined by McDonald and Harbaugh (1988). An example of part of the model input is included for listings of large arrays. Model input values for simulating steady-state conditions are contained in listings 1-18 and model input values for simulating hypothetical ground-water development schemes are contained in listings 19-23:

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Listing 1. Input for the BASIC package of the MODULAR program for the steady-state simulation

```
U.S. GEOLOGICAL SURVEY GROUND-WATER FLOW MODEL FOR THE ROCHESTER, MINNESOTA
  AREA, JANUARY 1990
        3         64         52          1          4      *LAY/COL/ROW/S.P./T.U.
  7 16  0  8  0  0  0  9 11  0  0 39
        0          1                                       *BUFF SHR?/ST HDS SAVED?
       37          1 (15I5)                         3      *IBOUND LAYER 1
       37          1 (15I5)                         3      *IBOUND LAYER 2
       37          1 (15I5)                         3      *IBOUND LAYER 3
        0                                                  *INACTIVE CELL VALUE
       31          1 (15F5.0)                       3      *HEADS LAYER 1
       31          1 (15F5.0)                       3      *HEADS LAYER 2
       31          1 (15F5.0)                       3      *HEADS LAYER 3
        1          1        1.0                            *SP LEN/# TS/TS MULT
```

Listing 2. Partial listing of input for the IBOUND array in the BASIC package of the MODULAR program for the steady-state simulation

```
   -1   -1   -1   -1    0    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0    0
   -1    1    1    1    0    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0    0
   -1    1    1    1    1    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0    0
   -1    1    1    1    1    1    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0    0    1    1    1    1    1    1    1    1
    1    1    1    0    0    0    0
   -1    1    1    1    1    1    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0    0    1    1    1    1    1    1    1    1
    1    1    1    1    1    0    0
   -1    1    1    1    1    1    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0    1    1    1    1    1    1    1    1    1
    1    1    1    1    1    0    0
   -1    1    1    1    1    1    1    0    0    0    0    0    0    0    0
    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0    1    1    1    1    1    1    1    1    1
    1    1    1    1    1    0    0
   -1    1    1    1    1    1    1    0    0    0    0    0    0    0    0
    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0    1    1    1    1    1    1    1    1    1
    1    1    1    1    1    0    0
```

Listing 3. Partial listing of input for the starting heads in the BASIC package of the MODULAR program for the steady-state simulation

```
1010 1006 1003 1000  980  960  955  950  945  940  930  920  910  910  910
 910  910  910  910  910  910  910  910  910  910  910  910  910  910  910
 910  910  910  910  910  910  910  910  910  910  910  910  910  910  910
 920  930  940  950  960  970  980
1011 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225
1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225
1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225
1225 1225 1225 1225 1225 1225  990
1012 1225 1225 1225  960  957  953  950  935  930  927  925  922  920  919
 918  918  917  917  916  916  915  915 1225 1225 1225 1225 1225 1225 1225
1014 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225
1225 1225 1225 1225 1225 1225  985
1016 1225 1225 1225  980 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225
1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225
1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225
1225 1225 1225 1065 1040 1010  985
1020 1225 1225 1225 1005 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225
1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225
1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225
1225 1225 1225 1075 1225 1225  985
1225 1225 1225 1225 1015 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225
1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225
1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225
1225 1225 1225 1080 1225 1225  990
1030 1225 1225 1225 1020 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225
1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225
1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225
1225 1225 1225 1225 1225 1030  990
1035 1225 1225 1030 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225
1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225
1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225
1225 1225 1225 1225 1225 1225  990
1040 1225 1225 1035 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225
1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225
1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225
1225 1225 1225 1225 1225 1225  990
1045 1225 1050 1040 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225
1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225
1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225
1225 1225 1225 1225 1225 1225  990
1050 1225 1052 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225
1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225
1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225
1225 1225 1225 1225 1225 1225  995
1055 1225 1055 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225
1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225
1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225 1225
1225 1225 1225 1225 1225 1225  995
```

Listing 4. Input for the Output Control Option in the BASIC package of the MODULAR program for the steady-state simulation

```
      -3        -3        54        35     IHEDFM IDDNFM IHEDUN IDDNUN
       0         1         1        -1     INCODE IHDDFL IBUDFL ICBCFL
       1         1         1         1     HDPR   DDPR   HDSV   DDSV
```

Listing 5. Input for the BCF package of the MODULAR program for the steady-state simulation

```
         1        53                                  *BCF PACKAGE
 3 3 0                                                *LAYCON
         7         1 (3F10.3)                    0    *ANISOTROPY FACTOR
     1.000     1.000     1.000                        *ANISISOTROPY (COL/ROW)
         7         1 (12F6.0)                    3    *WIDTH ALONG ROWS
 11100 11100 11100 11100 11100  7400  4950  3300  2250  1500  1500  1000
  1000  1000  1000  1000  1000  1000  1000  1000  1000  1000  1000  1000
  1000  1000  1000  1000  1000  1000  1000  1000  1000  1000  1000  1000
  1000  1000  1000  1000  1000  1500  1500  2250  3300  4950  7400 11100
 11100 11100 11100 11100
         7         1 (12F6.0)                    3    *WIDTH ALONG COLUMNS
 11100 11100 11100  7400  4950  3300  2250  1500  1500  1000  1000  1000
  1000  1000  1000  1000  1000  1000  1000  1000  1000  1000  1000  1000
  1000  1000  1000  1000  1000  1000  1000  1000  1000  1000  1000  1000
  1000  1000  1000  1000  1000  1000  1000  1000  1000  1000  1000  1000
  1000  1000  1000  1500  1500  2250  3300  4950  7400 11100 11100 11100
 11100 11100 11100 11100
        47       0.7 (10F8.1)                    3    *COND. ST. PETER (LAY 1)
        46         1 (10F8.1)                    3    *BOTTOM OF  ST. PETER
        20       1.0 (10F8.5)                    0    *VCONT12
        42         1 (10F8.1)                    3    *TOP OF ST. PETER
        14       1.0 (10F8.1)                    3    *COND. PDCN
        43         1 (10F8.1)                    3    *BOTTOM OF PDCN (LAY 2)
        29       1.0 (10F8.5)                    0    *VCONT23
        41         1 (10F8.1)                    3    *TOP OF PDCN (LAY 2)
        45        80 (10F8.1)                    3    *COND. JORDAN (LAY 3)
```

Listing 6. Partial listing of input for the St. Peter hydraulic conductivity in the BCF package of the MODULAR program for the steady-state simulation

10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0								
10.0	10.0	10.0	50.0	50.0	10.0	10.0	50.0	50.0	50.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	50.0	50.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	50.0	50.0
50.0	50.0	50.0	50.0	50.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0								
10.0	10.0	10.0	50.0	50.0	10.0	50.0	10.0	50.0	50.0
50.0	50.0	50.0	50.0	50.0	50.0	50.0	10.0	10.0	50.0
50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	50.0	50.0
50.0	50.0	50.0	50.0	50.0	10.0	50.0	10.0	10.0	10.0
10.0	10.0								
10.0	10.0	10.0	50.0	50.0	10.0	10.0	50.0	50.0	50.0
10.0	10.0	50.0	50.0	50.0	10.0	50.0	10.0	10.0	10.0
50.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0								
10.0	10.0	10.0	10.0	50.0	10.0	40.0	30.0	30.0	40.0
10.0	50.0	50.0	50.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	15.0	15.0	15.0	15.0	15.0	15.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	50.0	10.0	10.0	10.0
10.0	10.0								
10.0	10.0	10.0	10.0	50.0	10.0	50.0	50.0	40.0	30.0
40.0	40.0	40.0	50.0	50.0	50.0	50.0	10.0	10.0	10.0
10.0	10.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
15.0	15.0	15.0	15.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	50.0	10.0	10.0	10.0
10.0	10.0								
10.0	10.0	10.0	10.0	50.0	10.0	50.0	50.0	40.0	40.0
50.0	50.0	40.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
15.0	15.0	15.0	15.0	15.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0								
10.0	10.0	10.0	50.0	50.0	50.0	30.0	30.0	40.0	40.0
40.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
15.0	15.0	15.0	15.0	15.0	15.0	10.0	10.0	10.0	10.0
10.0	10.0								

Listing 7. Partial listing of input for the bottom of the St. Peter in the BCF package of the MODULAR program for the steady-state simulation

```
  950.0   950.0   950.0   950.0  1000.0  1000.0  1050.0  1050.0  1050.0  1000.0
 1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0
 1000.0  1000.0  1000.0  1000.0  1000.0  1050.0  1050.0  1050.0  1050.0  1050.0
 1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0
 1075.0  1075.0  1075.0  1075.0  1075.0  1075.0  1075.0  1075.0  1075.0  1075.0
 1075.0  1100.0
  900.0   900.0   900.0   950.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0
 1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0
 1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0
 1000.0  1000.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0
 1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1075.0  1075.0  1075.0  1075.0
 1075.0  1100.0
  900.0   900.0   900.0   900.0   950.0  1000.0  1000.0  1000.0  1000.0   950.0
 1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0
 1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0
 1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0
 1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1075.0  1075.0  1075.0
 1075.0  1100.0
  900.0   900.0   900.0   900.0   900.0   950.0   950.0   950.0   950.0   950.0
 1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0
 1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0
 1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0   990.0   990.0  1000.0
  975.0   975.0   975.0   975.0   975.0  1000.0  1000.0  1000.0  1075.0  1075.0
 1075.0  1100.0
  900.0   900.0   900.0   900.0   900.0   950.0   950.0   950.0   950.0   950.0
  950.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0
 1000.0  1000.0  1000.0  1000.0  1000.0  1000.0   950.0   900.0   950.0   950.0
 1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0   990.0   990.0  1000.0
  975.0   975.0   975.0   975.0   975.0  1000.0  1000.0  1025.0  1025.0  1025.0
 1075.0  1075.0
  900.0   900.0   900.0   900.0   900.0   950.0   950.0   950.0   950.0   950.0
  950.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0
  980.0   970.0   960.0   950.0   950.0   950.0   950.0   900.0   900.0   900.0
  950.0   950.0  1000.0  1000.0  1000.0  1000.0   990.0   990.0  1000.0   975.0
  975.0   975.0   975.0  1000.0  1000.0  1000.0  1000.0  1025.0  1025.0  1025.0
 1075.0  1075.0
  900.0   900.0   900.0   900.0   900.0   950.0   950.0   950.0   950.0   950.0
 1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0   950.0   950.0   950.0
  950.0   950.0   950.0   900.0   950.0   950.0   950.0   950.0   950.0   950.0
  950.0   950.0   950.0  1000.0  1000.0  1000.0   990.0   990.0   990.0   975.0
  975.0   975.0   975.0   975.0   950.0   950.0  1000.0  1025.0  1025.0  1050.0
 1075.0  1075.0
  900.0   900.0   900.0   950.0   900.0   950.0   950.0   950.0   950.0   950.0
  950.0  1000.0  1000.0  1000.0  1000.0   950.0   950.0   950.0   950.0   950.0
  950.0   950.0   950.0   950.0   950.0   950.0   950.0   950.0   950.0   950.0
  950.0   950.0   950.0   950.0   950.0   950.0   950.0   975.0   975.0   975.0
  975.0   975.0   975.0   975.0   950.0   950.0  1000.0  1025.0  1025.0  1050.0
 1075.0  1075.0
```

Listing 8. Partial listing of input for the vertical conductance between model layers one and two in the BCF package of the MODULAR program for the steady-state simulation

```
0.05000 0.05000 0.05000 0.05000 0.05000 0.05000 0.05000 0.05000 0.05333 0.05714
0.06667 0.07273 0.07273 0.07273 0.07273 0.07273 0.07273 0.07273 0.07273 0.07273
0.07273 0.07273 0.06667 0.05714 0.05333 0.05333 0.05333 0.05333 0.05333 0.05333
0.05333 0.05333 0.05333 0.05333 0.05333 0.05333 0.05333 0.05333 0.05333 0.05333
0.05333 0.05333 0.05333 0.05333 0.05333 0.05333 0.05333 0.05333 0.05333 0.05333
0.05333 0.05333
0.05000 0.05000 0.05000 0.06250 0.06250 0.05333 0.05333 0.06780 0.06780 0.06780
0.06061 0.06667 0.06667 0.06667 0.06667 0.06667 0.06667 0.06667 0.06667 0.06667
0.06667 0.06667 0.05714 0.05714 0.05714 0.07407 0.07407 0.05714 0.05333 0.05333
0.05333 0.05333 0.05333 0.05333 0.05333 0.05333 0.05333 0.05333 0.06780 0.06780
0.06780 0.06780 0.06780 0.06780 0.06780 0.05333 0.05333 0.05333 0.05333 0.05333
0.05333 0.05333
0.05000 0.05000 0.05000 0.06250 0.06250 0.05000 0.06452 0.05128 0.06452 0.06452
0.06452 0.06780 0.06780 0.06780 0.06780 0.06780 0.06780 0.05333 0.05333 0.06780
0.06780 0.06780 0.06780 0.06780 0.06780 0.06780 0.06250 0.06250 0.06250 0.06250
0.05000 0.05000 0.05000 0.05000 0.05000 0.05000 0.05000 0.05000 0.06250 0.06250
0.06250 0.06250 0.06250 0.06250 0.06250 0.05333 0.06780 0.05333 0.05333 0.05333
0.05333 0.05333
0.05000 0.05000 0.05000 0.06250 0.06250 0.05000 0.05000 0.06452 0.06250 0.06250
0.05000 0.05000 0.06250 0.06250 0.06250 0.05000 0.06250 0.05000 0.05000 0.05000
0.06250 0.05000 0.05000 0.05333 0.05333 0.05333 0.05333 0.06154 0.05714 0.05714
0.05714 0.05714 0.05714 0.05714 0.05714 0.05714 0.05714 0.05714 0.05714 0.05000
0.05000 0.05000 0.05000 0.05000 0.05000 0.05000 0.05000 0.05000 0.05333 0.05333
0.05333 0.05333
0.05000 0.05000 0.05000 0.05000 0.06250 0.05000 0.06154 0.06186 0.06000 0.06154
0.05000 0.06250 0.06250 0.06250 0.05000 0.05000 0.05000 0.05000 0.05000 0.05000
0.05000 0.05000 0.07500 0.07500 0.08000 0.08000 0.08000 0.08000 0.05333 0.05333
0.05333 0.05333 0.05333 0.05000 0.05000 0.05000 0.05000 0.05000 0.05000 0.05000
0.05000 0.05000 0.05000 0.05000 0.05000 0.05000 0.06250 0.05000 0.05000 0.05000
0.05000 0.05000
0.05000 0.05000 0.05000 0.05000 0.06250 0.05000 0.06250 0.06452 0.06154 0.06000
0.06154 0.06154 0.06154 0.06250 0.06250 0.06250 0.06250 0.05000 0.05000 0.05000
0.05000 0.05000 0.07500 0.07500 0.08571 0.07500 0.08000 0.08000 0.08000 0.07500
0.07500 0.07500 0.07500 0.07500 0.05000 0.05000 0.05000 0.05000 0.05000 0.05000
0.05000 0.05000 0.05000 0.05000 0.05000 0.05000 0.06250 0.05000 0.05000 0.05000
0.05000 0.05000
0.05000 0.05000 0.05000 0.05000 0.06250 0.05000 0.06250 0.06452 0.06154 0.06154
0.06250 0.06250 0.06154 0.05000 0.05000 0.05000 0.05000 0.05000 0.05000 0.05000
0.05000 0.05000 0.05000 0.05333 0.05333 0.05333 0.05333 0.05333 0.05000 0.05000
0.08571 0.07500 0.07500 0.07500 0.07500 0.07500 0.07500 0.07500 0.07500 0.07500
0.07500 0.07500 0.07500 0.07500 0.07500 0.05000 0.05000 0.05000 0.05000 0.05000
0.05000 0.05000
0.05000 0.05000 0.05000 0.06250 0.06250 0.06250 0.06000 0.06186 0.06154 0.06154
0.06154 0.05000 0.05000 0.05333 0.05333 0.05333 0.05333 0.05333 0.05333 0.05333
0.05333 0.05333 0.05333 0.05333 0.05333 0.05333 0.05333 0.05714 0.05714 0.05714
0.08571 0.08571 0.08571 0.07500 0.07500 0.07500 0.07500 0.07500 0.07500 0.07500
0.07500 0.07500 0.07500 0.07500 0.07500 0.07500 0.05000 0.05000 0.05000 0.05000
0.05000 0.05000
```

Listing 9. Partial listing of input for the top elevations of the St. Peter in the BCF package of the MODULAR program for the steady-state simulation

```
1050.0  1050.0  1050.0  1050.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0
1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0
1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0
1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0
1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0
1030.0  1030.0
1040.0  1040.0  1040.0  1040.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0
1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0
1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0
1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0
1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0
1030.0  1030.0
1020.0  1020.0  1020.0  1030.0  1040.0  1030.0  1030.0  1030.0  1030.0  1030.0
1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0
1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0
1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0
1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0  1030.0
1030.0  1030.0
1025.0  1025.0  1025.0  1025.0  1025.0  1030.0  1030.0  1030.0  1030.0  1030.0
1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0
1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0
1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0
1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0
1050.0  1050.0
1030.0  1030.0  1030.0  1030.0  1040.0  1040.0  1040.0  1040.0  1040.0  1040.0
1040.0  1040.0  1040.0  1040.0  1040.0  1040.0  1040.0  1040.0  1100.0  1100.0
1100.0  1100.0  1100.0  1100.0  1100.0  1100.0  1100.0  1100.0  1100.0  1100.0
1100.0  1100.0  1100.0  1100.0  1100.0  1100.0  1100.0  1100.0  1100.0  1100.0
1100.0  1100.0  1100.0  1100.0  1110.0  1110.0  1120.0  1120.0  1120.0  1120.0
1120.0  1120.0
1050.0  1050.0  1050.0  1040.0  1020.0  1020.0  1020.0  1020.0  1020.0  1020.0
1020.0  1020.0  1020.0  1020.0  1020.0  1020.0  1110.0  1110.0  1100.0  1100.0
1100.0  1100.0  1100.0  1100.0  1100.0  1100.0  1100.0  1100.0  1100.0  1100.0
1100.0  1100.0  1080.0  1080.0  1080.0  1080.0  1080.0  1080.0  1080.0  1080.0
1080.0  1080.0  1080.0  1100.0  1110.0  1110.0  1120.0  1130.0  1140.0  1140.0
1140.0  1140.0
1050.0  1050.0  1050.0  1050.0  1040.0  1040.0  1040.0  1040.0  1040.0  1040.0
1040.0  1040.0  1040.0  1040.0  1040.0  1040.0  1040.0  1100.0  1100.0  1100.0
1100.0  1100.0  1100.0  1100.0  1100.0  1100.0  1100.0  1100.0  1100.0  1100.0
1100.0  1100.0  1100.0  1100.0  1100.0  1100.0  1100.0  1100.0  1100.0  1100.0
1080.0  1080.0  1080.0  1100.0  1070.0  1060.0  1070.0  1100.0  1120.0  1140.0
1140.0  1140.0
1050.0  1050.0  1050.0  1050.0  1040.0  1040.0  1040.0  1040.0  1040.0  1040.0
1040.0  1040.0  1040.0  1040.0  1040.0  1040.0  1100.0  1100.0  1100.0  1100.0
1100.0  1100.0  1100.0  1100.0  1100.0  1100.0  1100.0  1100.0  1100.0  1100.0
1100.0  1100.0  1100.0  1100.0  1100.0  1100.0  1100.0  1100.0  1100.0  1100.0
1080.0  1080.0  1080.0  1100.0  1070.0  1060.0  1070.0  1100.0  1120.0  1140.0
1140.0  1140.0
```

Listing 10. Partial listing of input for the Prairie du Chien hydraulic conductivity in the BCF package of the MODULAR program for the steady-state simulation

10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0								
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0								
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0								
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0								
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	15.0	15.0	15.0	15.0	15.0	15.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0								
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
15.0	15.0	15.0	15.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0								
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
15.0	15.0	15.0	15.0	15.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0								
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
36.0	35.0	35.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
15.0	15.0	15.0	15.0	15.0	15.0	10.0	10.0	10.0	10.0
10.0	10.0								

Listing 11. Partial listing of input for the bottom elevations of the Prairie du Chien in the BCF package of the MODULAR program for the steady-state simulation

600.0	600.0	600.0	600.0	600.0	675.0	700.0	725.0	750.0	750.0
750.0	750.0	750.0	750.0	750.0	750.0	750.0	750.0	750.0	750.0
775.0	800.0	800.0	800.0	800.0	800.0	800.0	800.0	800.0	800.0
800.0	800.0	800.0	800.0	800.0	800.0	800.0	800.0	800.0	800.0
800.0	800.0	800.0	800.0	800.0	800.0	800.0	800.0	800.0	800.0
800.0	800.0								
600.0	600.0	600.0	625.0	650.0	675.0	700.0	725.0	750.0	750.0
750.0	750.0	750.0	750.0	750.0	750.0	750.0	750.0	750.0	750.0
775.0	775.0	775.0	775.0	775.0	800.0	800.0	800.0	800.0	800.0
800.0	800.0	800.0	800.0	800.0	800.0	800.0	800.0	800.0	800.0
800.0	800.0	800.0	800.0	800.0	800.0	800.0	800.0	800.0	800.0
800.0	800.0								
600.0	600.0	600.0	625.0	650.0	650.0	675.0	675.0	725.0	725.0
725.0	725.0	725.0	725.0	725.0	725.0	725.0	725.0	725.0	725.0
725.0	725.0	725.0	725.0	725.0	725.0	725.0	725.0	725.0	725.0
725.0	725.0	725.0	725.0	725.0	625.0	625.0	725.0	725.0	725.0
750.0	750.0	750.0	750.0	750.0	775.0	775.0	800.0	800.0	800.0
800.0	800.0								
600.0	600.0	600.0	625.0	650.0	675.0	675.0	675.0	700.0	700.0
750.0	750.0	750.0	750.0	750.0	750.0	750.0	750.0	750.0	750.0
675.0	675.0	675.0	675.0	675.0	700.0	700.0	700.0	700.0	700.0
700.0	700.0	700.0	700.0	700.0	700.0	700.0	700.0	725.0	725.0
725.0	725.0	725.0	725.0	725.0	750.0	750.0	775.0	775.0	800.0
800.0	800.0								
600.0	600.0	600.0	625.0	650.0	650.0	675.0	675.0	675.0	700.0
700.0	700.0	700.0	700.0	700.0	700.0	700.0	700.0	700.0	700.0
700.0	700.0	700.0	700.0	725.0	725.0	700.0	700.0	700.0	700.0
700.0	700.0	700.0	725.0	725.0	725.0	725.0	700.0	700.0	700.0
700.0	700.0	700.0	700.0	700.0	750.0	750.0	775.0	775.0	800.0
800.0	800.0								
600.0	600.0	600.0	625.0	650.0	650.0	650.0	650.0	675.0	700.0
700.0	700.0	700.0	700.0	700.0	700.0	700.0	700.0	700.0	700.0
700.0	700.0	700.0	700.0	700.0	700.0	700.0	700.0	700.0	700.0
700.0	700.0	700.0	700.0	700.0	725.0	725.0	725.0	725.0	700.0
700.0	700.0	700.0	700.0	700.0	700.0	700.0	725.0	725.0	775.0
775.0	800.0								
600.0	600.0	600.0	625.0	650.0	650.0	650.0	650.0	650.0	675.0
700.0	700.0	700.0	700.0	700.0	700.0	700.0	700.0	700.0	700.0
675.0	675.0	675.0	675.0	675.0	675.0	675.0	675.0	700.0	700.0
700.0	700.0	700.0	700.0	700.0	700.0	700.0	700.0	700.0	700.0
700.0	700.0	700.0	700.0	700.0	725.0	725.0	725.0	750.0	750.0
800.0	800.0								
600.0	600.0	600.0	625.0	650.0	650.0	650.0	650.0	650.0	675.0
675.0	675.0	700.0	700.0	700.0	700.0	700.0	675.0	675.0	675.0
675.0	675.0	675.0	675.0	675.0	675.0	700.0	700.0	700.0	700.0
700.0	700.0	700.0	700.0	700.0	700.0	700.0	700.0	700.0	700.0
700.0	700.0	700.0	700.0	700.0	725.0	725.0	725.0	750.0	775.0
800.0	800.0								

Listing 12. Partial listing of input for the vertical conductance between model layers two and three in the BCF package of the MODULAR program for the steady-state simulation

```
0.05000 0.05000 0.05000 0.05000 0.05000 0.05000 0.05000 0.05000 0.05333 0.05714
0.06667 0.07273 0.07273 0.07273 0.07273 0.07273 0.07273 0.07273 0.07273 0.07273
0.07273 0.07273 0.06667 0.05714 0.05333 0.05333 0.05333 0.05333 0.05333 0.05333
0.05333 0.05333 0.05333 0.05333 0.05333 0.05333 0.05333 0.05333 0.05333 0.05333
0.05333 0.05333 0.05333 0.05333 0.05333 0.05333 0.05333 0.05333 0.05333 0.05333
0.05333 0.05333
0.05000 0.05000 0.05000 0.06250 0.06250 0.05333 0.05333 0.06780 0.06780 0.06780
0.06061 0.06667 0.06667 0.06667 0.06667 0.06667 0.06667 0.06667 0.06667 0.06667
0.06667 0.06667 0.05714 0.05714 0.05714 0.07407 0.07407 0.05714 0.05333 0.05333
0.05333 0.05333 0.05333 0.05333 0.05333 0.05333 0.05333 0.05333 0.06780 0.06780
0.06780 0.06780 0.06780 0.06780 0.06780 0.05333 0.05333 0.05333 0.05333 0.05333
0.05333 0.05333
0.05000 0.05000 0.05000 0.06250 0.06250 0.05000 0.06452 0.05128 0.06452 0.06452
0.06452 0.06780 0.06780 0.06780 0.06780 0.06780 0.06780 0.05333 0.05333 0.06780
0.06780 0.06780 0.06780 0.06780 0.06780 0.06780 0.06250 0.06250 0.06250 0.06250
0.05000 0.05000 0.05000 0.05000 0.05000 0.05000 0.05000 0.05000 0.06250 0.06250
0.06250 0.06250 0.06250 0.06250 0.06250 0.05333 0.06780 0.05333 0.05333 0.05333
0.05333 0.05333
0.05000 0.05000 0.05000 0.06250 0.06250 0.05000 0.05000 0.06452 0.06250 0.06250
0.05000 0.05000 0.06250 0.06250 0.06250 0.05000 0.06250 0.05000 0.05000 0.05000
0.06250 0.05000 0.05000 0.05333 0.05333 0.05333 0.05333 0.06154 0.05714 0.05714
0.05714 0.05714 0.05714 0.05714 0.05714 0.05714 0.05714 0.05714 0.05714 0.05000
0.05000 0.05000 0.05000 0.05000 0.05000 0.05000 0.05000 0.05000 0.05333 0.05333
0.05333 0.05333
0.05000 0.05000 0.05000 0.05000 0.06250 0.05000 0.06154 0.06186 0.06000 0.06154
0.05000 0.06250 0.06250 0.06250 0.05000 0.05000 0.05000 0.05000 0.05000 0.05000
0.05000 0.05000 0.07500 0.07500 0.08000 0.08000 0.08000 0.08000 0.05333 0.05333
0.05333 0.05333 0.05333 0.05000 0.05000 0.05000 0.05000 0.05000 0.05000 0.05000
0.05000 0.05000 0.05000 0.05000 0.05000 0.05000 0.06250 0.05000 0.05000 0.05000
0.05000 0.05000
0.05000 0.05000 0.05000 0.05000 0.06250 0.05000 0.06250 0.06452 0.06154 0.06000
0.06154 0.06154 0.06154 0.06250 0.06250 0.06250 0.06250 0.05000 0.05000 0.05000
0.05000 0.05000 0.07500 0.07500 0.08571 0.07500 0.08000 0.08000 0.08000 0.07500
0.07500 0.07500 0.07500 0.07500 0.05000 0.05000 0.05000 0.05000 0.05000 0.05000
0.05000 0.05000 0.05000 0.05000 0.05000 0.05000 0.06250 0.05000 0.05000 0.05000
0.05000 0.05000
0.05000 0.05000 0.05000 0.05000 0.06250 0.05000 0.06250 0.06452 0.06154 0.06154
0.06250 0.06250 0.06154 0.05000 0.05000 0.05000 0.05000 0.05000 0.05000 0.05000
0.05000 0.05000 0.05000 0.05333 0.05333 0.05333 0.05333 0.05333 0.05000 0.05000
0.08571 0.07500 0.07500 0.07500 0.07500 0.07500 0.07500 0.07500 0.07500 0.07500
0.07500 0.07500 0.07500 0.07500 0.07500 0.05000 0.05000 0.05000 0.05000 0.05000
0.05000 0.05000
0.05000 0.05000 0.05000 0.06250 0.06250 0.06250 0.06000 0.06186 0.06154 0.06154
0.06154 0.05000 0.05000 0.05333 0.05333 0.05333 0.05333 0.05333 0.05333 0.05333
0.05333 0.05333 0.05333 0.05333 0.05333 0.05333 0.05333 0.05714 0.05714 0.05714
0.08571 0.08571 0.08571 0.07500 0.07500 0.07500 0.07500 0.07500 0.07500 0.07500
0.07500 0.07500 0.07500 0.07500 0.07500 0.07500 0.05000 0.05000 0.05000 0.05000
0.05000 0.05000
```

Listing 13. Partial listing of input for the top elevations of the Prairie du Chien in the BCF package of the MODULAR program for the steady-state simulation

```
  950.0   950.0   950.0   950.0  1000.0  1000.0  1050.0  1050.0  1050.0  1000.0
 1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0
 1000.0  1000.0  1000.0  1000.0  1000.0  1050.0  1050.0  1050.0  1050.0  1050.0
 1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0
 1075.0  1075.0  1075.0  1075.0  1075.0  1075.0  1075.0  1075.0  1075.0  1075.0
 1075.0  1100.0
  900.0   900.0   900.0   950.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0
 1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0
 1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0
 1000.0  1000.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0
 1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1075.0  1075.0  1075.0  1075.0
 1075.0  1100.0
  900.0   900.0   900.0   900.0   950.0  1000.0  1000.0  1000.0  1000.0   950.0
 1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0
 1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0
 1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0
 1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1050.0  1075.0  1075.0  1075.0
 1075.0  1100.0
  900.0   900.0   900.0   900.0   900.0   950.0   950.0   950.0   950.0   950.0
 1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0
 1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0
 1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0   990.0   990.0  1000.0
  975.0   975.0   975.0   975.0   975.0  1000.0  1000.0  1000.0  1075.0  1075.0
 1075.0  1100.0
  900.0   900.0   900.0   900.0   900.0   950.0   950.0   950.0   950.0   950.0
  950.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0
 1000.0  1000.0  1000.0  1000.0  1000.0  1000.0   950.0   900.0   950.0   950.0
 1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0   990.0   990.0  1000.0
  975.0   975.0   975.0   975.0   975.0  1000.0  1000.0  1025.0  1025.0  1025.0
 1075.0  1075.0
  900.0   900.0   900.0   900.0   900.0   950.0   950.0   950.0   950.0   950.0
  950.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0
  980.0   970.0   960.0   950.0   950.0   950.0   950.0   900.0   900.0   900.0
  950.0   950.0  1000.0  1000.0  1000.0  1000.0   990.0   990.0  1000.0   975.0
  975.0   975.0   975.0  1000.0  1000.0  1000.0  1000.0  1025.0  1025.0  1025.0
 1075.0  1075.0
  900.0   900.0   900.0   900.0   900.0   950.0   950.0   950.0   950.0   950.0
 1000.0  1000.0  1000.0  1000.0  1000.0  1000.0  1000.0   950.0   950.0   950.0
  950.0   950.0   950.0   900.0   950.0   950.0   950.0   950.0   950.0   950.0
  950.0   950.0   950.0  1000.0  1000.0  1000.0   990.0   990.0   990.0   975.0
  975.0   975.0   975.0   975.0   950.0   950.0  1000.0  1025.0  1025.0  1050.0
 1075.0  1075.0
  900.0   900.0   900.0   950.0   900.0   950.0   950.0   950.0   950.0   950.0
  950.0  1000.0  1000.0  1000.0  1000.0   950.0   950.0   950.0   950.0   950.0
  950.0   950.0   950.0   950.0   950.0   950.0   950.0   950.0   950.0   950.0
  950.0   950.0   950.0   950.0   950.0   950.0   950.0   975.0   975.0   975.0
  975.0   975.0   975.0   975.0   950.0   950.0  1000.0  1025.0  1025.0  1050.0
 1075.0  1075.0
```

Listing 14. Partial listing of input for the Jordan hydraulic conductivity in the BCF package of the MODULAR program for the steady-state simulation

10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0								
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0								
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0								
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0								
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	15.0	15.0	15.0	15.0	15.0	15.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0								
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
15.0	15.0	15.0	15.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0								
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
15.0	15.0	15.0	15.0	15.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0								
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
36.0	35.0	35.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
15.0	15.0	15.0	15.0	15.0	15.0	10.0	10.0	10.0	10.0
10.0	10.0								

Listing 15. Input for the WELL package of the MODULAR program for the steady-state simulation

```
       100        19                           WELL PACKAGE
        50                                     BASED ON 1979-88 RECORDS
         3        34        39 -8588.788       ROSE HARBOR
         3        38        40 -2149.470       CHRISTOPHER COURT
         3        47        25 -7651.779       WILLOW HEIGHTS
         2        31        25 -54310.50       #11 PDCN (68%)
         3        31        25 -25557.88       #11 JRDN (32%)
         3        25        28 -8833.420       #12      (64%)
         2        21        27 -45821.12       #13 PDCN (60%)
         3        21        27 -30547.41       #13 JRDN (40%)
         2        18        18 -55782.30       #15 PDCN (71%)
         3        18        18 -22784.32       #15 JRDN (29%)
         3        19        29 -13131.11       #17      (54%)
         3        28        19 -46646.36       #18      (56%)
         3        37        28 -50094.69       #19      (55%)
         3        29        28 -38022.59       #20      (52%)
         3        13        18 -34402.57       #22      (59%)
         3        31        31 -68509.50       #23
         3        17        25 -19701.88       #24      (58%)
         3        34        22 -61994.95       #25      (57%)
         2        27        10 -11197.33       #26 PDCN (63%)
         3        27        10 -6576.211       #26 JRDN (37%)
         3        25        33 -160596.2       #27
         3         9        21 -170728.4       #28
         3        39        25 -65303.74       #29
         3        23        31 -136207.8       #30
         2        25        28  -31409.9       SILVER LAKE POWER
         2        34        27  -5428.26       SENECA   PDCN (41%)
         3        34        27  -7811.14       SENECA   JRDN (59%)
         2        15        13  -4633.26       IBM      PDCN (69%)
         3        15        13  -1410.86       IBN      JRDN (21%)
         2        23        17  -19567.6       STAUFFER CHEMICAL
         2        33        20   -271.36       SUNNY SLOPES
         2        28        25  -70816.4       FRANKLIN HEATING
         2        38        45  -1630.28       ROCHESTER BLOCK
         3        48        41  -2096.68       OSJOR ESTATES
         2         5        29   -8580.7       ANDERSON SAND & GRAVEL
         2        57        19  -2387.12       ROCH AIRPORT  PDCN (82%)
         3        57        19   -523.64       ROCH AIRPORT  JRDN (18%)
         3        26        27  -1940.86       MARIGOLD FOODS
         2        29        22  -21328.2       ST. MARYS HOSP  PDCN (63%)
         3        29        22  -12526.0       ST. MARYS HOSP  JRDN (37%)
         3        30        27  -94275.3       AMPI
         3         8        28   -193.98       HALLMARK TERRACE
         3         9        28  -3532.98       BOOKS MOBILE HOME PARK
         3        36        45  -1048.34       ROBERT C. NEILL
         3        40        24  -1980.08       DONALD L. CLOSE
         3        39        19   -543.78       LENWOOD HEIGHTS
         3        21        10     -2120       ROMAC
         3        33        41  -1755.36       EASTWOOD G.C. (#21) (60%)
         3        29        14     -1908       ROCHESTER C.C.
         3        26        35   -18855.       ROCHESTER STATE HOSPITAL
```

Listing 16. Partial listing of input for the RIVER package of the MODULAR program for the steady-state simulation

170	48						RIVER PACKAGE
123							
2	4	26	920.	37000.	847.	6	S.FK. ZUM
2	4	27	925.	37000.00	858.	6	
2	5	28	930.	24750.00	860.	6	
2	6	28	935.	16500.00	868.	6	
2	7	29	940.	11250.0	872.	6	
2	7	27	941.	8000.0	878.	6	
2	7	26	942.	6000.0	884.	6	
2	7	25	943.	6000.0	890.	6	
2	8	25	944.	750.0	892.	6	
2	9	26	945.	750.0	894.	6	
2	10	25	946.	500.0	896.	6	
2	11	25	947.	500.0	897.	6	
2	12	26	948.	500.0	898.	6	
2	13	26	949.	500.0	899.	6	
2	14	26	950.	5000.00	900.	6	
2	15	26	950.	5000.00	905.	6	
2	16	26	951.	5000.00	910.	6	
2	17	27	953.	5000.00	915.	6	
2	18	27	955.	5000.00	920.	6	
2	19	26	956.	5000.00	925.	6	
2	20	26	957.	5000.00	930.	6	
2	21	26	958.	500.00	935.	6	
2	22	26	959.	100.00	940.	6	
2	22	27	960.	100.00	945.	6	
2	23	28	978.	200.00	950.	6	SILVER LK
2	24	28	978.	500.00	950.	6	SILVER LK
2	24	29	978.	500.00	950.	6	SILVER LK
2	25	28	978.	500.00	955.	6	
2	26	28	978.	500.00	960.	6	
2	27	28	979.	500.00	965.	6	
2	28	28	979.	100.00	970.	6	
2	29	28	979.	5000.0	976.	6	
2	29	27	980.	5000.0	979.	6	
2	30	27	981.	5000.0	980.	6	
2	31	26	982.	5000.0	980.	6	
2	32	25	984.	5000.0	979.	6	
2	33	25	986.	5000.0	975.	6	
2	34	24	988.	5000.00	965.	6	
2	35	23	990.	5000.00	960.	6	
2	36	23	992.	5000.00	955.	6	
2	37	22	994.	5000.00	950.	6	
2	37	21	996.	5000.00	950.	6	
2	38	20	998.	5000.00	950.	6	
2	37	19	1000.	5000.00	950.	6	
2	37	18	1002.	5000.00	950.	6	
2	37	17	1005.	500.00	953.	6	
2	37	16	1008.	500.00	956.	6	
2	36	15	1010.	500.00	968.	6	
2	36	14	1012.	500.00	960.	6	

Listing 17. Partial listing of input for the RECHARGE package of the MODULAR program for the steady-state simulation

```
         3        38         1                      RECHARGE PACKAGE
         1         0
         9  2.28E-04  (15F5.1)                    0     INCHES PER YEAR
  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0
  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0
  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0
  4.0  4.0  4.0  4.0  4.0  4.0  4.0
  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0
  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0
  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0
  4.0  4.0  4.0  4.0  4.0  4.0  4.0
  4.0  4.0  4.0  4.0  4.0  4.0  1.5  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0
  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0
  4.0  4.0  4.0  4.0  4.0  4.0  6.0  6.0  6.0  6.0  6.0  6.0  6.0  6.0  6.0
  6.0  4.0  4.0  4.0  4.0  4.0  4.0
  4.0  4.0  4.0  4.0 15.0 15.0  1.5  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0
  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0
  4.0  4.0  4.0  4.0  4.0  4.0 15.0  0.4  0.4  0.4  0.4  0.4  0.4  0.4  0.4
  0.4  6.0  6.0  6.0  4.0  4.0  4.0
  4.0  4.0  4.0  4.0 15.0 15.0  1.5  1.5  1.5  1.5  1.5  1.5  1.5  4.0  4.0
  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0
  4.0  4.0  4.0  4.0  4.0  4.0  4.0 15.0 15.0 15.0  0.4  0.4  0.4  0.4  0.4
  0.4  0.4  0.4  0.4  6.0  4.0  4.0
  4.0  4.0  4.0  4.0  0.4  0.4  1.5  1.5  1.5  1.5  1.5  1.5  1.5  4.0  4.0
 15.0 15.0 15.0 15.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0
 15.0 15.0 15.0 15.0 15.0 15.0  0.4  0.4  0.4  0.4  0.4  0.4  0.4  0.4  0.4
  0.4  0.4  0.4  0.4  6.0  4.0  4.0
  4.0  4.0  4.0  4.0  0.4  0.4  1.5  1.5  1.5  1.5  4.0  4.0  4.0  4.0  4.0
  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0 15.0
  0.4  0.4  0.4  0.4  0.4  0.4  0.4  0.4  0.4  0.4  0.4  0.4  0.4  0.4  0.4
  0.4  0.4  0.4  0.4  6.0  4.0  4.0
  4.0  4.0  4.0  0.4  0.4  0.4  1.5  1.5  1.5  1.5  4.0  4.0  4.0  4.0  4.0
  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0
 15.0 15.0 15.0 15.0 15.0 15.0  0.4  0.4  0.4  0.4  0.4  0.4  0.4  0.4  0.4
  0.4  0.4  0.4  0.4  0.4  6.0  4.0
  4.0  4.0  4.0  0.4  0.4 15.0  1.5  1.5  1.5  1.5  1.5  4.0  4.0  4.0  4.0
  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0
  4.0  4.0  4.0  4.0  4.0  4.0 15.0 15.0 15.0 15.0 15.0 15.0 15.0  0.4  0.4
  0.4  0.4  0.4  0.4  0.4  6.0  4.0
  4.0  4.0  0.4  0.4  1.5 15.0  1.5  1.5  1.5  1.5  1.5  4.0  4.0  4.0  4.0
  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0
  4.0  4.0  4.0 15.0  4.0  4.0  4.0  4.0 15.0  0.4  0.4  0.4  0.4  0.4  0.4
  0.4  0.4  0.4  0.4  0.4  0.4  4.0
  4.0  4.0  0.4  0.4  1.5 15.0  1.5  1.5  1.5  1.5  1.5  1.5  4.0  4.0  4.0
  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0  4.0 15.0
 15.0 15.0 15.0  0.4 15.0  4.0  4.0 15.0 15.0  0.4  0.4  0.4  0.4  0.4  0.4
  0.4  0.4  0.4  0.4  0.4  0.4  4.0
  4.0  4.0  0.4  0.4  1.5 15.0  1.5  1.5  1.5  1.5  1.5  1.5  4.0  4.0  4.0
  4.0  2.0  2.0  2.0  2.0  2.0  2.0  2.0  2.0  4.0  4.0  4.0  4.0 15.0  0.4
  0.4  0.4 15.0  0.4 15.0 15.0  4.0 15.0 15.0 15.0  0.4  0.4  0.4  0.4  0.4
  0.4  0.4  0.4  0.4  0.4  0.4  4.0
```

Listing 18. Input for the SIP package of the MODULAR program for the steady-state simulation

```
      300         5                                         SIP PACKAGE
     1.00      .001         0  2.29E-05                     ACC. PAR./CLOSE/SEED
```

Listing 19. Input for the WELL package of the MODULAR program for the simulation of a hypothetical drought - simulation B (Delin, 1990)

```
      100        19                             WELL PACKAGE - DROUGHT
       50
        3        34        39    -12883            ROSE HARBOR
        3        38        40     -3224            CHRISTOPHER COURT
        3        47        25    -11477            WILLOW HEIGHTS
        2        31        25    -81465            #11 PDCN (68%)
        3        31        25    -38336            #11 JRDN (32%)
        3        25        28    -13250            #12      (64%)
        2        21        27    -68731            #13 PDCN (60%)
        3        21        27    -45821            #13 JRDN (40%)
        2        18        18    -83673            #15 PDCN (71%)
        3        18        18    -34176            #15 JRDN (29%)
        3        19        29    -19696            #17      (54%)
        3        28        19    -69969            #18      (56%)
        3        37        28    -75142            #19      (55%)
        3        29        28    -57033            #20      (52%)
        3        13        18    -51603            #22      (59%)
        3        31        31   -102764            #23
        3        17        25    -29552            #24      (58%)
        3        34        22    -92992            #25      (57%)
        2        27        10    -16795            #26 PDCN (63%)
        3        27        10     -9864            #26 JRDN (37%)
        3        25        33   -240894            #27
        3         9        21   -256092            #28
        3        39        25    -97955            #29
        3        23        31   -204311            #30
```

Listing 20. Input for the RECHARGE package of the MODULAR program for the simulation of a hypothetical drought - simulation B

```
        3        19         1                                DROUGHT RECHARGE
        1         0
        9 1.596E-04  (15F5.1)                  0
```

(Input array is identical to recharge array shown, in part, earlier above)

Listing 21. Input for the WELL package of the MODULAR program for the simulation of hypothetical ground-water development - simulation C

```
       100        19                         WELL PACKAGE
        56                                   EXPANDED DEVELOPMENT
         3        34       39 -8588.788        ROSE HARBOR
         3        38       40 -2149.470        CHRISTOPHER COURT
         3        47       25 -7651.779        WILLOW HEIGHTS
         2        31       25 -54310.50        #11 PDCN (68%)
         3        31       25 -25557.88        #11 JRDN (32%)
         3        25       28 -8833.420        #12      (64%)
         2        21       27 -45821.12        #13 PDCN (60%)
         3        21       27 -30547.41        #13 JRDN (40%)
         2        18       18 -55782.30        #15 PDCN (71%)
         3        18       18 -22784.32        #15 JRDN (29%)
         3        19       29 -13131.11        #17      (54%)
         3        28       19 -46646.36        #18      (56%)
         3        37       28 -50094.69        #19      (55%)
         3        29       28 -38022.59        #20      (52%)
         3        13       18 -34402.57        #22      (59%)
         3        31       31 -68509.50        #23
         3        17       25 -19701.88        #24      (58%)
         3        34       22 -61994.95        #25      (57%)
         2        27       10 -11197.33        #26 PDCN (63%)
         3        27       10 -6576.211        #26 JRDN (37%)
         3        25       33 -160596.2        #27
         3         9       21 -170728.4        #28
         3        39       25 -65303.74        #29
         3        23       31 -136207.8        #30
         3        49       23-155000.00           0     #31      106.14.23CCC
         3        21       35-155000.00           0     #32      107.13.30CA
         3        43       13-155000.00           0     #33      106.14.16CD
         3        33       13-155000.00           0     #34      106.14.4CD
         3         8       10-155000.00           0     #35      107.14.8DC
         3        43       43-155000.00           0     #36      106.13.16CC
```

Listing 22. Input for the WELL package of the MODULAR program for the simulation of a hypothetical discontinuation of pumping from selected Rochester municipal wells - simulation D

```
   100        19                        WELL PACKAGE
    42                     ROCHESTER WELLS 11,12,13,20, 23, AND 30 REMOVED
     3        34        39 -8588.788      ROSE HARBOR
     3        38        40 -2149.470      CHRISTOPHER COURT
     3        47        25 -7651.779      WILLOW HEIGHTS
     2        18        18 -55782.30      #15 PDCN (71%)
     3        18        18 -22784.32      #15 JRDN (29%)
     3        19        29 -13131.11      #17      (54%)
     3        28        19 -46646.36      #18      (56%)
     3        37        28 -50094.69      #19      (55%)
     3        13        18 -34402.57      #22      (59%)
     3        17        25 -19701.88      #24      (58%)
     3        34        22 -61994.95      #25      (57%)
     2        27        10 -11197.33      #26 PDCN (63%)
     3        27        10 -6576.211      #26 JRDN (37%)
     3        25        33 -160596.2      #27
     3         9        21 -170728.4      #28
     3        39        25 -65303.74      #29
     2        25        28  -31409.9      SILVER LAKE POWER
     2        34        27  -5428.26      SENECA   PDCN (41%)
     3        34        27  -7811.14      SENECA   JRDN (59%)
     2        15        13  -4633.26      IBM      PDCN (69%)
     3        15        13  -1410.86      IBN      JRDN (21%)
     2        23        17  -19567.6      STAUFFER CHEMICAL
     2        33        20   -271.36      SUNNY SLOPES
     2        28        25  -70816.4      FRANKLIN HEATING
     2        38        45  -1630.28      ROCHESTER BLOCK
     3        48        41  -2096.68      OSJOR ESTATES
     2         5        29   -8580.7      ANDERSON SAND & GRAVEL
     2        57        19  -2387.12      ROCH AIRPORT  PDCN (82%)
     3        57        19   -523.64      ROCH AIRPORT  JRDN (18%)
     3        26        27  -1940.86      MARIGOLD FOODS
     2        29        22  -21328.2      ST. MARYS HOSP  PDCN (63%)
     3        29        22  -12526.0      ST. MARYS HOSP  JRDN (37%)
     3        30        27  -94275.3      AMPI
     3         8        28   -193.98      HALLMARK TERRACE
     3         9        28  -3532.98      BOOKS MOBILE HOME PARK
     3        36        45  -1048.34      ROBERT C. NEILL
     3        40        24  -1980.08      DONALD L. CLOSE
     3        39        19   -543.78      LENWOOD HEIGHTS
     3        21        10     -2120      ROMAC
     3        33        41  -1755.36      EASTWOOD G.C. (#21) (60%)
     3        29        14     -1908      ROCHESTER C.C.
     3        26        35    -18855      ROCH STATE HOSP
```

Listing 23. Input for the WELL package of the MODULAR program for the simulation of a hypothetical discontinuation of pumping from selected non-municipal wells - simulation E

100	19			WELL PACKAGE
39				SELECTED INDUSTRIAL WELLS REMOVED
3	34	39	-8588.788	ROSE HARBOR
3	38	40	-2149.470	CHRISTOPHER COURT
3	47	25	-7651.779	WILLOW HEIGHTS
2	31	25	-54310.50	#11 PDCN (68%)
3	31	25	-25557.88	#11 JRDN (32%)
3	25	28	-8833.420	#12 (64%)
2	21	27	-45821.12	#13 PDCN (60%)
3	21	27	-30547.41	#13 JRDN (40%)
2	18	18	-55782.30	#15 PDCN (71%)
3	18	18	-22784.32	#15 JRDN (29%)
3	19	29	-13131.11	#17 (54%)
3	28	19	-46646.36	#18 (56%)
3	37	28	-50094.69	#19 (55%)
3	29	28	-38022.59	#20 (52%)
3	13	18	-34402.57	#22 (59%)
3	31	31	-68509.50	#23
3	17	25	-19701.88	#24 (58%)
3	34	22	-61994.95	#25 (57%)
2	27	10	-11197.33	#26 PDCN (63%)
3	27	10	-6576.211	#26 JRDN (37%)
3	25	33	-160596.2	#27
3	9	21	-170728.4	#28
3	39	25	-65303.74	#29
3	23	31	-136207.8	#30
2	25	28	-31409.9	SILVER LAKE POWER
2	33	20	-271.36	SUNNY SLOPES
2	38	45	-1630.28	ROCHESTER BLOCK
3	48	41	-2096.68	OSJOR ESTATES
2	5	29	-8580.7	ANDERSON SAND & GRAVEL
2	57	19	-2387.12	ROCH AIRPORT PDCN (82%)
3	57	19	-523.64	ROCH AIRPORT JRDN (18%)
3	8	28	-193.98	HALLMARK TERRACE
3	9	28	-3532.98	BOOKS MOBILE HOME PARK
3	36	45	-1048.34	ROBERT C. NEILL
3	40	24	-1980.08	DONALD L. CLOSE
3	39	19	-543.78	LENWOOD HEIGHTS
3	21	10	-2120	ROMAC
3	33	41	-1755.36	EASTWOOD G.C. (#21) (60%)
3	29	14	-1908	ROCHESTER C.C.