SIMULATION OF GROUND-WATER FLOW IN THE PRAIRIE DU CHIEN-JORDAN AND OVERLYING AQUIFERS NEAR THE MISSISSIPPI RIVER, FRIDLEY, MINNESOTA

By R. J. Lindgren

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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

Multiply inch-pound unit	By	To obtain SI unit
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
cubic foot per second (ft^3/s)	10.028321	cubic meter per second
foot squared per day (ft^2/d)	0.09290	meter squared per day
gallon per minute (gal/min)	0.06309	liter per second
million gallons per day (Mgal/d)	0.04381	cubic meter per second
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929--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.

SIMULATION OF GROUND-WATER FLOW IN THE PRAIRIE DU CHIEN-JORDAN AND OVERLYING AQUIFERS NEAR THE MISSISSIPPI RIVER, FRIDLEY, MINNESOTA

By Richard J. Lindgren

ABSTRACT

A three-dimensional, ground-water-flow model was developed to gain an improved understanding of the ground-water-flow system and its response to withdrawals near the Minneapolis Water Works in Fridley, Minnesota. Eight hydrogeologic units are represented in the ground-water-flow model. Aquifers represented are the unconfined-drift, confined-drift, St. Peter, and Prairie du Chien-Jordan. Confining units represented are the upper drift, basal-drift, Decorah-Platteville-Glenwood, and basal St. Peter confining units.

The ground-water-flow model was calibrated for steady-state conditions for a period before substantial ground-water development (1885-1930) and for a period of significant pumping stress (winter conditions, 1970-79). The principle of superposition was used in the steady-state simulation for 1970-79. Transient conditions were simulated for an aquifer test conducted at the Minneapolis Water Works site and for seasonal variations in ground-water withdrawals resulting in seasonal fluctuations of hydraulic heads of as much as about 45 ft. Sensitivity analysis indicated that hydraulic heads in the confined-drift and St. Peter aquifers and Prairie du Chien-Jordan aquifer were most affected by varying the vertical hydraulic conductivity of the upper drift confining unit and recharge to the confined-drift and St. Peter aquifers.

Spatially variable leakage to the confined-drift and St. Peter aquifers in the steady-state simulation for 1885-1930 ranged from 1.0 to 2.3 inches per year. Leakage to the confined-drift and St. Peter aquifers in the steady-state simulation for 1970-79 increased 0 to 3.0 inches per year above the initial steady-state results. This increase represents additional leakage caused by the lowering of hydraulic heads due to ground-water withdrawals. Simulated leakage to the confined-drift and St. Peter aquifers for the transient simulation for 1987 varied both seasonally (0.4 to 2.1 inches per stress period) and spatially (2.6 to 5.7 inches per year).

The calibrated transient simulation for 1987 was used to determine the effects of hypothetical ground-water withdrawals near the Minneapolis Water Works under transient conditions. A simulation assuming total additional ground-water withdrawals of 27.5 million gallons per day, during late summer (July, August, and September), from the Prairie du Chien-Jordan aquifer in four model cells resulted in a maximum increased drawdown of about 80 feet in the Prairie du Chien-Jordan aquifer and about 60 feet in the confined-drift and St. Peter aquifers at the end of September. Hydraulic heads rebounded following the cessation of the hypothetical withdrawals and at the end of the 1-year simulation period, the heads were only about 2.5 feet lower than they were at the beginning of the simulation. The water supplying the additional ground-water withdrawals was derived mostly from (1) changes in leakage

between the Mississippi River and the unconfined-drift aquifer (about 34 percent), (2) increased ground-water inflow from areas beyond the model boundaries (about 34 percent), and (3) water released from storage in the aquifers (about 29 percent). A 5-year hypothetical transient simulation was done to determine if a cumulative drawdown in hydraulic heads would occur. The seasonal recharge and ground-water withdrawal rates used in the 1-year hypothetical simulation were cycled five times. Drawdowns in the confined-drift and St. Peter aquifers and the Prairie du Chien-Jordan aquifer at the end of late summer (September) and the end of the annual cycle (December) were about the same during the fifth year of simulation as they were after only 1 year. A hypothetical transient simulation, assuming total additional ground-water withdrawals of 55 million gallons per day during late summer from the Prairie du Chien-Jordan aquifer in eight model cells, resulted in a maximum increase in drawdown of about 130 feet in the Prairie du Chien-Jordan aquifer and about 105 feet in the confined-drift and St. Peter aquifers at the end of September.

The calibrated simulation for 1970-79, which is based on the principle of superposition, was used to determine possible long-term effects of increased ground-water withdrawals near the Minneapolis Water Works assuming steady-state conditions. A hypothetical steady-state simulation with additional ground-water withdrawals totaling 14.0 million gallons per day from the Prairie du Chien-Jordan aquifer in four model cells resulted in a maximum increase in drawdown in the aquifer of about 70 feet. The water supplying the additional ground-water withdrawals was derived from (1) leakage of water from the Mississippi River to the aquifer system and (or) reduction in the discharge of water from the aquifer system to the river (about 81 percent), and (2) increased ground-water inflow from areas beyond the model boundaries (about 19 percent).

Contaminated water from areas of known contamination could move toward depressions in the potentiometric surfaces of the confined-drift and St. Peter aquifers and Prairie du Chien-Jordan aquifer if additional ground water were withdrawn near the Minneapolis Water Works. The presence of a bedrock valley beneath the Minneapolis Water Works and discontinuities in the upper drift confining unit create the potential for the downward movement of contaminants from the surficial sand and gravel deposits to the underlying aquifers.

INTRODUCTION

The city of Minneapolis currently obtains all of the water for its public supply from the Mississippi River. Future availability of water from the Mississippi River is of concern in terms of both quantity and quality. Potential future problems include increases in demand that exceed the amount of water available, reductions in available streamflow, and degradation in water quality. During periods of drought, water available from the Mississippi River may be insufficient to meet the needs of the city of Minneapolis because of high demands in combination with low streamflows. The Mississippi River also is vulnerable to adverse changes in water quality caused by dissolved contaminants from upstream agricultural practices, industrial chemical spills, urban runoff, or a combination of these sources.

Ground water from drift and bedrock aquifers underlying the Minneapolis Water Works site may be an alternative source of water to supplement the current surface-water supply. An improved understanding of the ground-water-flow system and its response to withdrawals is needed to determine if use of ground water is feasible. In 1987, the U.S. Geological Survey, in cooperation with the city of Minneapolis, began a study to evaluate the ground-water-flow system near the Minneapolis Water Works and determine the effects of ground-water withdrawals on flow in the ground-water system and the Mississippi River.

Purpose and Scope

This report describes the hydrogeology and ground-water-flow system near the Minneapolis Water Works treatment plant in Fridley and, in lesser detail, a part of the seven-county Twin Cities (Minneapolis-St. Paul) Metropolitan Area (figs. 1 and 2; table 1, provides a cross-reference between the short name for each well shown on figure 2 and the township range section, U.S. Geological Survey identification number, and Minnesota unique number for each well). The report describes the construction, calibration, and application of a numerical ground-water-flow model that simulates the aquifer system, consisting of the Prairie du Chien-Jordan aquifer and overlying units, in the study area. The numerical ground-water-flow model was developed to help (1) estimate the hydrologic response of the aquifer system to increased ground-water withdrawals, (2) determine the hydraulic connection between the Prairie du Chien-Jordan aquifer, over- lying aquifer units, and the Mississippi River, and (3) estimate the effect of ground-water withdrawals on water levels in wells and the extent to which these withdrawals induce flow from areas of known ground-water contamination.

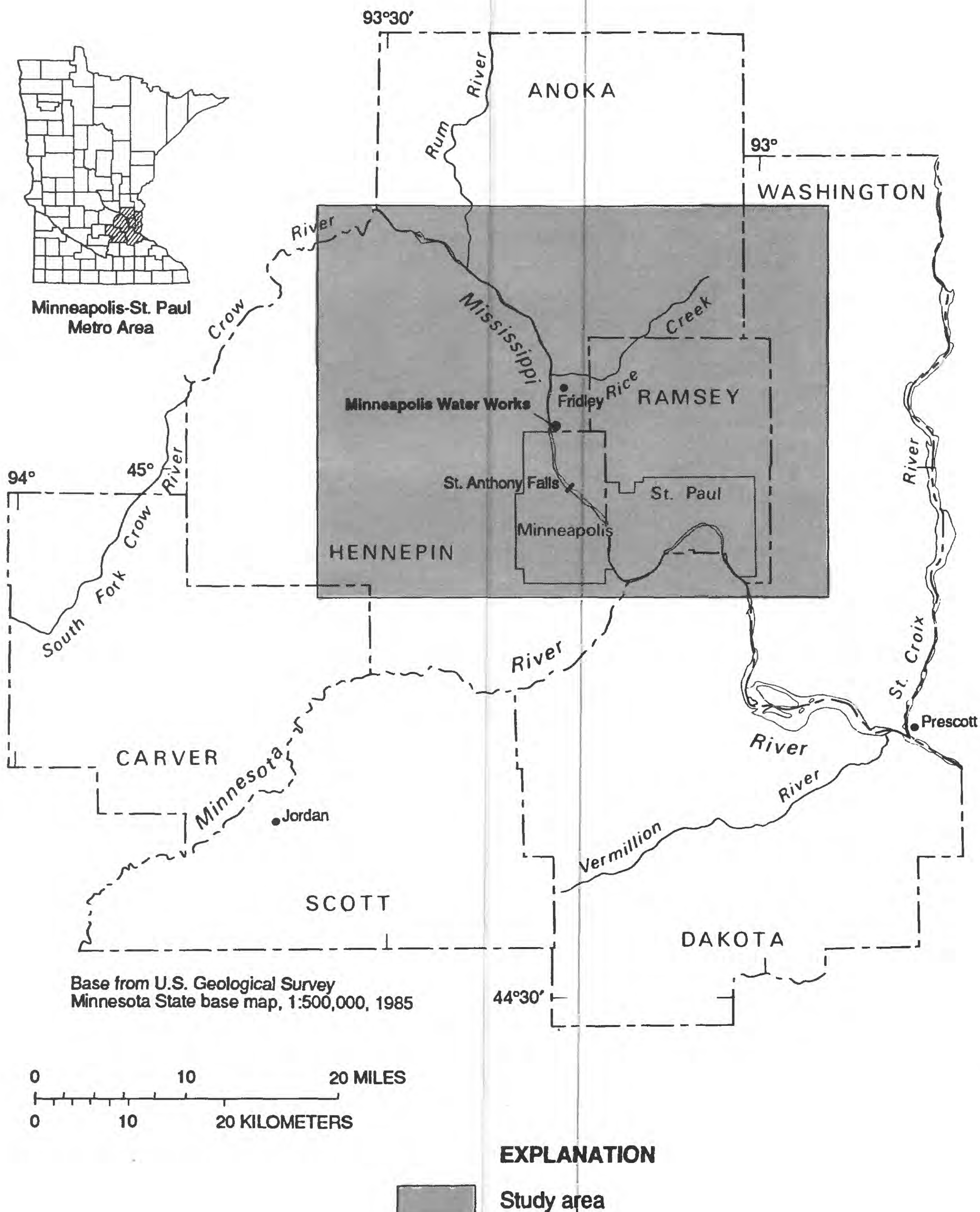
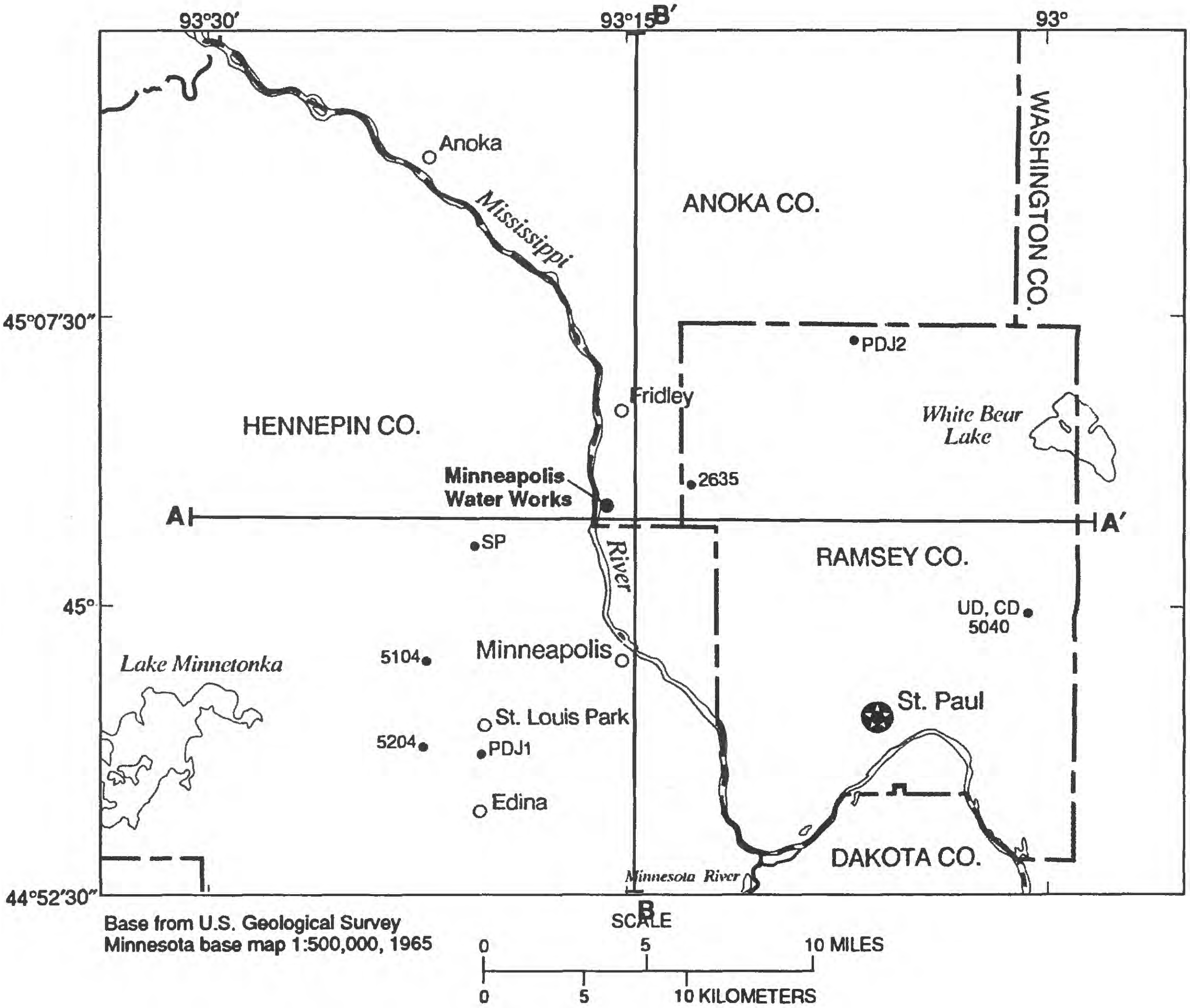


Figure 1.--Location of study area, the Minneapolis Water Works, and the seven-county Minneapolis-St. Paul Metropolitan Area.



EXPLANATION

B——B′ Trace of geologic section

PDJ1 • Observation well--Table 1 provides a cross-reference between the short name for each well shown on this figure and the township-range-section, U.S. Geological Survey identification number, and Minnesota unique number for each well.

Figure 2.--Trace of hydrogeologic sections, and locations of observation wells.

Table 1.--*Observation well information*

[--, no number assigned]

Short name used in figures 2 and 6	Township-Range section	U.S. Geological Survey identification number	Minnesota unique number
UD	29N22W14CAB03	445955093011003	--
CD	29N22W14CAB02	445955093011002	--
SP	29N24W06CCC01	450116093205301	--
PDJ1	117N21W16CCA01	445615093212301	206443
PDJ2	30N23W01BABB01	450723093071801	206707
2635	30N23W30CBA02	450323093133102	206796
5040	29N22W14CAB01	445955093011001	200443
5104	118N21W18DAB01	445857093223101	203914
5204	117N21W18DAB01	445631093230301	203196
FMC11	30N24W27DCCD01	--	196701
FMC19A	30N24W27DCCA01	--	196709
FMC21	30N24W27CDDD02	--	196733
FMC24	30N24W27DCDC01	--	196732
FMC31	30N24W27DCCA02	--	196715
FMC32	30N24W27DCDD01	--	196716
FMC37	30N24W34ABBD01	--	196731
FMC39	30N24W27CDDD01	--	196727
FMC43	30N24W27DCCC01	--	196726
MWW12	30N24W27CDA01	450313093164601	--
MWW13	30N24W27CDA02	450313093164602	--
Fridley #13	30N24W27BADC01	--	206696

Previous Investigations

Numerous studies have been made of the aquifer system in the Twin Cities Metropolitan Area. Norvitch and others (1974) describe the hydrologic system and its relation to the water supply of the metropolitan area. Helgesen and Lindholm (1973) describe the geology and water-supply potential of the Anoka Sand-Plain surficial aquifer. Larson-Higdem and others (1975) plotted the configuration of the water table in the Twin Cities Metropolitan Area and estimated, for steady-state conditions, comparative rates of downward leakage from several overlying deposits of differing lithology to the Prairie du Chien-Jordan aquifer. Schoenberg (1984) describes water levels and water-level changes in the Prairie du Chien-Jordan and Mount Simon-Hinckley aquifers in the Twin Cities Metropolitan Area from 1971-80. Horn (1983, 1984) analyzed ground-water use information for the Twin Cities Metropolitan Area from 1880 through 1980 and from 1970 through 1979 by category of use and by aquifer.

Several numerical ground-water-flow models of the aquifer system in the Twin Cities Metropolitan Area have been developed. Guswa and others (1982) developed a preliminary quasi-three-dimensional finite-difference ground-water-flow model of the seven-county Twin Cities Metropolitan Area; in that model, nine hydrogeologic units were incorporated into five layers. Stark and Hult (1985) describe the hydrogeology and ground-water-flow model of the Prairie du Chien-Jordan aquifer and overlying hydrogeologic units in the St. Louis Park area in Hennepin County. Schoenberg (1990) describes the hydrogeology and ground-water-flow model of the Mount Simon-Hinckley aquifer and overlying hydrogeologic units in the Twin Cities Metropolitan Area. In that model, the aquifer system includes five aquifers and four confining units.

A few studies have been made of the aquifer system and ground-water contamination near the Minneapolis Water Works. Ranney Company (1978) conducted a hydrogeological investigation within the Water Works property to evaluate the potential for developing a ground-water supply from the alluvial-drift aquifer along the Mississippi River. This investigation included a geophysical survey, test drilling, an aquifer test, and well design. Papadopulos and Associates, Inc., (1984) conducted an investigation to define ground-water conditions near a naval weapons systems manufacturing facility in Fridley, Minnesota. RMT, Inc. (1987) described multiple sources of ground-water contamination near the same manufacturing facility and stated that contaminated ground water from these sources had migrated to the Mississippi River.

HYDROLOGIC SETTING

During the Pleistocene Epoch, four continental glaciers traversed the metropolitan area and blanketed the bedrock surface with drift (Wright and Ruhe, 1965). Two major ice lobes passed over the area--the Superior lobe from the northeast and the Des Moines lobe from the southwest (fig. 3). The Superior lobe traversed terrain composed largely of Precambrian crystalline rocks, and the Des Moines lobe traversed terrain composed largely of limestone and clay. The deposits laid down by the Superior lobe are generally coarse and more permeable than those laid down by the Des Moines lobe because of differences in source materials.

A thick sequence of sedimentary rocks, ranging in age from Precambrian to Ordovician, were deposited in a north-south trending trough in the Precambrian rock surface. The deepest part of the trough, commonly called the Twin Cities basin, lies almost directly beneath the Twin Cities. The sedimentary rocks in the basin, with the exception of the Hinckley Sandstone (Precambrian in age), were deposited in or marginal to Cambrian and Ordovician seas. The rock record is absent from the middle Ordovician to Quarternary time. The bedrock units and their positions in the geologic column are shown in table 2.

Three major rivers drain the Twin Cities Metropolitan Area (fig. 1). The Mississippi River flows southeastward, diagonally across the central part of the area. The Minnesota River flows northeastward and joins the Mississippi River near the southwest border of St. Paul. The St. Croix River flows southward near the eastern margin of the Metropolitan Area and joins the Mississippi River near Prescott.

Ground Water

Geologic formations, or parts of formations, are considered to be aquifers if they contain sufficient saturated permeable material to yield water to wells or springs. Aquifers have either one or both of two types of permeability--primary (intergranular porosity) or secondary (solution-cavity and fracture permeability). Permeability depends on the interconnection of pores by passageways of capillary and supercapillary size. A fine-grained deposit, such as silt or clay, may have a high porosity and contain a large volume of water when saturated, but the interstices are so small that most of the water is held by molecular attraction and yields to wells are small. Sand and gravel aquifers transmit water freely and commonly yield large amounts of water to wells.

Ground water is under unconfined (water-table) or confined conditions. Ground water in contact with the atmosphere through the unsaturated zone immediately below the land surface is under water-table conditions and is unconfined. Under confined conditions, the aquifer is overlain by a confining layer of lesser permeability; water in the aquifer is under sufficient pressure to rise above the base of the confining unit in a well or open hole.

Two bedrock aquifers, two aquifers in glacial drift, and four confining units underlying the study area are discussed in this report. The bedrock aquifers are, in descending order, the St. Peter and the Prairie du Chien-Jordan. Unconfined-drift and confined-drift aquifers overlie the bedrock aquifers. The sequence of bedrock hydrogeologic units underlying the study area is illustrated in figure 4. The hydrogeologic units underlying the St. Lawrence-Franconia confining unit are not discussed in this report.

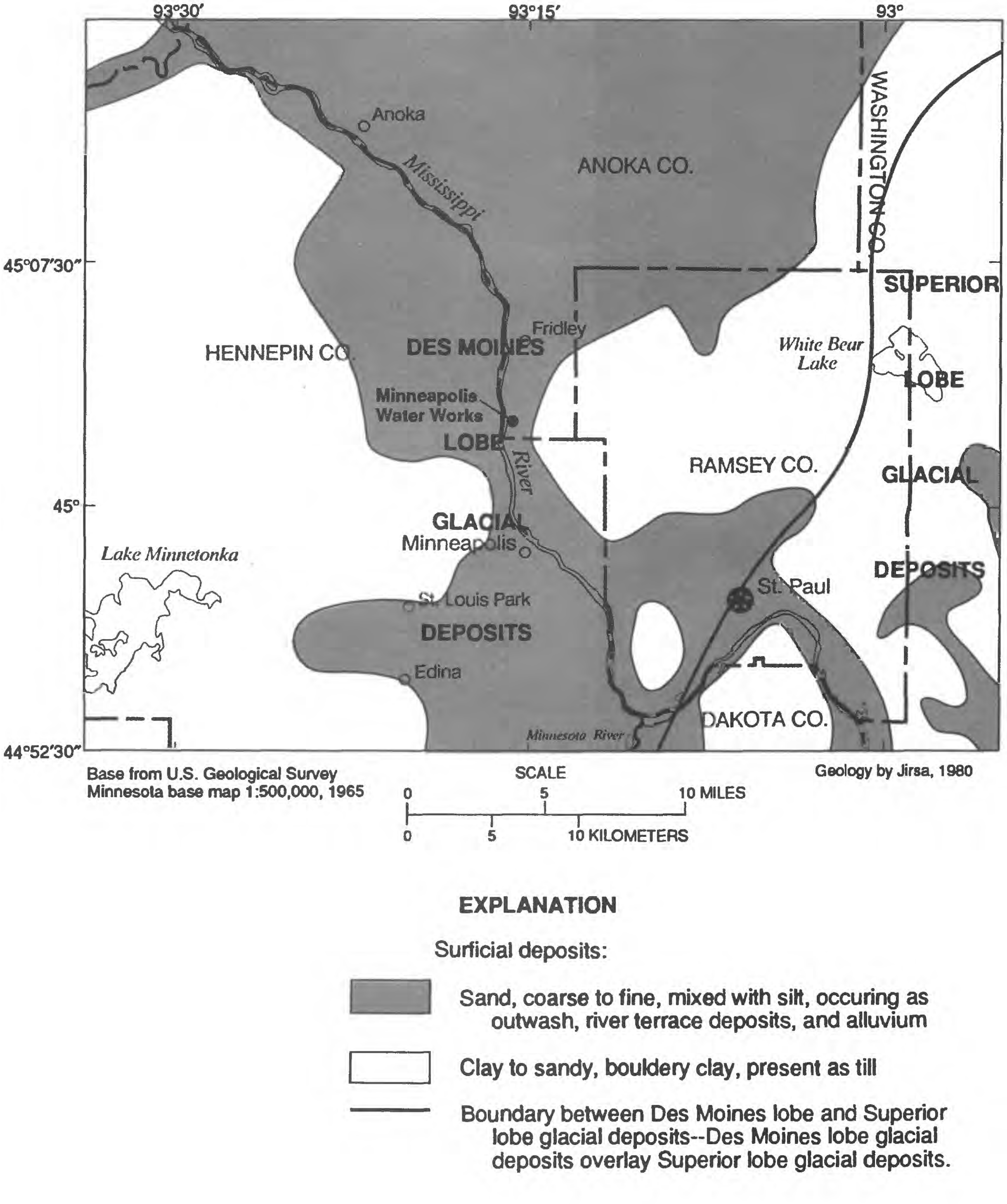


Figure 3.--Surficial deposits in the study area.

Table 2.--*Geologic and water-bearing*

System	Geologic Unit	Approximate range in thickness (feet)	Description
Quaternary	Glacial drift	20-300	Undifferentiated over most of the study area. Till, outwash and valley train sand and gravel, lake deposits, and alluvium; vertical and horizontal distribution of units are complex.
Ordovician	Decorah Shale	0-95	Shale, bluish-green to bluish-gray, blocky. Locally present in southern part of study area.
	Platteville Formation	0-35	Dolomitic limestone and dolomite, gray to buff, thin to medium bedded, some shale partings, contains sand and gravel of glacial origin. Solution channels and fractures are concentrated in upper part. Locally present in the southern part of study area. Dissected by erosion.
	Glenwood Shale	0-18	Shale and claystone, green to buff, plastic to slightly fissile, lower 3 to 5 feet grade from claystone with disseminated sand grains to sandstone with clay matrix. Locally present in southern part of study area. Dissected by erosion.
	St. Peter Sandstone	0-200	Sandstone, white to yellow, very well sorted, fine- to medium-grained poorly cemented, quartzose. Lower 5 to 65 feet consists of siltstone and shale. Generally present over most of the southern one-third of the study area. Locally absent due to erosion.
	Prairie du Chien Group	0-170	Dolomite, sandstone, sandy dolomite, light-brown, buff, gray; thinly to thickly bedded. Absent in northern and western parts of study area. Locally absent due to erosion.
Cambrian	Jordan Sandstone	0-130	Sandstone, white to pink, fine- to coarse-grained, moderately well cemented, quartzose to dolomitic. Absent in northwestern part of study area.
	St. Lawrence and Franconia Formations	150-250	Siltstone and sandstone, gray to green, poorly sorted, glauconitic and dolomitic.

characteristics of hydrogeologic units

Water-bearing characteristics	Hydrogeologic units defined for this study
Distribution of aquifers and confining units within drift are poorly known outside the area of the Minneapolis Water Works. Stratified, well sorted deposits of sand and gravel yield moderate to large supplies of water to to wells (240-2,000 gallons per minute).	Unconfined-drift aquifer Upper drift confining unit Confined-drift aquifer Basal-drift confining unit
Confining unit. Hydraulic characteristics are poorly known.	
Hydraulic conductivity primarily is from fractures, open joints, and solution channels. Specific capacities of wells are generally between 10 and 100 gallons per minute per foot of drawdown, if pumped at about 12 gallons per minute for 1 hour. Results from one aquifer test indicate that the transmissivity of the unit is about 9,000 feet squared per day near the test site.	Decorah-Platteville-Glenwood confining unit
Confining unit. Very low hydraulic conductivity. Vertical hydraulic conductivity based on laboratory measurements of core samples is estimated to be about 10^{-5} foot per day.	
Most wells completed in the sandstone are of small diameter and are used for domestic supply.	St. Peter aquifer
Confining units near the bottom of the Formation separate the sandstone from the underlying Prairie du Chien-Jordan aquifer.	Basal St. Peter confining unit
Generally yields more than 1,000 gallons per minute to high-capacity wells. Hydraulic conductivity is due to fractures, open joints, and solution channels.	Prairie du Chien-Jordan aquifer
Hydraulic conductivity is mostly intergranular but may be due to open joints in cemented zones. Prairie du Chien-Jordan aquifer generally yields more than 1,000 gallons per minute to high-capacity wells. Supplies about 80 percent of ground water pumped in the study area.	Prairie du Chien-Jordan aquifer
Confining unit. Hydraulic characteristics are poorly known.	St. Lawrence-Franconia confining unit

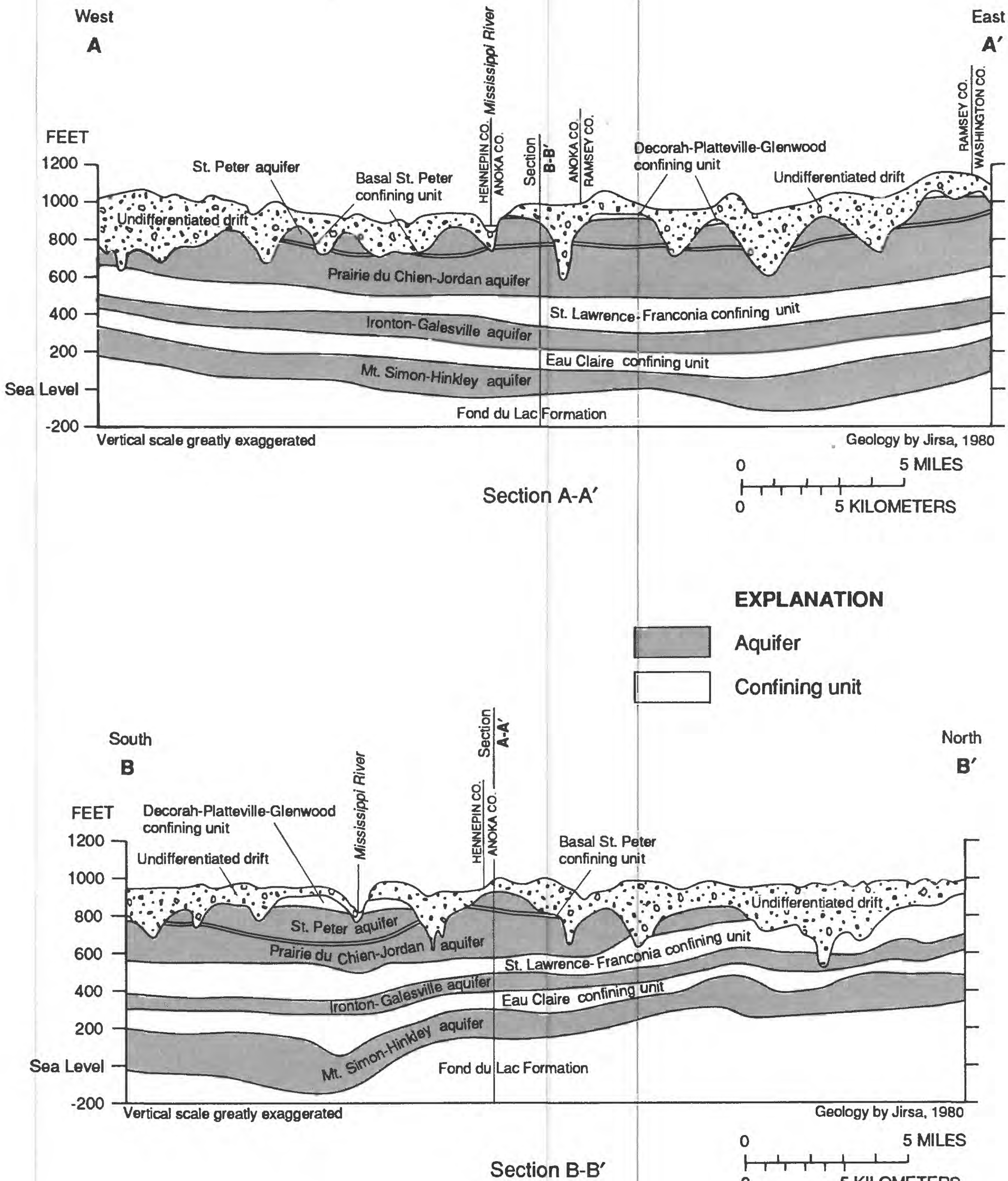


Figure 4.--Hydrogeologic sections traversing the study area (trace of sections shown in figure 2).

Hydrogeologic Units

The entire study area is covered by glacial drift that is as much as 400 ft (feet) thick (fig. 5). Drift material ranges in composition from clay and silt to well sorted deposits of sand and gravel. Types of drift include till, outwash, valley train and lake deposits.

Till is an unsorted, unstratified mixture of clay, silt, sand, gravel, and boulders. Till deposited by the Superior lobe is mostly reddish brown to brown and sandy and gravelly, whereas till deposited by the Des Moines lobe is yellowish brown to gray and clayey.

Deposits of outwash sand and gravel were laid down by meltwaters of the Superior and Des Moines lobes during their advancing and retreating stages. The largest areal deposit of outwash is the Anoka Sand Plain, which extends north from the Twin Cities. The deposit was laid down as a result of the diversion of the Mississippi River from its preglacial or interglacial course to around the front of the Grantsburg sublobe (Farnham, 1956). The sand was deposited upon melting of the ice and movement of the river through the area to its present channel.

Valley train sands and gravels are present along the valleys of the major streams and were deposited when the valleys were filled with glacial meltwater. A succession of terraces were formed along the stream courses down to the level of the present stream development. The city of Minneapolis is built largely on valley train sand and gravel deposited at the confluence of the glacial Mississippi and Minnesota Rivers (Norvitch and others, 1974).

Major aquifers in the glacial drift are composed of valley train deposits in the valleys of the larger streams and surficial and buried outwash deposits. Water in surficial outwash, valley train, and sand-and-gravel alluvial deposits is generally under unconfined conditions. Water in buried outwash deposits within the glacial drift is confined in most places. The permeability of the overlying till is so low compared to that of the outwash that it acts as a confining unit. The distribution of sand-and-gravel deposits and much less permeable clay and silt confining units within the drift is highly variable and complex and is generally not well known in the study area.

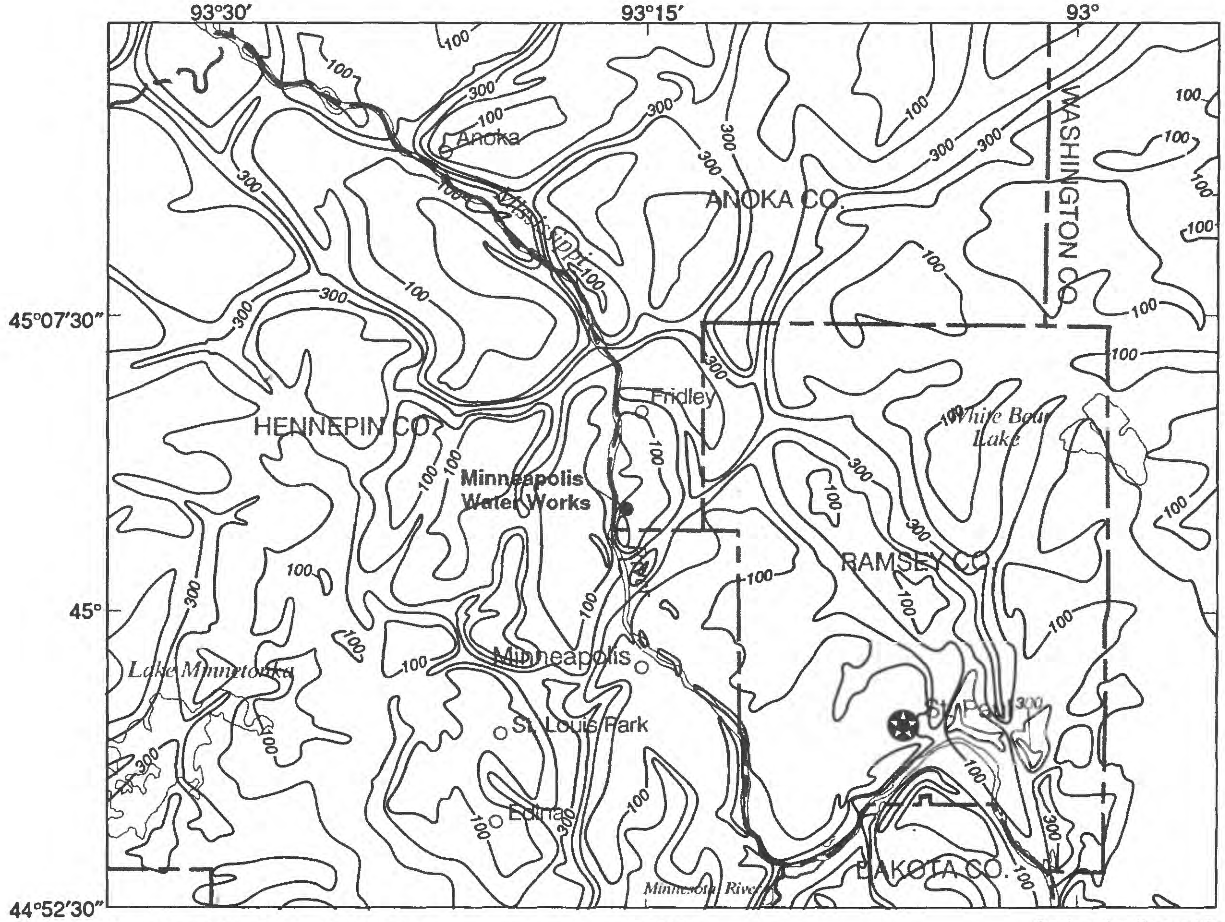
The distribution of sand-and-gravel aquifers and clay-and-silt confining units, as well as underlying bedrock units, near the Minneapolis Water Works (fig. 6) is illustrated by hydrogeologic sections in figures 7 and 8. These sections clearly show the vertically and horizontally complex and heterogeneous distributions of hydrogeologic units. A surficial layer of sand and gravel as much as about 60 ft thick underlies the Mississippi River valley and comprises the unconfined-drift aquifer. Helgesen and Lindholm (1973) report saturated thicknesses ranging from about 0 to 60 ft for the surficial outwash aquifer underlying the Anoka Sand Plain in the northern part of the study area. Relatively impermeable layers of clay, silty clay, sandy clay, or clayey silt may be present at varying depths throughout a vertical section of the drift. A generally continuous layer of silty to sandy clay 20- to 40- ft thick (upper drift confining unit) underlies the surficial sand and gravel (unconfined-drift aquifer) near the Minneapolis Water Works. North of the Minneapolis Water Works the upper drift confining unit becomes a sandy silt with less clay and higher vertical hydraulic conductivity.

Drillers' logs indicate that the upper drift confining unit is absent at some locations, as shown by the hydrogeologic sections in figures 7 and 8. A confined-drift aquifer ranging in composition from silty sand to coarse sand and gravel underlies the Minneapolis Water Works within a buried preglacial valley. The confined-drift aquifer is up to 120-ft thick. A continuous sequence of sand and gravel may extend from land surface to the bedrock surface where the upper drift confining unit is absent.

Estimates of hydraulic conductivity and storage properties of the drift aquifers in the Twin Cities Metropolitan Area exhibit a range in values and are limited to only a few actual aquifer tests. Estimates of horizontal hydraulic conductivity range from about 50 to 200 ft/d (feet per day). Estimates of vertical hydraulic conductivity of drift confining units range from about 0.2 to 0.00004 ft/d. Ranney Company (1978), which conducted an aquifer test at the Minneapolis Water Works, reported ranges of transmissivity and storage coefficients for the lower (confined) zone and the total thickness of the drift aquifer (table 3). Norris (1962) listed values of vertical hydraulic conductivity of glacial till in South Dakota (table 3). Norvitch and others (1974) suggested that these vertical hydraulic conductivities were probably comparable to those of the till deposited by the Des Moines lobe in the study area. Norvitch and others (1974) also suggested that vertical hydraulic conductivities ranging from 0.01 to 0.2 ft/d for drift with considerable sand and gravel in Illinois (Walton, 1965) were probably comparable to vertical hydraulic conductivities of the outwash, valley train, valley fill, and alluvial deposits in the study area.

The drift is underlain by the St. Peter aquifer and (or) the Prairie du Chien-Jordan aquifer in the northern and central parts of the study area and by the Decorah-Platteville-Glenwood confining unit in the southern part. The thickness of the Decorah-Platteville-Glenwood confining unit ranges from zero in bedrock valleys to about 150 ft east of the Mississippi River (fig. 9). This confining unit hydraulically impedes the downward flow of water between the drift and the underlying St. Peter aquifer. The vertical hydraulic conductivity of the Glenwood Shale is very low, about 10^{-5} ft/d based on laboratory measurements of core samples (Stark and Hult, 1985).

The St. Peter aquifer is composed of a white to yellow, fine- to medium-grained, well sorted, friable sandstone. The thickness of the St. Peter aquifer in the study area ranges from zero ft in bedrock valleys to about 150 ft (fig. 10). The base of the St. Peter Sandstone consists of 5 to 65 ft of siltstone and shale. This low-permeability bed at the base of the St. Peter Sandstone, where present, acts as a confining unit and separates the St. Peter aquifer from the underlying Prairie du Chien-Jordan aquifer. In the northern part of the study area, however, the basal St. Peter confining unit is discontinuous; the physical extent of these discontinuities is poorly known. Reported values for hydraulic properties of the St. Peter aquifer are listed in table 3. Horizontal hydraulic conductivities for the St. Peter aquifer are relatively uniform in the study area, ranging from about 5 to 25 ft/d, because of the relatively uniform composition and generally friable nature of the aquifer material. Norvitch and others (1974) report that the vertical hydraulic conductivity of the basal St. Peter confining unit is as low as 4.0×10^{-6} ft/d. The effectiveness of the basal St. Peter confining unit in impeding the vertical leakage of water, however, is reduced by the discontinuous nature of the basal unit in much of the study area.



Base from U.S. Geological Survey
Minnesota base map 1:500,000, 1965

SCALE
0 5 10 MILES
0 5 10 KILOMETERS

Geology by Jirsa, 1980

EXPLANATION

—300— Line of equal thickness of glacial drift--
Interval 100 feet

Figure 5.--Thickness of the glacial drift.

EXPLANATION

E|——|E' Trace of hydrogeologic section

——— Boundary of bedrock valley--Dashed where approximate.

FMC32 • Observation well and short name

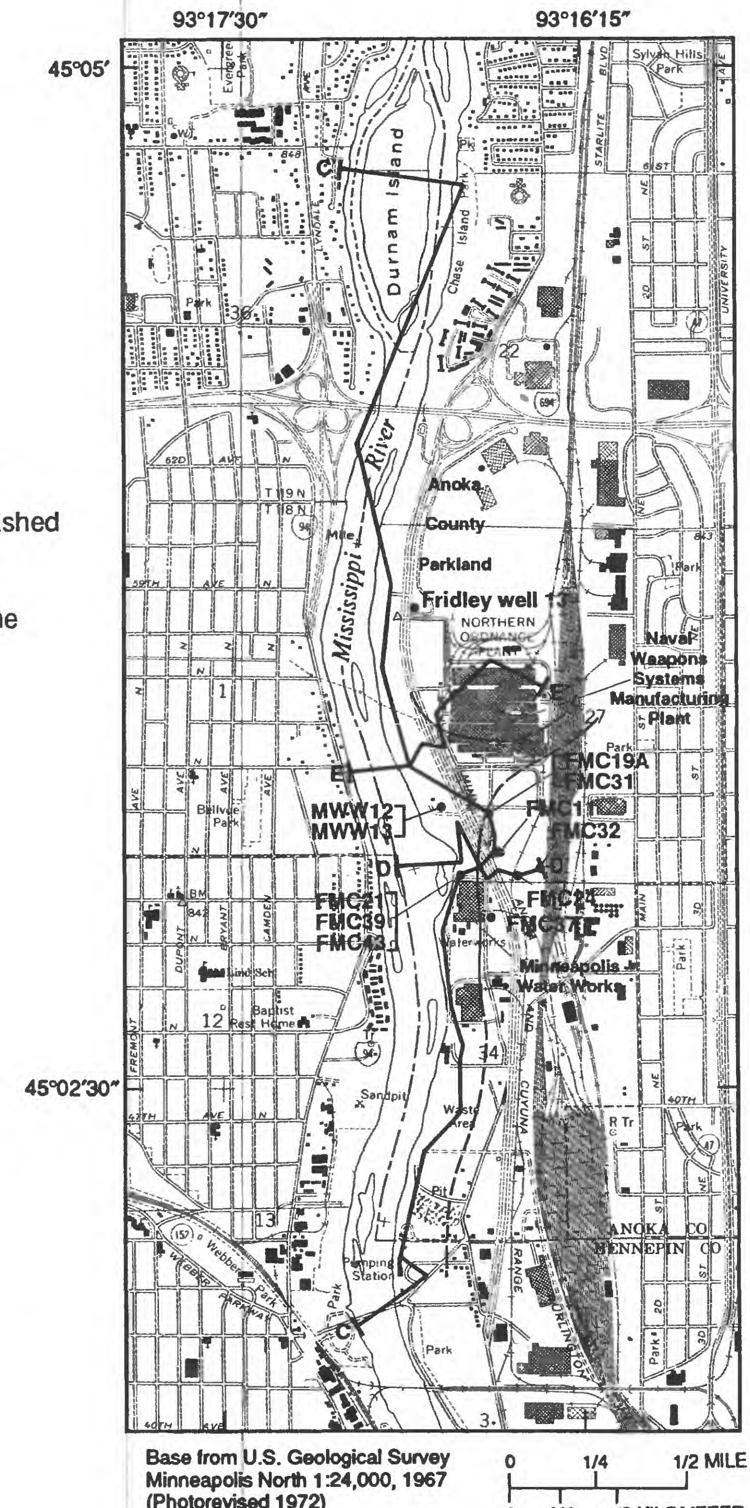


Figure 6.--Trace of hydrogeologic sections near the Minneapolis Water Works and locations of observation wells and bedrock valley.

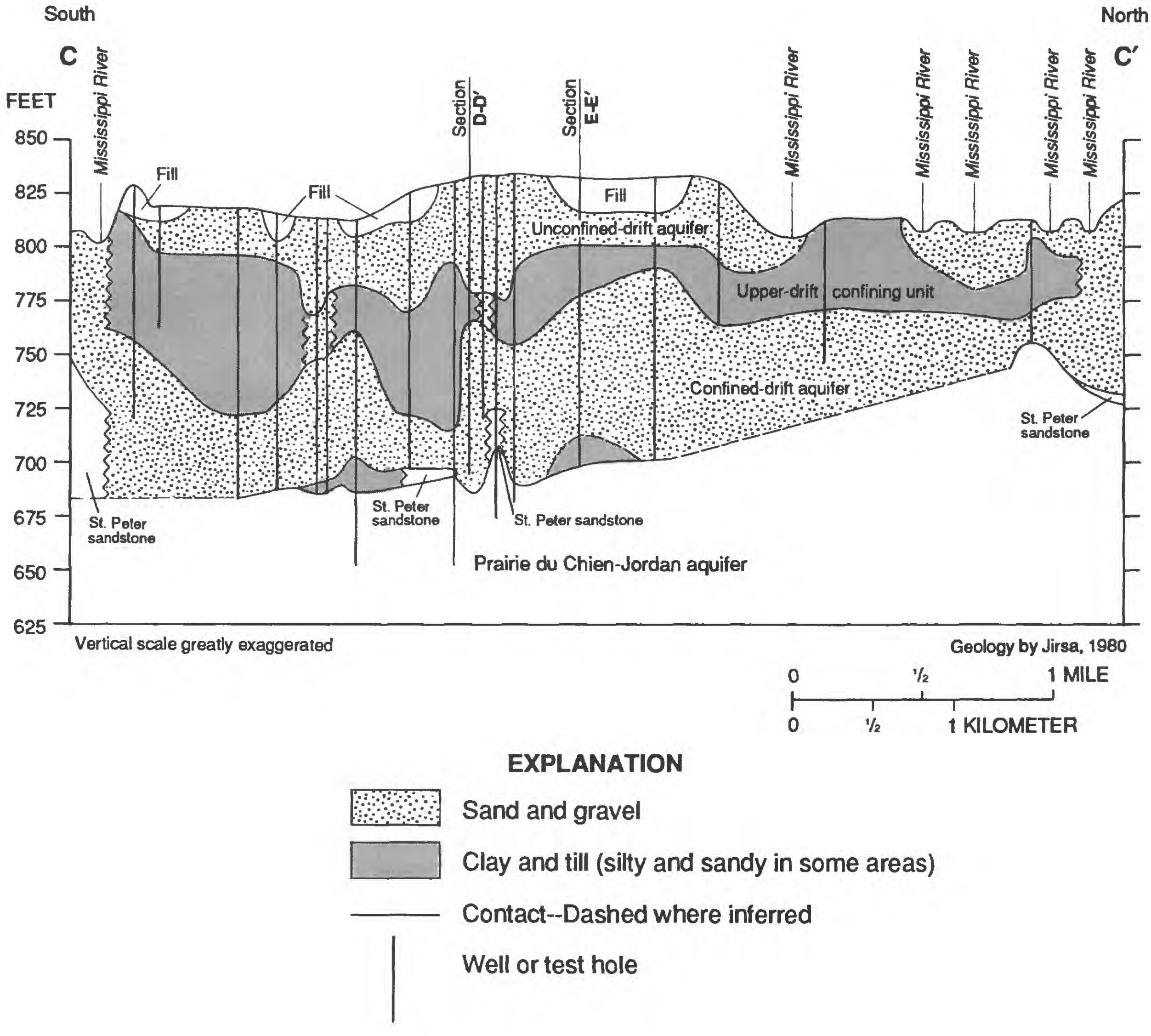


Figure 7.--South-to-north hydrogeologic section near the Minneapolis Water Works (trace of section shown in figure 6).

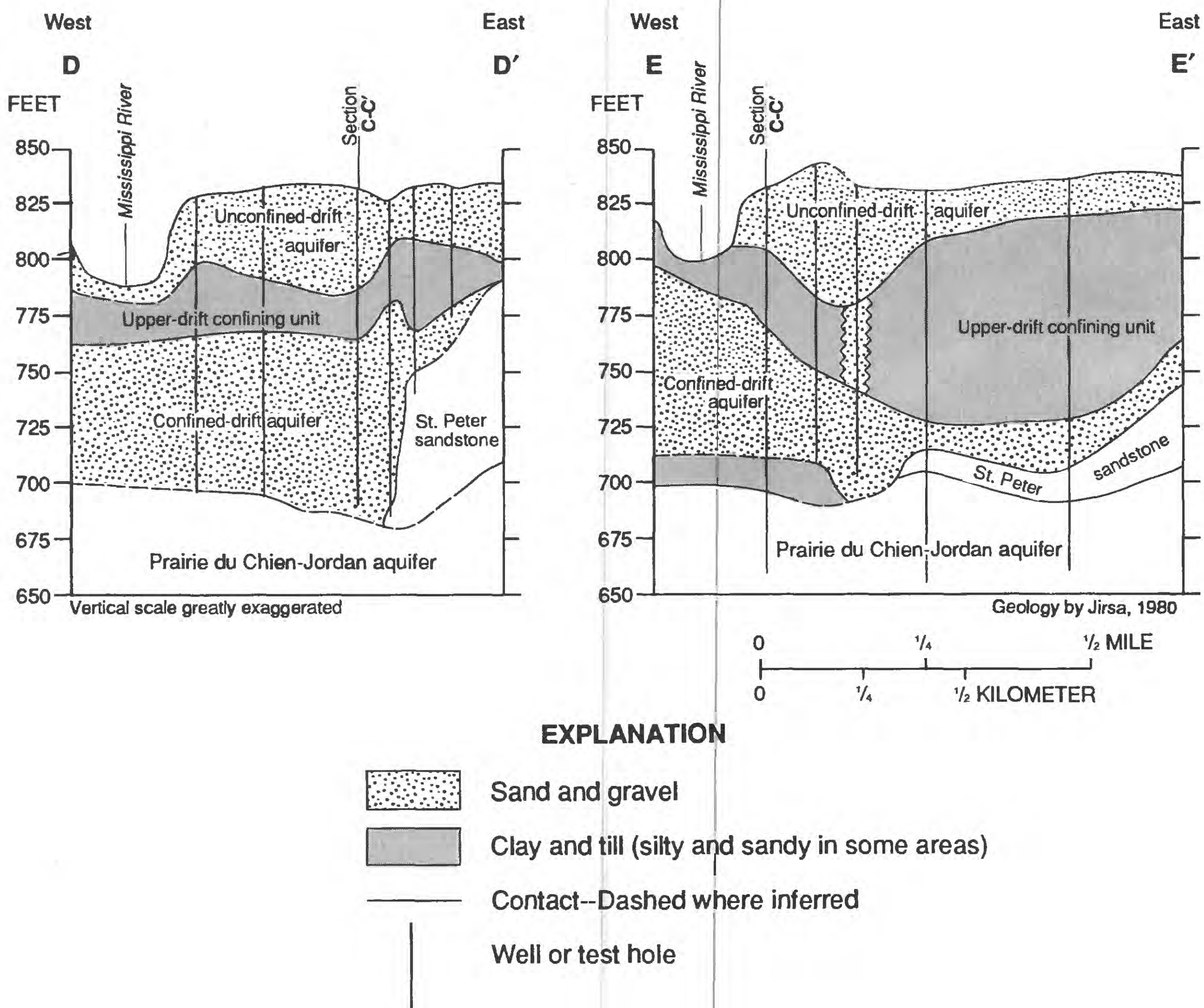
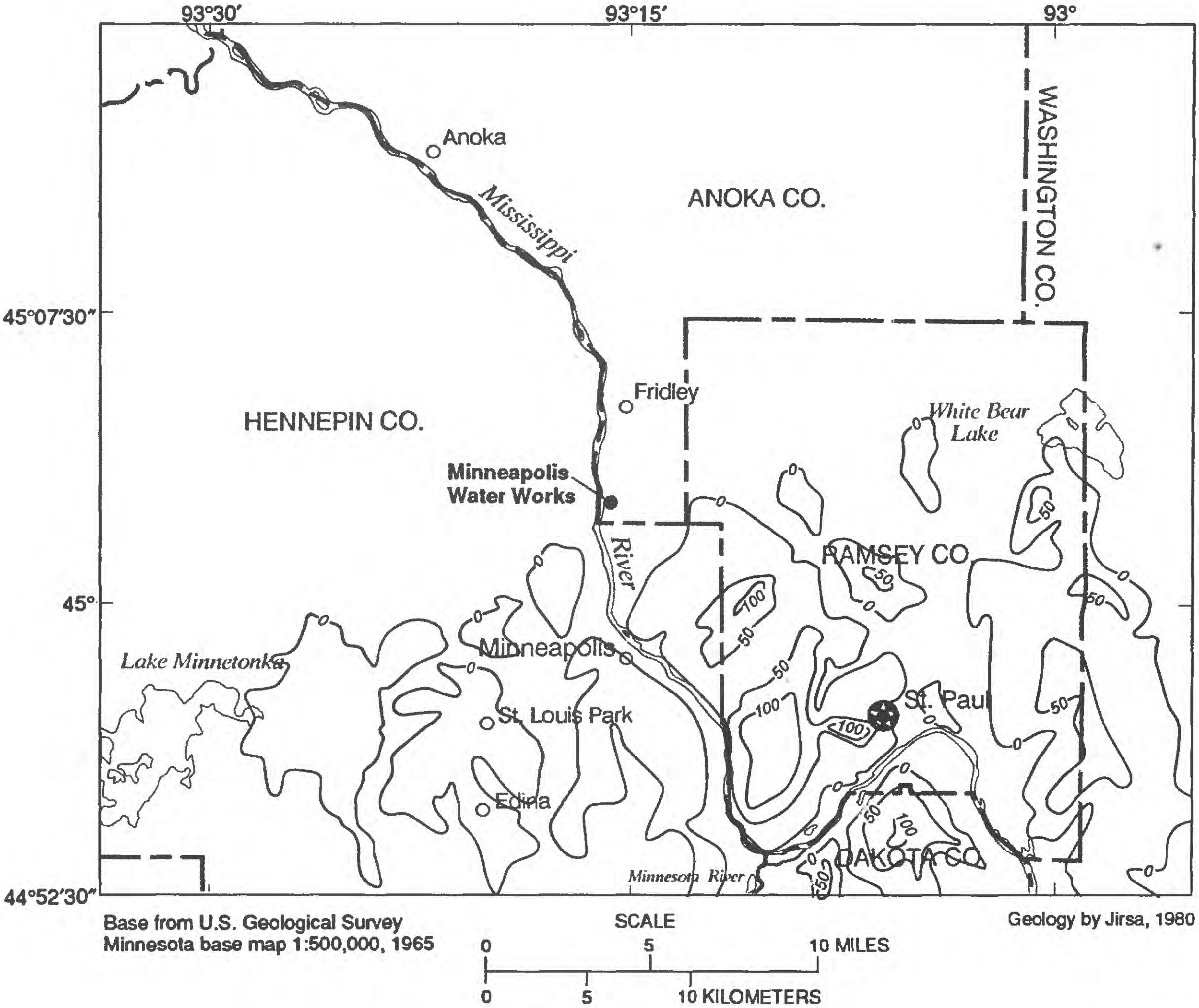


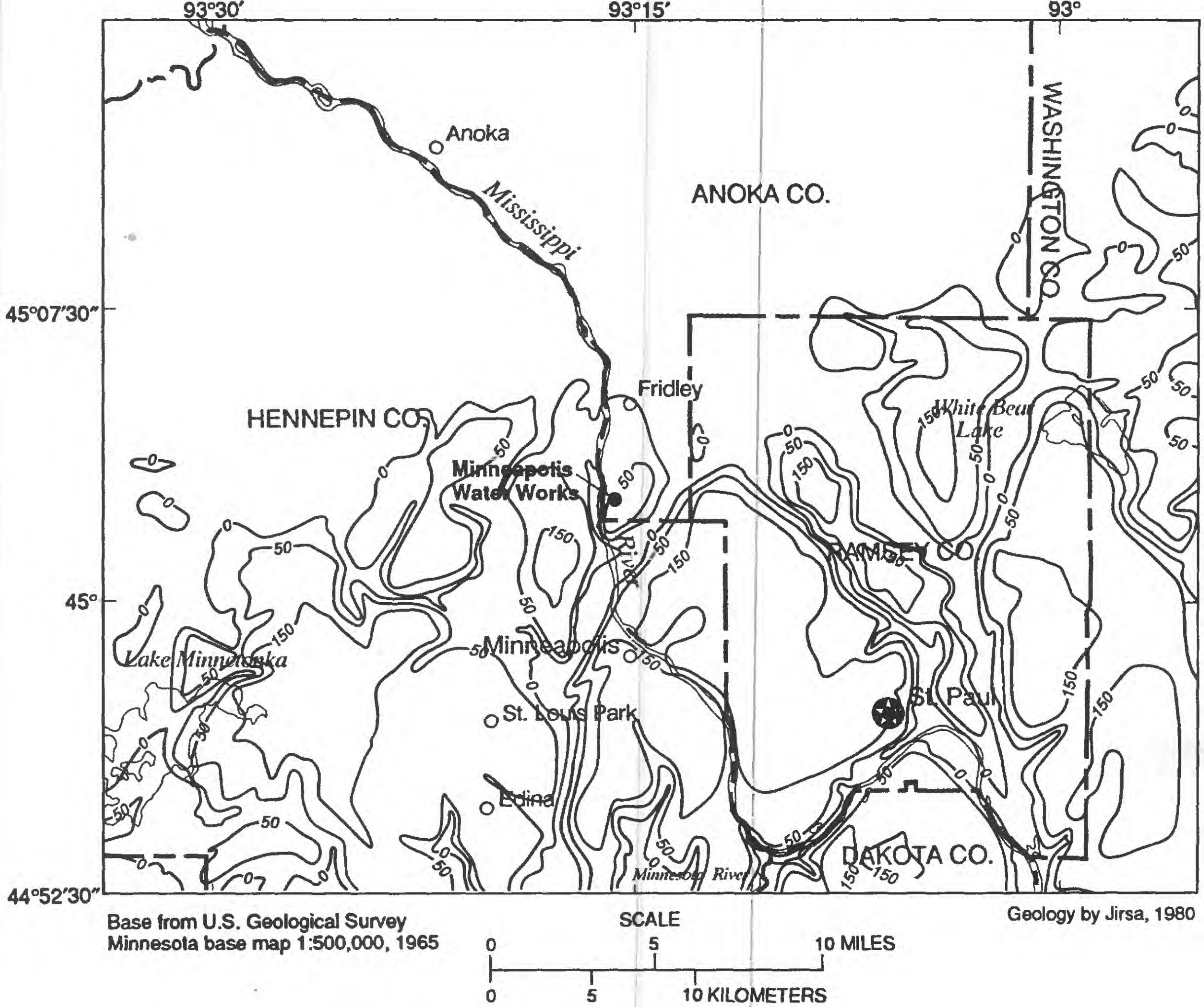
Figure 8.--West-to-east hydrogeologic sections near the Minneapolis Water Works (trace of sections shown in figure 6).



EXPLANATION

—100— Line of equal thickness of the Decorah-Platteville-Glenwood confining unit --Interval 50 feet.

Figure 9.--Thickness of the Decorah-Platteville-Glenwood confining unit.



EXPLANATION

—150— Line of equal thickness of the St. Peter aquifer--Interval variable, in feet.

Figure 10.--Thickness of the St. Peter aquifer.

Table 3.--*Reported values for hydraulic properties of hydrogeologic units*

[ft/d, feet per day; ft^2/d, feet squared per day. Sources: (a), Helgesen and Lindholm (1973); (b), Ranney Company (1978); (c), Norris (1962); (d), Walton (1965); (e), Norvitch and others (1974); (f), Meyer (1933); (g), Stark and Hult (1985). Numbers in parentheses are median (i.e. m12.5) or average values (i.e. a6830). - -, none reported.]

Hydrogeologic unit	Aquifer thickness (feet)	Horizontal hydraulic conductivity (ft/d)	Transmissivity (ft^2/d)	Storage coefficient	Vertical hydraulic conductivity (ft/d)
Unconfined-drift aquifer	(a) 0-60	(a) 50-200	--	(a) 0.25	--
Confined-drift aquifer	(b) 25-65	(b) 60-115	(b) 2,735-6,600	--	--
Drift aquifer, undifferentiated	(b) 60-115	(b) 65-135	(b) 7,200-9,000	(b) $3.7X10^{-4}$-$1.3X10^{-3}$	--
Drift confining units	--	--	--	--	(c) $4.0X10^{-5}$-$6.7X10^{-2}$ (a$9.4X10^{-3}$) (d) $6.7X10^{-4}$-.2
St. Peter aquifer	--	(e) .16-26.9 (m12.5)	--	(g) 1.0×10^{-4}	--
Basal St. Peter confining unit	--	--	--	--	(e) $4.0X10^{-6}$
Prairie du Chien aquifer	(e) 145-150	(e) 40-50	(e) 6,255-7,355 (a6,830)	(e) $1.1X10^{-5}$-$3.4X10^{-4}$ (a$1.3X10^{-4}$)	--
Jordan aquifer	(e) 30-100	(e) 4.6-166.0 (a70) (f) 50	(e) 1,900-10,700 (a5,880)	(e) $4.9X10^{-5}$-$1.2X10^{-4}$ (a$7.2X10^{-5}$)	--
Prairie du Chien-Jordan aquifer	(e) 120-275	(e) 25-210 (a55)	(e) 4,975-26,470 (a11,060)	(e) $4.8X10^{-5}$-$6.5X10^{-4}$ (a$4.0X10^{-4}$)	--

The surface of the St. Peter Sandstone was highly dissected by erosion before the deposition of the overlying glacial drift and recent alluvial deposits. Within the Mississippi River valley, the St. Peter aquifer and basal St. Peter confining unit are completely eroded away in places. The St. Peter aquifer and basal St. Peter confining unit are also absent in the bedrock valley traversing the Minneapolis Water Works property.

The St. Peter aquifer is confined where it is fully saturated and overlain by the Glenwood Shale. Where overlain by and in hydraulic connection with unconfined sand-and-gravel aquifers in the glacial drift or where not fully saturated, the St. Peter aquifer is unconfined. Differences in altitude between the confined potentiometric surface and the water-table surface in the St. Peter aquifer are not great, however, and the two surfaces may be treated as one for most purposes.

The Prairie du Chien Group consists of the Shakopee and Oneota Dolomites. The Shakopee Dolomite is much less dolomitic than the Oneota. The basal beds of the Shakopee are sandy, and the succeeding layers are thin-bedded in many places. Much of the formation is a massive, drab, dolomitic limestone with cavities filled with white calcite. The Oneota Dolomite is thick-bedded, drab to buff, in places pink, and may be sandy or shaley. The upper part may be cherty, and in many locations it is porous to cavernous. The Prairie du Chien Group is overlain by the St. Peter aquifer or the basal St. Peter confining unit or by glacial drift where the St. Peter aquifer and basal St. Peter confining unit have been removed by erosion.

The Jordan Sandstone, which underlies the Prairie du Chien Group, is a white to yellowish-white, loosely to moderately well-cemented, fine- to coarse-grained, quartz-rich sandstone, grading from fine-grained at its base to coarse-grained in its upper parts.

The Jordan Sandstone is underlain by the St. Lawrence Formation, which consists of dolomitic siltstone and fine-grained dolomitic sandstone that is glauconitic in part. The St. Lawrence Formation is underlain by the Franconia Sandstone. The Franconia Sandstone is a very fine-grained, orange to buff, moderately to highly glauconitic sandstone containing interbedded, very fine-grained silty sandstone and shale. The St. Lawrence Formation and Franconia Sandstone form a regional confining unit beneath the Prairie du Chien-Jordan aquifer. The hydrogeologic units lying stratigraphically below the St. Lawrence-Franconia confining unit are thought to be in poor hydraulic connection with overlying units (Stark and Hult, 1985).

Permeability in the Prairie du Chien aquifer is predominantly due to secondary (solution-cavity and fracture) permeability. Permeability in the Jordan (sandstone) aquifer is predominantly due to intergranular porosity. The Jordan aquifer may also have secondary permeability because it is partially cemented and, therefore, may be fractured and jointed. The Prairie du Chien has a lower effective porosity (about 6 percent compared to 32 percent for the Jordan) and more variability in hydraulic properties, including permeability, than the Jordan (Norvitch and others, 1974).

The Prairie du Chien Group and Jordan Sandstone are defined as a single aquifer unit because the hydraulic connection between the two units is good and production wells commonly are open to both units. Locally, confining units of small areal extent between the Prairie du Chien and Jordan strata may cause small differences in static water levels in wells completed in the two strata in the same general location. Pumping from one stratum, however, will affect the water level in the other to the extent that, for all practical purposes, the two strata can be considered a single hydrogeologic unit.

Within the study area, the Prairie du Chien-Jordan aquifer ranges in thickness from zero ft, where the units have been removed by glacial or preglacial erosion, to about 250 ft (fig. 11). The Prairie du Chien-Jordan aquifer underlying the Minneapolis Water Works is about 130 ft thick. Reported values for hydraulic properties of the Prairie du Chien-Jordan aquifer are listed in table 3. Estimates of horizontal hydraulic conductivity for the Prairie du Chien-Jordan aquifer exhibit a wide range of values, from 25 to 210 ft/d, averaging 55 ft/d. The distribution of spatial variability in hydraulic conductivities and storage properties in the aquifer are poorly known.

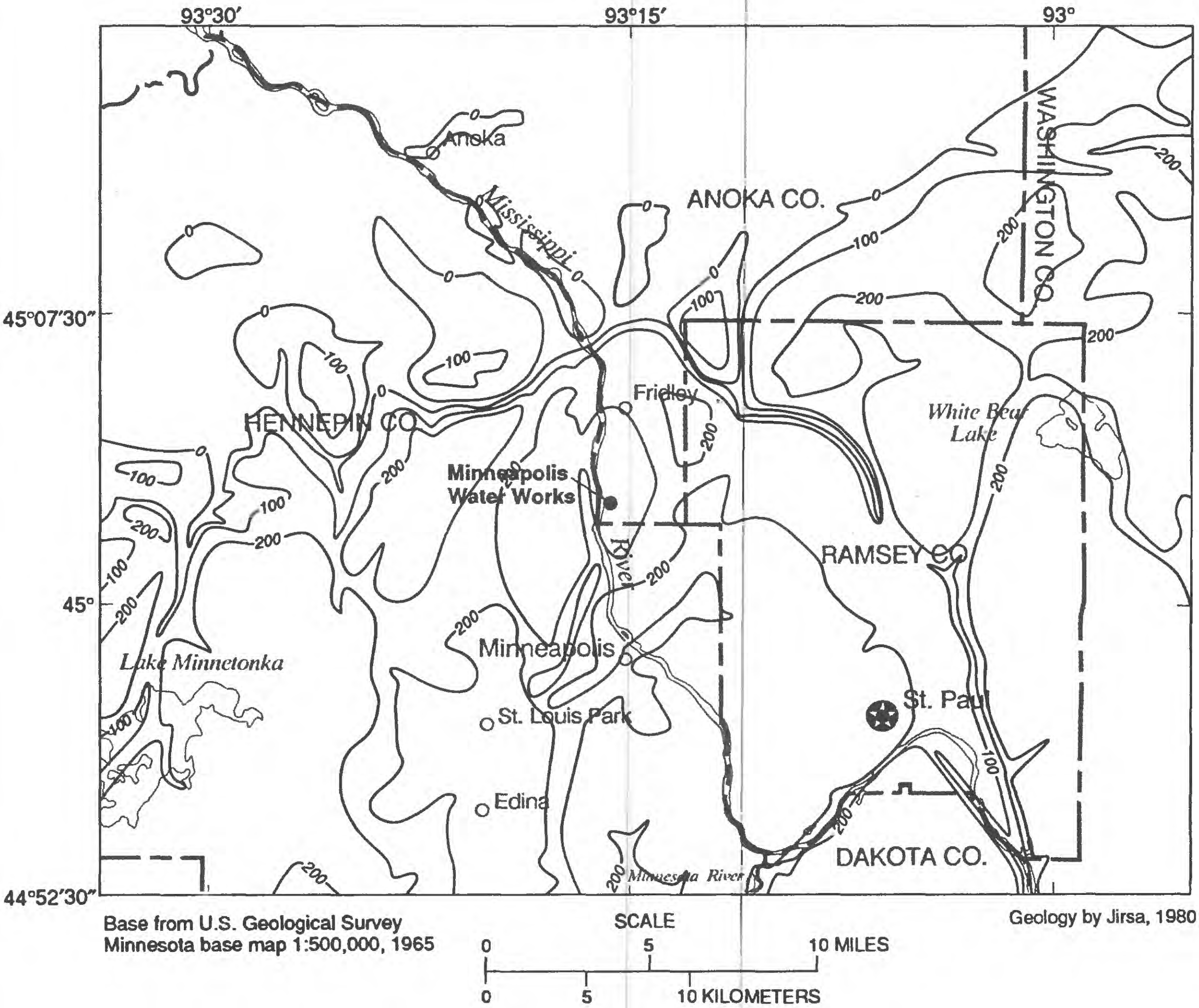
The Prairie du Chien-Jordan aquifer is confined in the study area. The aquifer is unconfined to the east of the study area near the St. Croix River (fig. 1).

The bedrock surface in the study area is dissected by deep valleys that were formed either from the middle Ordovician to the Quaternary Periods (when the rock record is absent) or during the interglacial periods. The bedrock surface was further dissected by streams tunneling beneath the glacial ice (Lindholm and others, 1972). Bedrock valleys substantially affect the hydraulic continuity between the bedrock aquifers and the overlying glacial drift and between the bedrock aquifers and the Mississippi, Minnesota, and St. Croix Rivers.

In the buried bedrock valley underlying the Minneapolis Water Works site, the St. Peter aquifer and the basal St. Peter confining unit are absent and there is a direct hydraulic connection between the Prairie du Chien-Jordan aquifer and the overlying drift valley fill. In places where the sand and gravel of the confined-drift aquifer directly overlies the Prairie du Chien-Jordan aquifer, water can flow relatively unimpeded between the two aquifers. At other places within the bedrock valley, lower permeability material, including sandy silt and clay, acts as a basal-drift confining unit separating the Prairie du Chien-Jordan aquifer from the overlying confined-drift aquifer.

Ground-Water Flow

Recharge to the drift aquifers is mainly from precipitation that percolates down to the saturated zone. Recharge to surficial drift aquifers in the river valleys also occurs during periods of high river stage, such as spring snowmelt. In areas where hydraulic heads in the bedrock aquifers are higher than hydraulic heads in the drift aquifers, the drift aquifers receive leakage from the underlying bedrock aquifers. This occurs in areas near the major rivers which are the regional discharge points for the bedrock aquifers; here, the vertical hydraulic gradients are upward.



EXPLANATION

—100— Line of equal thickness of the Prairie du Chien-Jordan aquifer--Interval 100 feet

Figure 11.--Thickness of the Prairie du Chien-Jordan aquifer.

Induced recharge occurs where wells, pumped in an aquifer adjacent to and in hydraulic connection with a stream, cause a decline in hydraulic head in the aquifer to below the water surface of the stream. Water that, under unstressed conditions, would discharge to the stream and flow out of the area is induced to flow toward the pumping wells (Heath, 1983). A delayed form of induced recharge also may occur if pumping of wells in the Prairie du Chien-Jordan aquifer induces flow from the overlying sediments by lowering the hydraulic head in the Prairie du Chien-Jordan aquifer below that in the drift aquifers. The water removed from storage in the drift aquifers is then replaced with water from the stream if hydraulic head in the drift aquifers has been drawn down below river stage. The time in which replacement (recharge) occurs depends upon the hydraulic properties of the drift and the distance between the stream channel and the point of withdrawal. If substantial pumpage occurs in an area where natural discharge is to a stream, the hydraulic gradient toward the stream is diminished and ground-water discharge to the stream, therefore, is lessened, even if flow from the stream to the aquifer does not occur. In summary, induced recharge caused by ground-water withdrawals results in the capture by wells of (1) surface water that would ordinarily flow out of the area during seasons of low pumpage, and (2) ground water that, under unstressed conditions, would discharge to the streams. It may also reduce the amount of ground-water evapotranspiration from plants that use water from the capillary fringe of the water table.

Water from the surficial-drift aquifers discharges naturally through springs, seeps, and directly into streams, lakes, ponds, and wetlands. Where the water table is at or near the land surface, such as in swampy areas, or where the water table is above the root zone or within reach of roots through capillary attraction, ground water discharges by direct evaporation from the water table and by transpiration from vegetation. Water also discharges from the drift aquifers through pumped wells and, in the Twin Cities Metropolitan Area, through drainage ditches, sewers, and storm drains that are deep enough to penetrate the water table. The drift aquifers are not extensively used as a source of water in the Metropolitan Area. During 1961-79, only about 6 percent of the ground water withdrawn by wells in the seven-county Metropolitan Area came from the drift aquifers (Horn, 1983). Leakage from both the unconfined-drift and confined-drift aquifers occurs by downward percolation into the underlying aquifers.

The stratigraphy of the drift is so complex and variable that a regional map of its potentiometric surface cannot be made because of a lack of data. For the unconfined-drift aquifer, however, the water table is generally a subdued reflection of the surface topography; therefore, the direction of ground-water flow is similar to that of the present-day drainage, and surface-drainage divides roughly coincide with ground-water divides.

Ground-water flow in the unconfined-drift and confined-drift aquifers near the Minneapolis Water Works is generally to the west toward the Mississippi River with horizontal hydraulic gradients that range from about 0.0005 to 0.01. A broad "valley" in the water table north of the Minneapolis Water Works corresponds to a deposit of clean sand that extends from the land surface down to the bedrock surface. Lower water levels near and in this "valley" may be caused by higher hydraulic gradients in the surrounding less permeable silty sands and ground-water flow into the area of the clean sand.

Ground water has a vertical as well as a lateral (horizontal) component of flow. Generally, water moves vertically down through the aquifer system in recharge areas and vertically up in discharge areas. Clusters of wells screened at different depths in the drift aquifers outside the buried bedrock valley underlying the Minneapolis Water Works indicate, for the most part, a decrease in hydraulic head with depth below land surface, which suggests a downward component of flow. Differences in hydraulic head at differing depths within the drift aquifers are generally small--less than 0.05 ft. Near the Mississippi River and within the buried bedrock valley underlying the Minneapolis Water Works, however, a strong upward component of ground-water flow is indicated by an increase in hydraulic head with depth below land surface. Hydraulic head in U.S. Geological Survey observation well MWW12 (fig. 6) at a screened depth of 56- to 60-ft below land surface, is 2.5- to 3.0-ft higher than that in well MWW13 (fig. 6) at a screened depth of 27- to-30 ft below land surface. The upward vertical component of flow is present because the Mississippi River is the regional discharge point for the Prairie du Chien-Jordan and overlying aquifers and because the present channel of the Mississippi River coincides with a buried preglacial valley.

Most recharge to the St. Peter aquifer in the study area is from downward leakage of ground water from saturated, overlying drift. Sources of water to the St. Peter aquifer also include downward leakage of water from the Platteville Formation in areas where the Platteville Formation is present. Leakage to the St. Peter aquifer from overlying deposits depends on the vertical hydraulic conductivity of the overlying deposits, the saturated thickness of the deposits, and the hydraulic-head difference between the water table and the potentiometric surface of the St. Peter aquifer. Some direct recharge occurs where the St. Peter aquifer is exposed at land surface. Norvitch and others (1974) estimated that about 450 mi^2 (square miles) of the St. Peter aquifer in the metropolitan area is in direct contact with the drift, whereas 200 mi^2 is overlain by the Platteville Limestone.

The regional ground-water discharge areas for the St. Peter aquifer, as for the other bedrock aquifers in the Metropolitan Area, are the three major rivers (Mississippi, Minnesota, and St. Croix) and their floodplains (fig. 1). Water moves up into the valley fill and subsequently into the rivers. In areas outside the major river floodplains, water moves down from the St. Peter aquifer to the underlying Prairie du Chien-Jordan aquifer. The St. Peter aquifer may be capable of transmitting large amounts of water to the underlying Prairie du Chien-Jordan aquifer, but the amount of water transmitted between the bedrock aquifers depends mostly on the vertical hydraulic conductivity of the intervening basal St. Peter confining unit. Where the St. Peter aquifer and the basal St. Peter confining unit, at its base, are dissected by erosional bedrock valleys, however, the rate of water movement between the aquifers depends on the characteristics of the much more permeable valley fill.

Water also discharges from the St. Peter aquifer through pumped wells. The St. Peter aquifer is not extensively used as a source of water in the Metropolitan Area. About 1 percent of the ground water withdrawn by wells in the Metropolitan Area during 1961-79 came from the St. Peter aquifer (Horn, 1983).

Recharge to the Prairie du Chien-Jordan aquifer occurs from downward leakage of ground water from saturated overlying drift in buried bedrock valleys and in the northern and western parts of the study area. The extent of the Prairie du Chien-Jordan aquifer subcrop in direct contact with the drift in the Metropolitan Area is about 1,350 mi^2 (Norvitch and others, 1974). Sources of water to the Prairie du Chien-Jordan aquifer in the study area also include downward leakage of ground water from the overlying St. Peter aquifer. Estimates of leakage to the Prairie du Chien-Jordan aquifer from overlying deposits ranges from 0 to about 6 in/yr (inches per year) for most of the Twin Cities Metropolitan Area (Larson-Higdem and others 1975). Estimates of 6 to about 12 in/yr coincide with areas where the Prairie du Chien-Jordan aquifer is directly overlain by the most permeable glacial drift, including the Anoka Sand-Plain deposits. Leakage rates to the Prairie du Chien-Jordan aquifer were calculated based on the vertical hydraulic conductivity of the overlying deposits, the saturated thickness of the deposits, and the hydraulic head difference between the water table and the potentiometric surface of the Prairie du Chien-Jordan aquifer, assuming steady-state conditions (Larson-Higdem and others, 1975). An attempt was also made to determine increased leakage to the Prairie du Chien-Jordan aquifer under nonsteady-state conditions because of increased summer ground-water withdrawals. Estimates of additional leakage range from 0 to about 1.5 in/yr for most of the Twin Cities Metropolitan Area, but are as great as about 6 in/yr in areas with large ground-water withdrawals and where sands and gravels are present at the land surface, overlying subcrop areas of the Prairie du Chien-Jordan aquifer (Larson-Higdem and others, 1975). Lake Minnetonka, in the southwestern part of the study area, is a natural recharge area to the Prairie du Chien-Jordan and overlying aquifers; water leaks down through the intervening drift and bedrock strata.

The regional ground-water discharge areas for the Prairie du Chien-Jordan aquifer are the three major rivers (Mississippi, Minnesota, and St. Croix) and their floodplains (fig. 1). The basin-storage discharge of the three major rivers in the Twin Cities Metropolitan Area [5.24 in/yr according to Norvitch and others (1974)] is mostly outflow from the Prairie du Chien-Jordan aquifer. Water also discharges from the Prairie du Chien-Jordan aquifer through springs and seeps along the valley walls. Although the St. Lawrence and Franconia Formations form an underlying regional confining unit, some vertical movement of water undoubtedly occurs between the Prairie du Chien-Jordan aquifer and the underlying aquifers in some areas.

Water is also discharged from the Prairie du Chien-Jordan aquifer through pumping wells. Horn (1983) reported that about 80 percent of all ground water pumped during 1961-79 in the seven-county metropolitan area was from the Prairie du Chien-Jordan aquifer and that withdrawals averaged about 140 Mgal/d (million gallons per day). Historically, ground-water withdrawals were initially concentrated within downtown Minneapolis and St. Paul; later, withdrawals increased in the suburban areas. During 1980-86, withdrawals within the study area ranged from 66.07 to 85.60 Mgal/d and averaged 76.26 Mgal/d. The percentages of ground-water withdrawals by category of use during 1976-79 for the seven-county metropolitan area were (1) municipal supply, 44 percent, (2) commercial uses (mostly for air conditioning), 10 percent, (3) self-supplied industrial uses, 32 percent, (4) irrigation (mostly for cemeteries and golf courses), 9 percent, and (5) dewatering and lake-level maintenance, 5 percent (Horn, 1983).

The volume of water withdrawn from the Prairie du Chien-Jordan and overlying aquifers by wells varies substantially on a seasonal basis. During 1987, summer withdrawals were about two times the withdrawals for nonsummer months. Increased summer withdrawals for commercial air conditioning and for public-supply uses (lawn watering) are the major cause for seasonal variability.

Regional flow in the St. Peter and Prairie du Chien-Jordan aquifers in the study area is from the White Bear Lake area in the northeast and the Lake Minnetonka area in the southwest, as indicated by their potentiometric surfaces, to the Mississippi River (figs. 12 and 13). Local flow patterns may be very complex and are affected not only by ground-water withdrawals from the St. Peter and Prairie du Chien-Jordan aquifers but also by the presence of buried bedrock valleys that dissect the aquifers. Heavy summer ground-water withdrawals in the downtown areas of Minneapolis and St. Paul and in the western suburbs of Minneapolis, including St. Louis Park and Edina, cause local depressions in the potentiometric surface and the diversion of ground water toward these depressions (fig. 14).

As mentioned previously, the Minneapolis Water Works is underlain by a buried bedrock valley. Water from the St. Peter and Prairie du Chien-Jordan aquifers flowing toward the Mississippi River discharges to the valley fill occupying the bedrock valley and subsequently to the river. In areas adjacent to the bedrock valley, a downward component of flow exists, and water leaks from the St. Peter aquifer to the underlying Prairie du Chien-Jordan aquifer through the basal St. Peter confining unit.

Ground-water flow in the study area may be summarized with the aid of a ground-water budget. For equilibrium conditions, the amount of water entering the aquifer system in the study area equals the amount of water leaving the system and no change in ground-water storage occurs. In equation form, a very generalized budget may be expressed as

$$(P-ET) + BI + RI - RO - GET - BO - WI \pm \Delta S = 0,$$

where P equals precipitation, ET equals evapotranspiration, BI equals ground-water inflow, RI equals leakage from streams to the aquifer system, RO equals discharge from the aquifer system to streams, GET equals ground-water evapotranspiration, BO equals ground-water outflow, WI equals ground-water withdrawals by wells, and ΔS equals the change, if any, in ground-water storage. The plus (+) items in the equation are inflow and the minus (-) items are outflow. The difference between precipitation and evapotranspiration is the amount of water available to the aquifer system as recharge to the water table, about 6.4 in/yr (Norvitch and others, 1974) in the Twin Cities Metropolitan Area. Surface runoff to streams and lakes is negligible compared to precipitation and evapotranspiration. Leakage from streams to the aquifer system is minimal, except locally during periods of heavy ground-water withdrawals and briefly during spring snowmelt and heavy rainfall events. Norvitch and others (1974) estimate that induced recharge from the Mississippi River alluvium and underlying glacial valley fill in the Twin Cities Metropolitan Area supplies about 13 percent, 30.6 Mgal/d, of the total water pumped from the Prairie du Chien-Jordan aquifer during the summer. An unknown percentage of induced recharge is leakage from the Mississippi River. The major discharges or losses from the aquifer system in the study area are leakage from the aquifer system to the Mississippi River and ground-water withdrawals by wells. Norvitch and others (1974) estimate that the discharge from the aquifer system to the three major rivers (Mississippi, Minnesota, and St. Croix) in the Twin Cities Metropolitan Area is about 5.2 in/yr (902 ft^3/s (cubic feet per second)). Ground-water discharge to the Mississippi River in the study area is about 110 ft^3/s. During 1980-86, ground-water withdrawals by wells in the study area averaged about 76 Mgal/d. Ground-water inflow to the study area occurs at the northern, western, and southeastern boundaries. The amount of ground-water inflow is not known. Ground-water outflow from the study area does not occur. Ground-water evapotranspiration in the study area is not known but is considered to be minimal in comparison with the other budget items. The change in storage is zero because no long-term reduction of water in storage has occurred during the 1970's or 1980's, as indicated by the lack of a long-term decline in hydraulic heads. Norvitch and others (1974) and Schoenberg (1984) reported that hydraulic heads in the Prairie du Chien-Jordan aquifer show little, if any, long-term permanent decline from about 1958 to 1980. The aquifer, at its present (1970's and 1980's) level of development, is near equilibrium. In effect, the cone of depression resulting from ground-water withdrawals has reached enough sources of recharge (including captured natural discharge) to supply the amount of water being withdrawn annually by wells. Based on available estimates, the budget equation for the study area becomes

$$\underset{(231.6\ \text{Mgal/d})}{(P-ET)} + \underset{(UN)}{BI} + \underset{(UNM)}{RI} - \underset{(71.1\ \text{Mgal/d})}{RO} - \underset{UNM}{GET}$$

$$- \underset{(0)}{BO} - \underset{(76\ \text{Mgal/d})}{WI} \pm \underset{(0)}{\Delta S} = 0,$$

where UN means the quantity is not known and UNM means the quantity is unknown but is considered to be minimal in comparison with the other budget items. The numbers given are gross estimates and are best used to indicate relative magnitudes. The magnitude of the estimate for precipitation minus evapotranspiration (P-ET, 231.6 Mgal/d) is much greater than the sum of estimated outflow components (RO + WI, 147.1 Mgal/d) because the estimate for discharge from the aquifer system to streams only includes discharge to the Mississippi River and omits ground-water discharge to other surface water bodies, including lakes. Total ground-water discharge to surface-water bodies (RO) in the study area is not known. The equation is useful for summarizing the flux terms that are or are not known quantitatively.

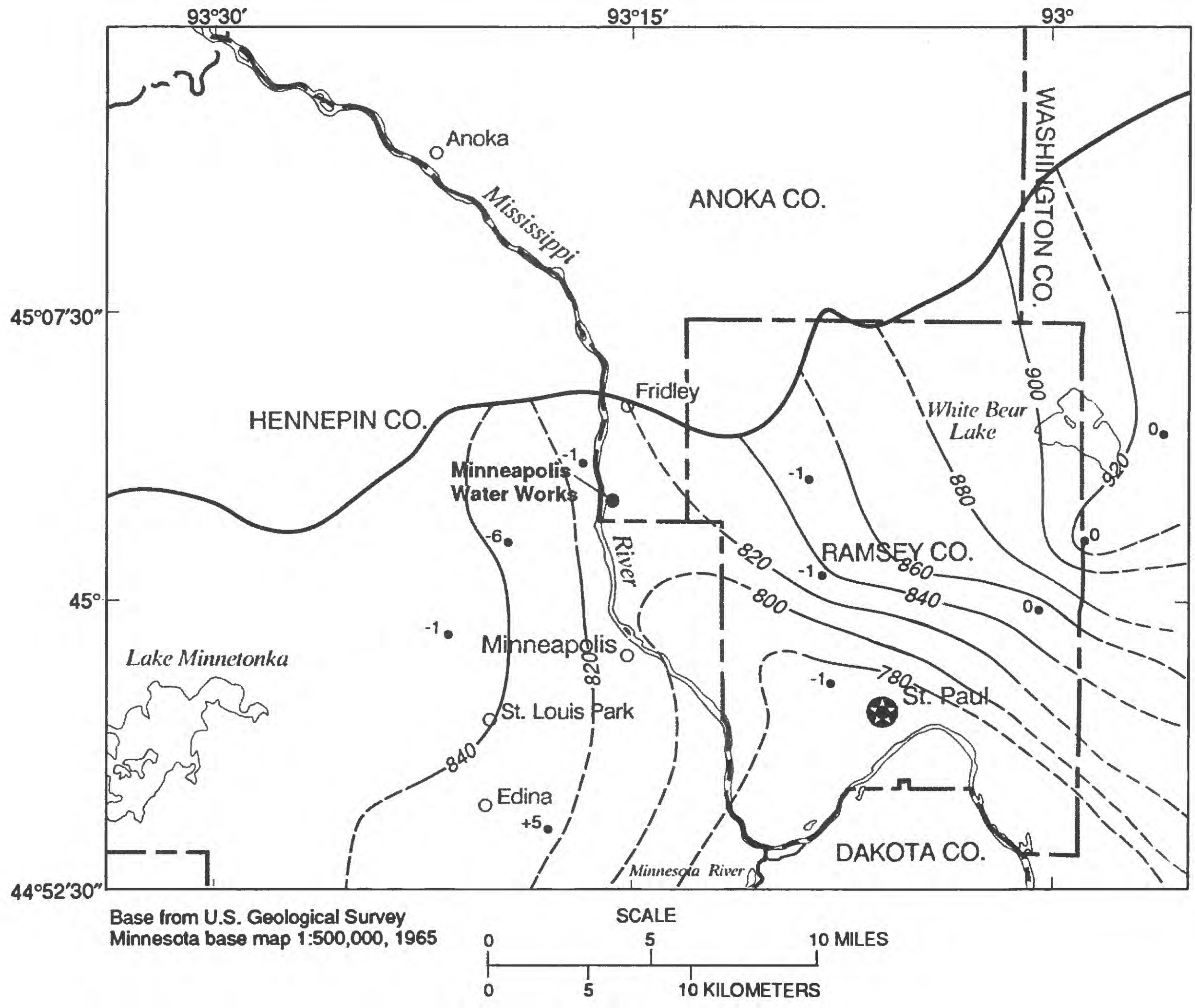
Water-Level Changes

Fluctuations of ground-water levels may be short term or long term. Under unstressed conditions, ground-water levels in the drift aquifers tend to follow a short-term cyclic pattern of seasonal fluctuations. Ground-water levels are generally highest in the spring, during maximum recharge from snowmelt and spring rainfall; decline during the summer, when evapotranspiration losses are high and the amount of precipitation and infiltration to the water table is less; tend to level out, but continue downward, during the fall; are lowest in winter, when potential recharge from precipitation is stored at the land surface as snow; and rise again in the spring, to complete the annual cycle.

Variations in the amount and timing of precipitation and subsequent recharge to the aquifer may result in deviations from this generalized cyclic pattern of fluctuations. In the Twin Cities Metropolitan Area the natural, unstressed pattern of seasonal fluctuations has also been altered by ground-water pumpage for air conditioning and lawn watering during the summer months; thus, the annual lowest water levels in wells generally occur during the summer (fig. 15). After the reduction in ground-water withdrawals in late summer, water levels generally rise. Water-level fluctuations in wells completed in the unconfined-drift and confined-drift aquifers near the Minneapolis Water Works are shown in figure 16. The seasonal pattern of observed water-level fluctuations in the unconfined-drift and confined-drift aquifers is similar. Differences in water-level fluctuations in the unconfined-drift and confined-drift aquifers may result from reduced interaction of the confined-drift aquifer with surface water bodies and increased ground-water withdrawals from the confined-drift aquifer. Observation well FMC21, completed in the unconfined-drift aquifer, is located within 100 ft of the Mississippi River and water-level fluctuations in the well are similar to fluctuations in river stage, indicating a good hydraulic connection between the aquifer and the river.

Water-level hydrographs also illustrate long-term, climatic fluctuations. The comparatively high water levels observed during the mid-1980's in wells completed in the drift aquifers were caused by above-normal precipitation (fig. 15), whereas, the comparatively low water levels observed during 1966-68 were caused by below-normal precipitation.

Short-term seasonal fluctuations in hydraulic head also occur in the St. Peter and Prairie du Chien-Jordan aquifers (figs. 17 and 18). Water levels in wells are generally highest during the spring when leakage from overlying units is greatest, and lowest during early to mid-summer when ground-water withdrawals are greatest. The short-term seasonal declines are nearly 25 ft in the St. Peter aquifer and about 50 ft in the Prairie du Chien-Jordan aquifer in downtown Minneapolis and St. Paul and in the western suburbs of Minneapolis, where seasonal summer ground-water withdrawals are greatest. Seasonal changes in water levels from August 1987 through January 1988 ranged from 0 to 43 ft in wells completed in the Prairie du Chien-Jordan aquifer in the study area (fig. 19). In downtown Minneapolis and downtown St. Paul, the altitude of the bottom of the summer-drawdown cone in the Prairie du Chien-Jordan and overlying aquifers is, at times, below the stage of the Mississippi River, and natural discharge from the aquifers and leakage from the river is diverted toward the pumped wells. At the Minneapolis Water Works, the elevation of the potentiometric surface of the Prairie du Chien-Jordan aquifer is about 10 ft higher than river stage even during the summer months; however, the potentiometric surfaces in the drift aquifers and the Prairie du Chien-Jordan aquifer about 1 mi (mile) north near Fridley city well #13 decline below river stage during periods of heavy ground-water withdrawals.



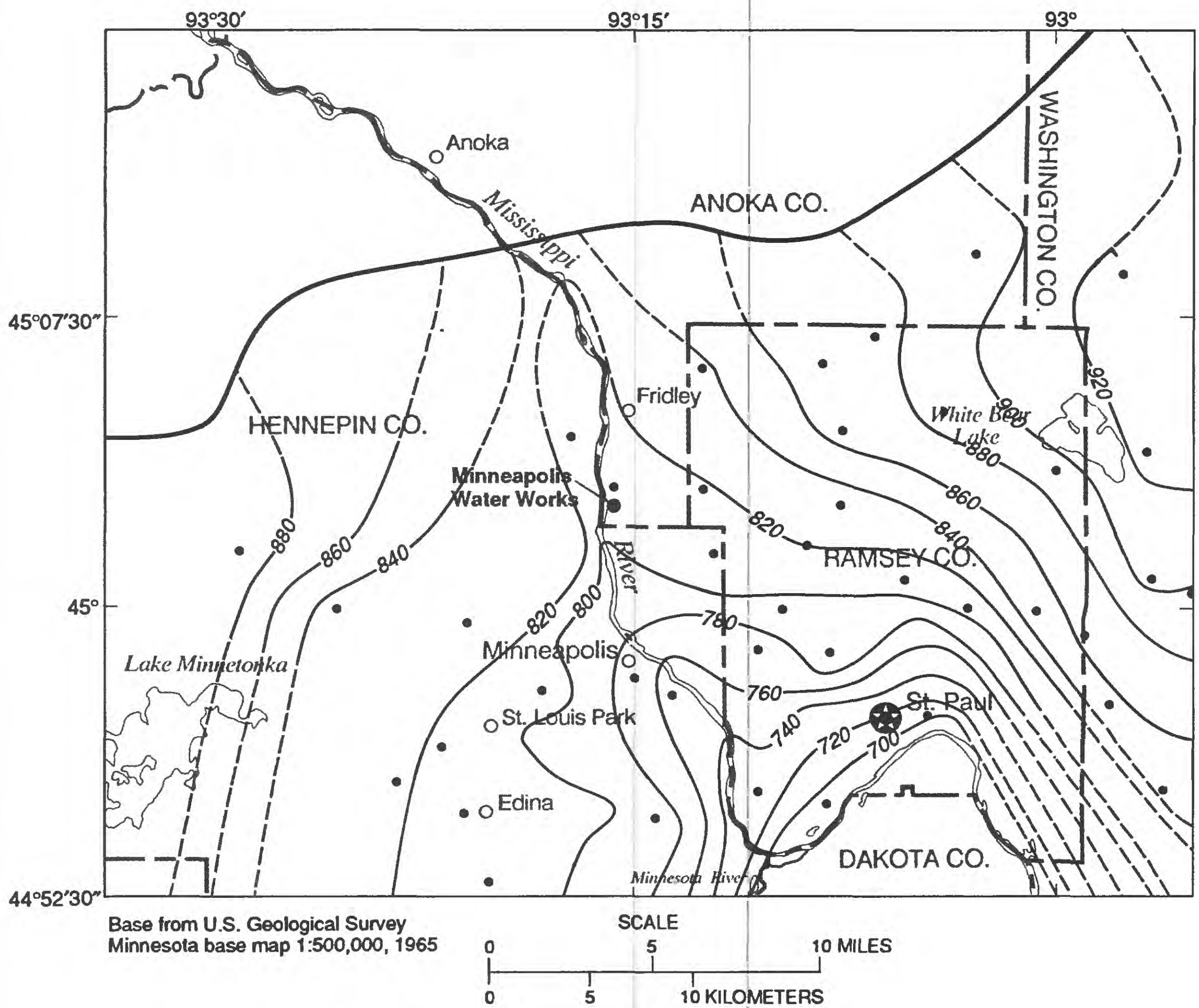
EXPLANATION

Generalized aquifer boundary

—800— Potentiometeric contour--Shows altitude at which water levels would stand in tightly cased wells. Dashed where approximate. Contour interval 20 feet. Datum is sea level

+5• Observation well--Number denotes the difference in hydraulic head from August 1987 through January 1988 (+ denotes a rise in hydraulic head).

Figure 12.--Potentiometric surface of the St. Peter aquifer, January 1988.



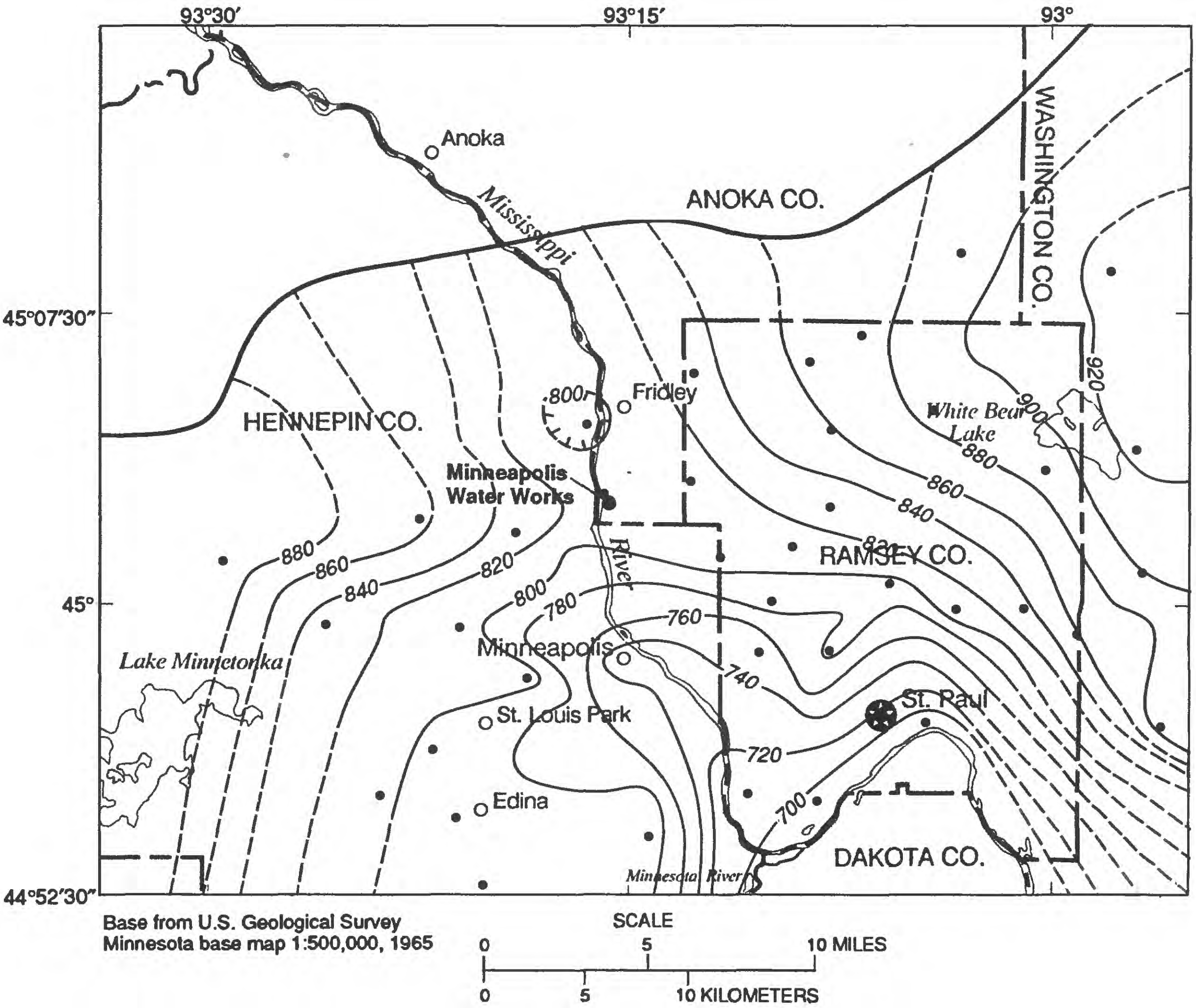
EXPLANATION

Generalized aquifer boundary

—800— Potentiometeric contour--Shows altitude at which water levels would stand in tightly cased wells. Dashed where approximate. Hachures indicate depression. Contour interval 20 feet. Datum is sea level.

• Observation well

Figure 13.--Potentiometric surface of the Prairie du Chien-Jordan aquifer, January 1988.



EXPLANATION

- Generalized aquifer boundary
- —*800*— Potentiometeric contour--Shows altitude at which water levels would stand in tightly cased wells. Dashed where approximate. Hachures indicate depression. Contour interval 20 feet. Datum is sea level.
- • Observation well

Figure 14.--Potentiometric surface of the Prairie du Chien-Jordan aquifer, August 1987.

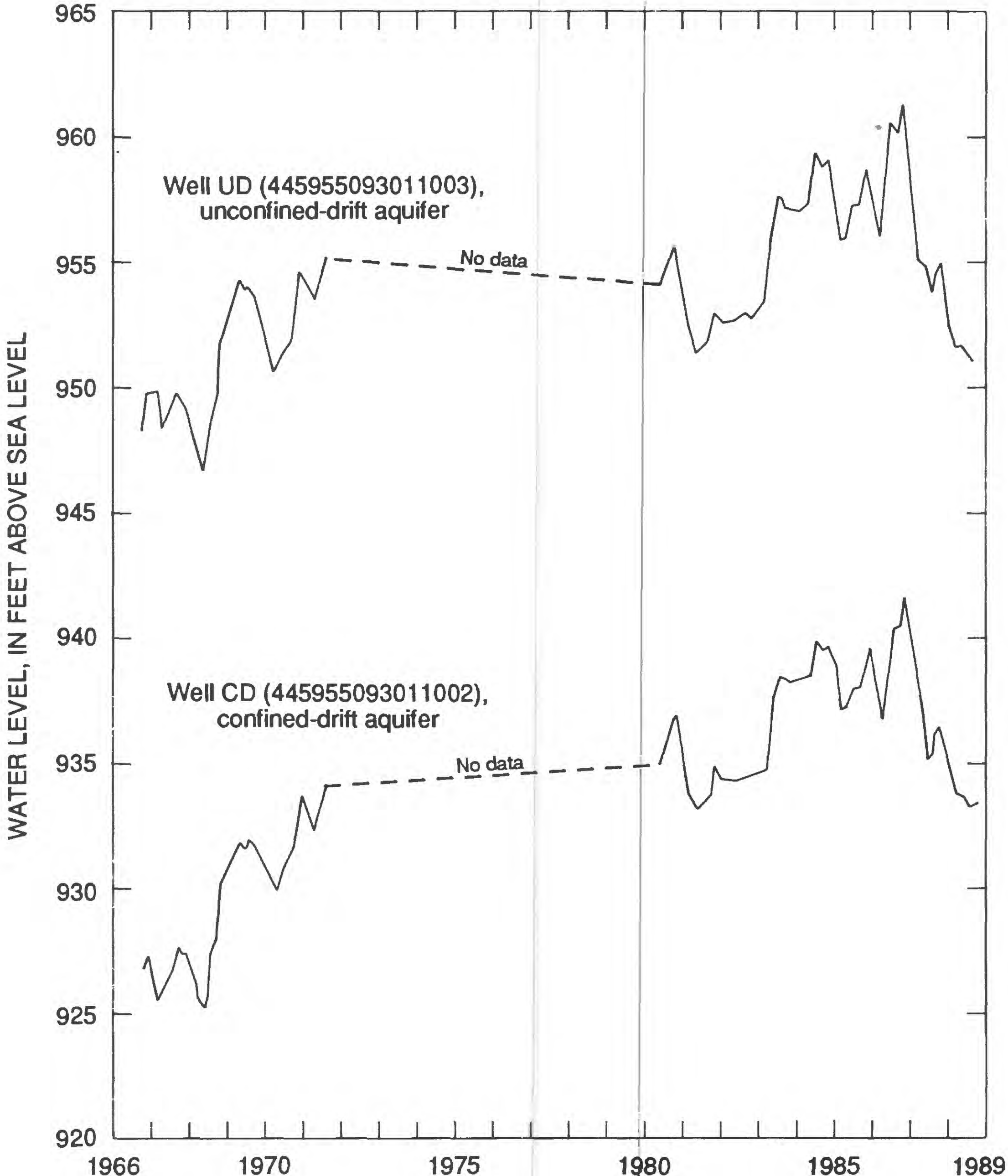


Figure 15.--Water-level fluctuations in wells completed in the unconfined- and confined-drift aquifers, 1966-89 (locations of wells shown in figure 2).

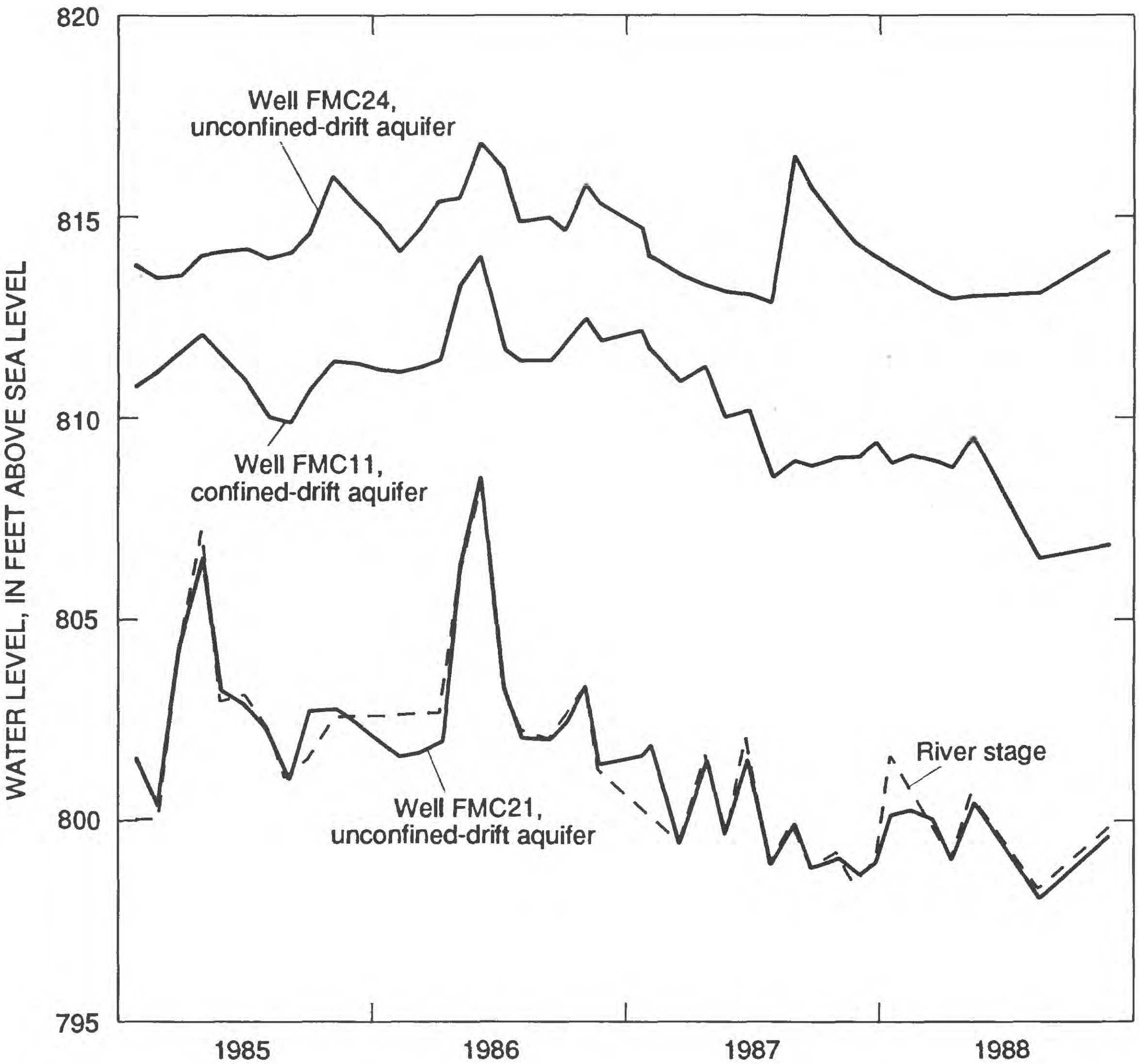


Figure 16.--Water-level fluctuations in wells completed in the unconfined-drift and confined-drift aquifers near the Minneapolis Water Works, 1985-88 (locations of wells shown in figure 6).

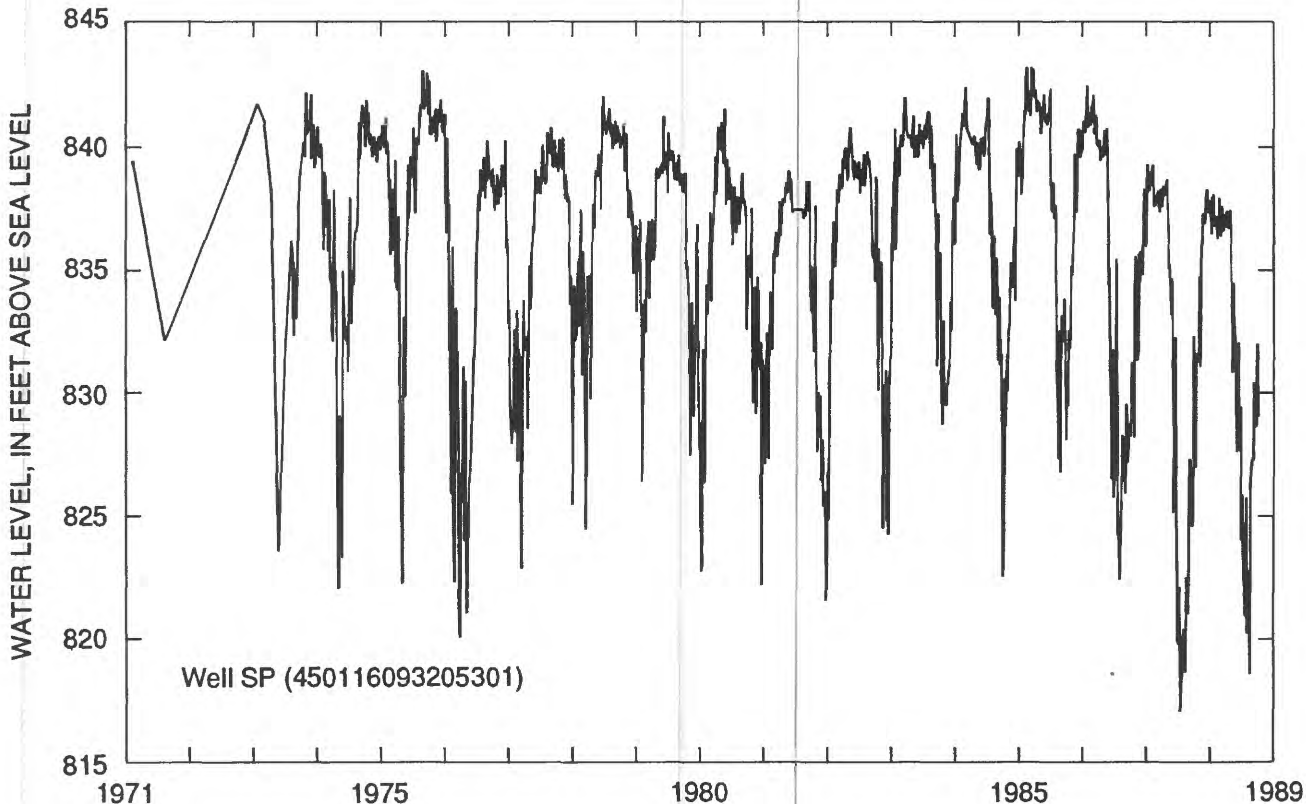


Figure 17.--Water-level fluctuations in well SP completed in the St. Peter aquifer, 1971-89 (location of well shown in figure 2).

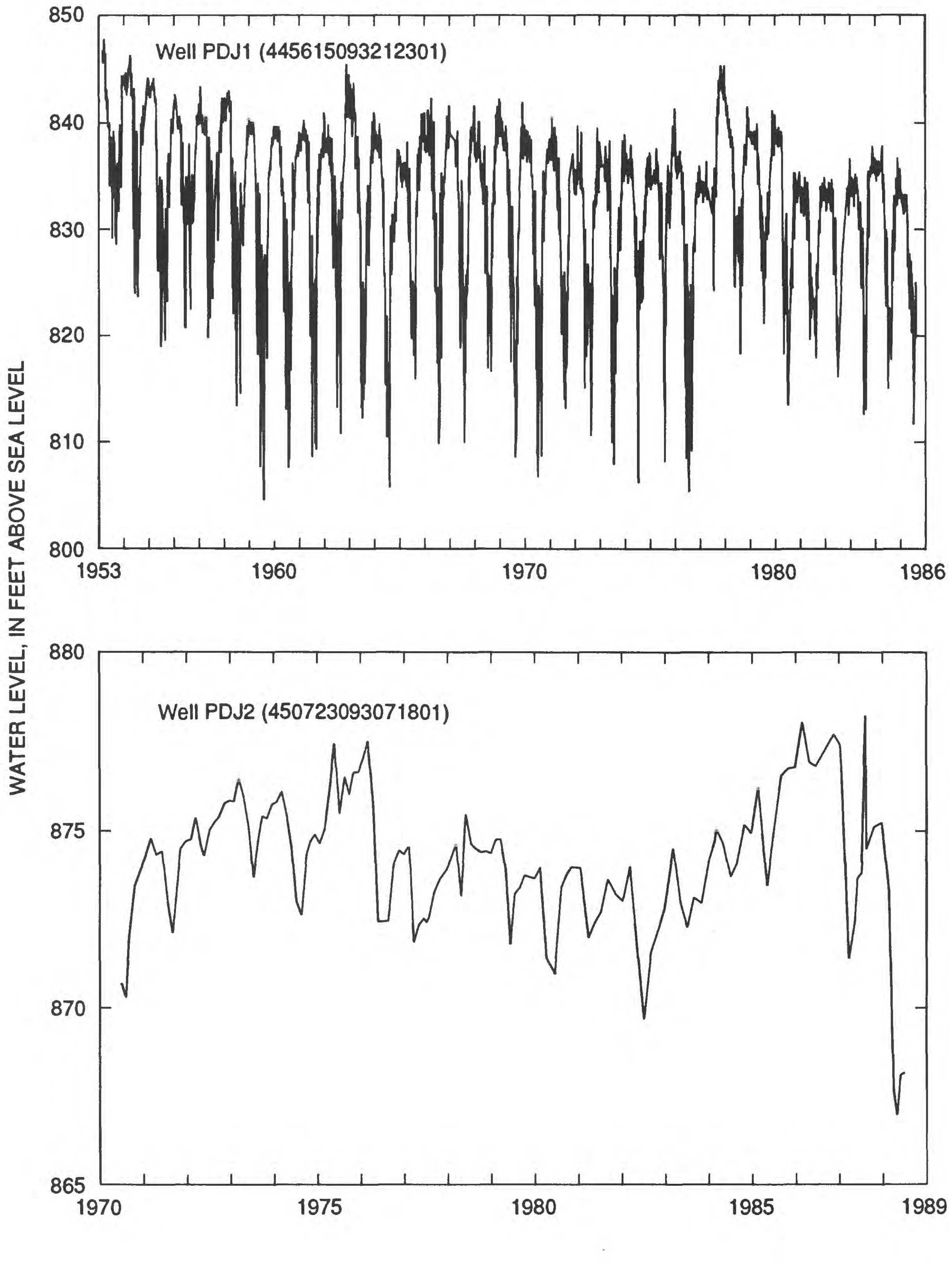
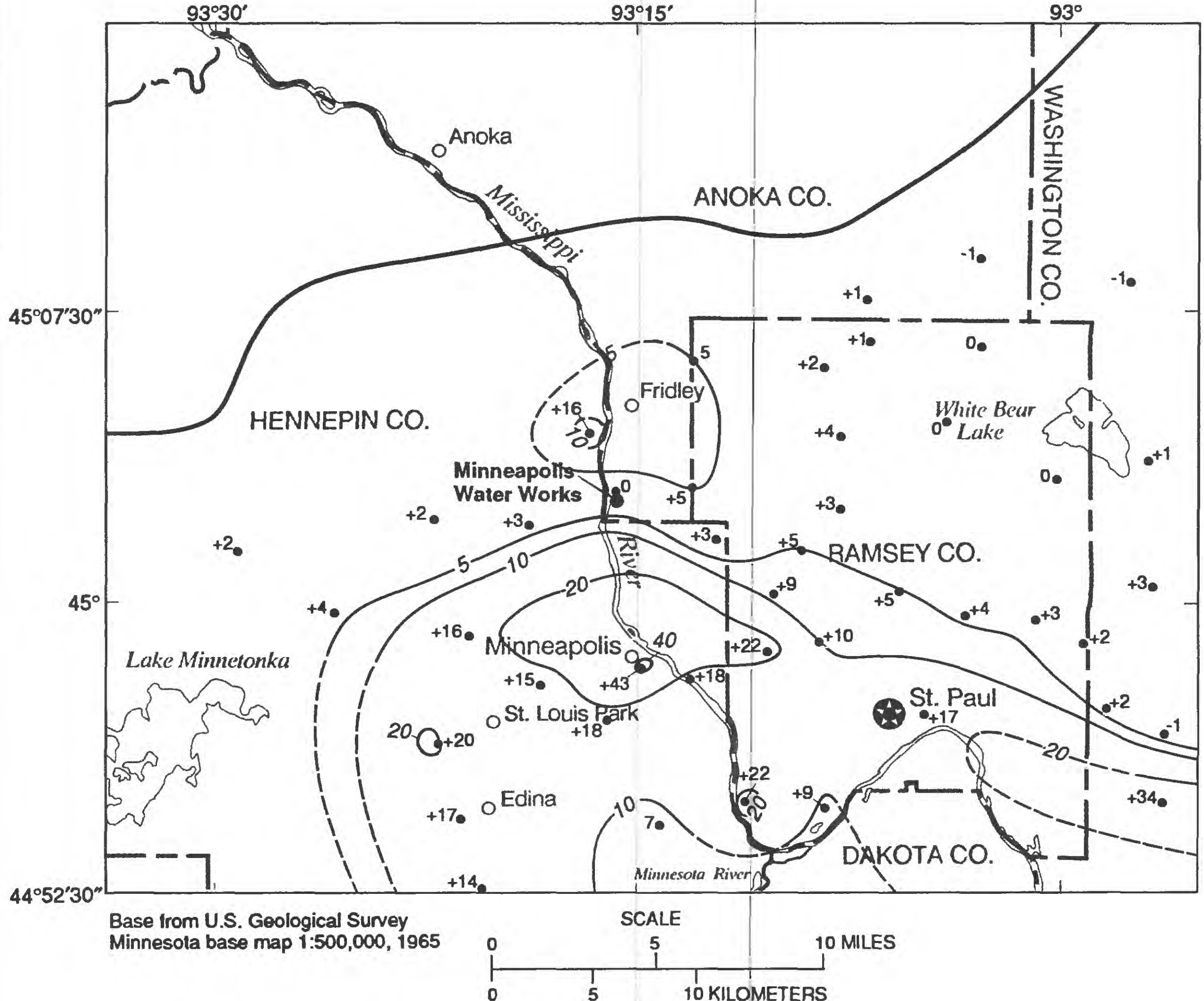


Figure 18.--Water-level fluctuations in wells completed in the Prairie du Chien-Jordan aquifer (locations of wells shown in figure 2).



EXPLANATION

——— Generalized aquifer boundary

—*20*— Line of equal hydraulic head change in the Prairie du Chien-Jordan aquifer from August 1987 through January 1988--Dashed where approximate. Interval variable, in feet.

+5• Observation well--Number denotes difference, in feet, between hydraulic heads measured in August 1987 and those measured in January 1988 in the Prairie du Chien-Jordan aquifer (+ indicates the hydraulic head was higher in January 1988 than in August 1987).

Figure 19.--Seasonal changes in the potentiometric surface of the Prairie du Chien-Jordan aquifer, August 1987 through January 1988.

If potentiometric surfaces annually return to about the same levels, considering climatic cycles, then recharge to and discharge from the aquifer is in equilibrium. Hydraulic heads in the St. Peter and Prairie du Chien-Jordan aquifers rebound and quickly approach equilibrium conditions following the lessening of ground-water withdrawals in the late summer and fall. Schoenberg (1984) reports that hydraulic heads in the Prairie du Chien-Jordan aquifer changed less than 5 ft in most of the Twin Cities Metropolitan Area from 1971-80 and that, despite large ground-water withdrawals, no large cones of depression have developed in the potentiometric surface. The seasonal rebound of hydraulic heads and lack of a large cone of depression indicate that the Prairie du Chien-Jordan aquifer is highly transmissive and in good hydraulic connection with potential sources of water, including the overlying drift and St. Peter aquifer and the major rivers in the area.

If potentiometric surfaces follow a declining trend from year to year, then discharge from the aquifer exceeds recharge to the aquifer, and water is being removed from storage in the aquifer. Ground-water withdrawals from the St. Peter and Prairie du Chien-Jordan aquifers have resulted in long-term (1885-1980) potentiometric surface declines. Declines in average winter water levels in wells from predevelopment (1885-1930) to 1970-79 ranged from 0 to 25 ft for the St. Peter aquifer and from 0 to 48 ft for the Prairie du Chien-Jordan aquifer. Nearly all of the decline in water levels occurred prior to about 1960, with no long-term change in water levels after about 1960. The largest declines occurred in the downtown areas of Minneapolis and St. Paul and in the western suburbs of Minneapolis (figs. 20 and 21).

Ground-Water Contamination

Several areas of known ground-water contamination that could ultimately affect the quality of the ground water withdrawn by production wells are located within about 1 mi of the Minneapolis Water Works to the east and northeast. An investigation conducted by RMT, Inc. (1987) indicated that multiple sources of ground-water contamination exist in the vicinity of the Minneapolis Water Works. Disposal of solvents, paint sludge, and plating wastes by industrial plants has contaminated local ground water with industrial solvents (Minnesota Pollution Control Agency, written commun., 1989). The contaminants detected in the ground water are primarily volatile organic compounds (VOCs). The primary organic compound detected in ground water at the contaminated sites is trichloroethylene (TCE). Other organic compounds are present at much lower concentrations than those for TCE. Contaminated ground water from the known source areas apparently has migrated to the Mississippi River, as indicated by the detection of TCE at the City of Minneapolis drinking-water intake downstream from these areas. Trace levels of TCE have also been detected in Fridley municipal well #13, which is completed in the Prairie du Chien-Jordan aquifer about 1 mi north of the Minneapolis Water Works.

Figure 22 shows TCE concentrations in water collected by the U.S. Geological Survey from the unconfined-drift aquifer near the Minneapolis Water Works in July and August 1988. High concentrations of TCE--up to 7,200 μg/L (micrograms per liter)--were found in water from some observation wells located between the Minneapolis Water Works and contaminated sites to the east and northeast. The available data from nested wells indicates that the concentration of TCE increases with depth in the unconfined-drift aquifer; the reason for this is unknown but may be caused by localized flow in the shallow part of the unconfined-drift aquifer.

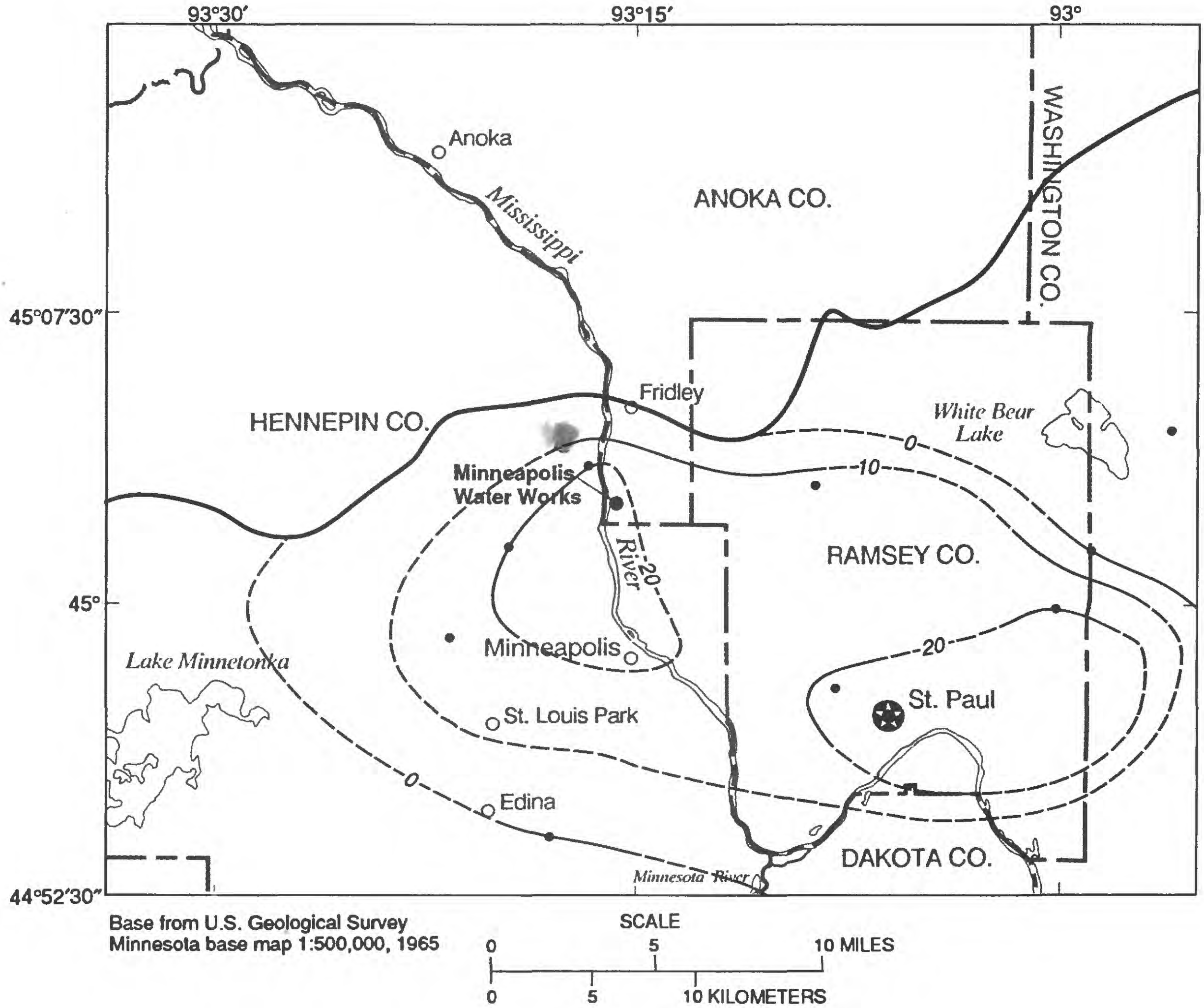
The presence of the bedrock valley beneath the Minneapolis Water Works and nearby areas of known ground-water contamination is significant in relation to the possible movement of contaminants within the aquifer system. The upper drift confining unit is discontinuous in the area, and downward migration of contaminants from the surficial sand and gravel (unconfined-drift aquifer) to the confined-drift aquifer is possible. Where the St. Peter aquifer and basal-confining unit are absent, there is a direct hydraulic connection between the Prairie du Chien-Jordan aquifer and the overlying drift, and migration of contaminants into the Prairie du Chien-Jordan aquifer is also possible.

Surface Water

The Mississippi River, the major stream draining the study area, is an important component of the hydrogeologic system. The Mississippi River generally is a discharge area, or sink, within the ground-water system. Norvitch and others (1974) determined that the basin storage portion of baseflow, derived from discharge from the underlying aquifers, accounts for about 68 percent of the gain in streamflow (about 902 ft^3/s or 5.24 in/yr) for the three major rivers (Mississippi, Minnesota, and St. Croix) in the Twin Cities Metropolitan Area; about 20 percent of the streamflow gain is bank-storage discharge, and the remaining 12 percent is attributed to direct surface runoff. Seasonally, during the summer, and locally the Mississippi River is a source of water to the ground-water system. Norvitch and others (1974) calculated that induced recharge, including captured natural discharge, from the Mississippi River alluvium and underlying glacial valley fill may be as much as 30.6 Mgal/d in the Twin Cities Metropolitan Area, and that potentiometric heads in the Prairie du Chien-Jordan aquifer were 25- to 75-ft below river stage in a few areas. An unknown percentage of the induced recharge is derived from leakage from the river.

The Mississippi River enters the study area from the northwest at an elevation of about 850-ft above sea level and leaves the study area to the southeast at an elevation of about 687 ft. Although the average gradient of the river is little changed from natural conditions, its distribution has been appreciably altered by four dams within the study area. The Upper St. Anthony Falls Lock and Dam is situated at a natural waterfall having a drop of about 50 ft. The river flows in a narrow gorge between Upper St. Anthony Falls Lock and Dam to its confluence with the Minnesota River. Below the confluence, it flows in a broad valley that was originally carved by the Glacial River Warren (Norvitch and others, 1974). The average discharge for the period of record is about 7,730 ft^3/s at Anoka (53 years of record) and about 10,910 ft^3/s at St. Paul (86 years of record).

Part of the gain in streamflow between the gaging stations at Anoka and St. Paul is attributable to ground-water discharge to the river. The gain in streamflow attributable to ground-water discharge was estimated to be about 110 ft^3/s on the basis of average values for January (low-flow) conditions from 1939 through 1986 for the Mississippi River at gaging stations at Anoka and St. Paul, and for the Minnesota River near Jordan. The estimated ground water discharge was calculated as the difference between the streamflow for the Mississippi River at St. Paul (3,316 ft^3/s) and the streamflow for the Mississippi River at Anoka (2,952 ft^3/s) plus the Minnesota River near Jordan (552 ft^3/s); 3,613 - (2,952 + 552) = 109. It should be noted that a streamflow of 109 ft^3/s is well within the generally accepted error of about ±5 percent deviation from the average January streamflow measurements for the Mississippi River at Anoka and at St. Paul.



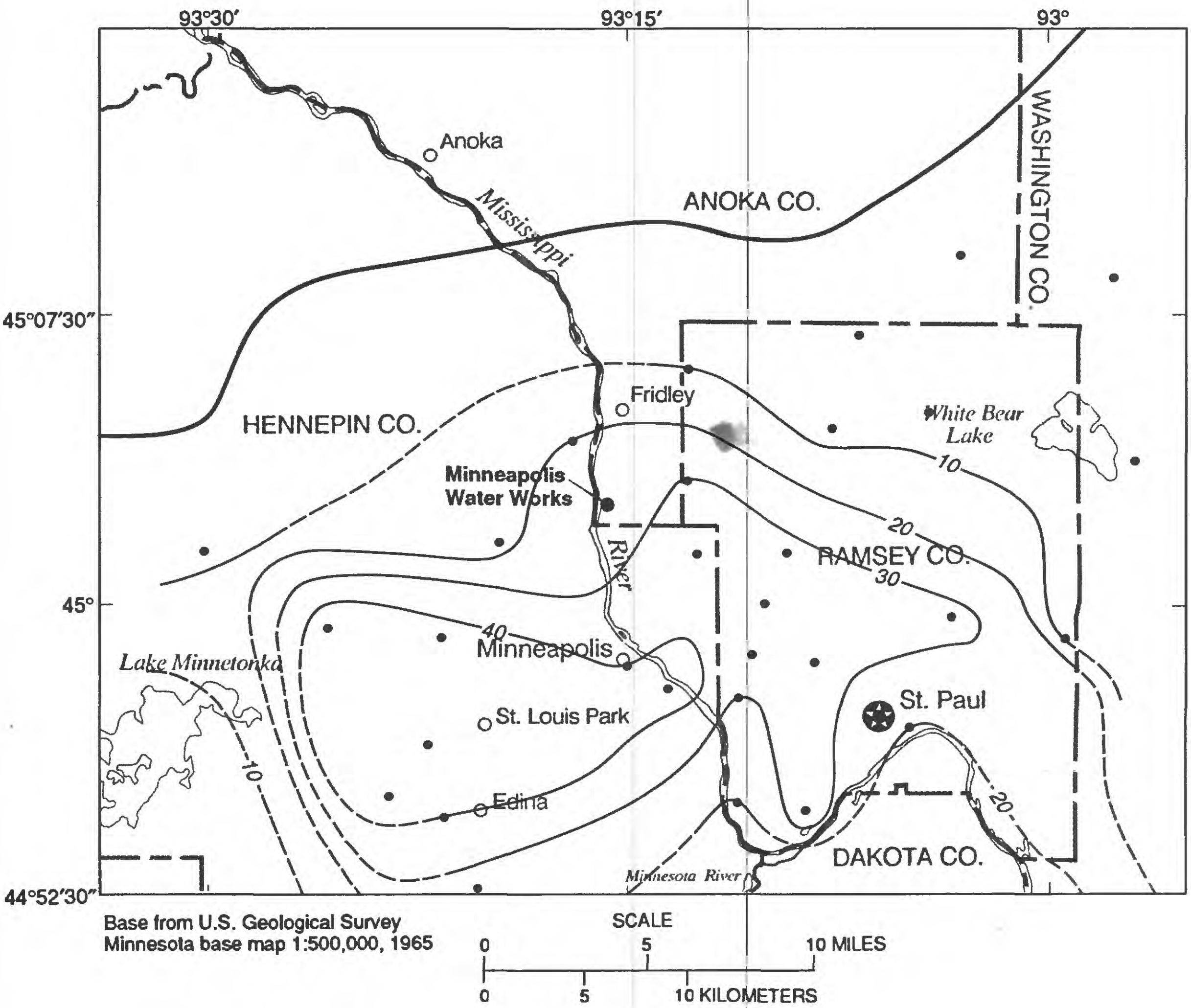
EXPLANATION

—— Generalized aquifer boundary

—20— Line of equal potentiometeric-surface decline in the St. Peter aquifer from 1885-1930 through the 1970's-- Dashed where approximate. Interval 10 feet.

• Observation well

Figure 20.--Long-term decline of the potentiometric surface in the St. Peter aquifer, 1885 through the 1970's.



EXPLANATION

Generalized aquifer boundary

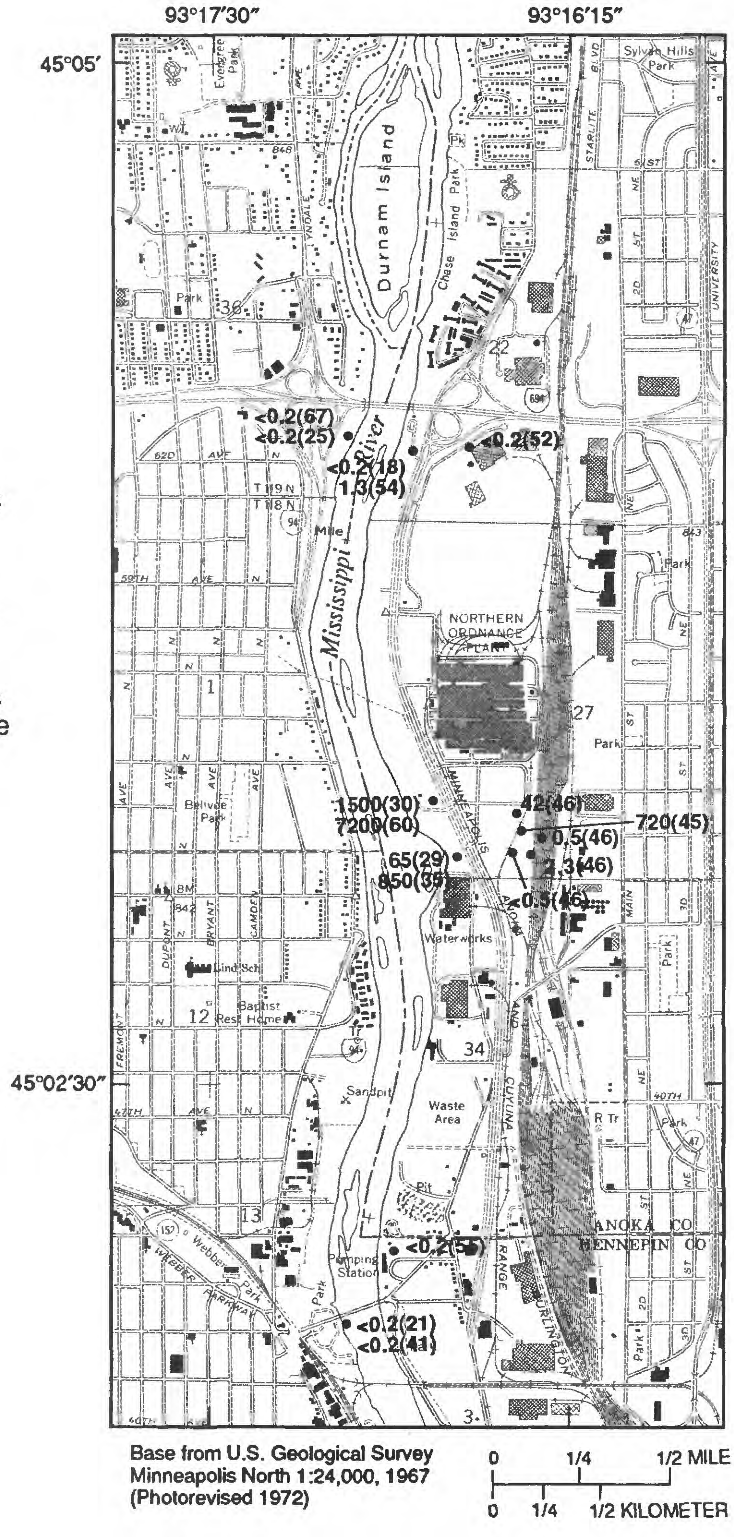
—20— Line of equal potentiometeric-surface decline in the Prairie du Chien-Jordan aquifer from 1885-1930 through the 1970's-- Dashed where approximate. Interval 10 feet.

• Observation well

Figure 21.--Long-term decline of the potentiometeric surface of the Prairie du Chien-Jordan aquifer, 1885 through the 1970's.

EXPLANATION

<0.2(18) • Sampled well--Number denotes concentration of trichloroethylene (TCE), in micrograms per liter (<, indicates a concentration less than the indicated detection level). Number in parentheses is the depth, in feet below land surface, to the bottom of the screened interval. All samples are from wells completed in the unconfined-drift aquifer.



Base from U.S. Geological Survey Minneapolis North 1:24,000, 1967 (Photorevised 1972)

Figure 22.--Trichloroethylene (TCE) concentrations in water from wells completed in the unconfined-drift aquifer near the Minneapolis Water Works in the summer of 1988.

SIMULATION OF GROUND-WATER FLOW

A numerical model of ground-water flow was constructed to represent the aquifer system in the study area. The computer code used in this study was the U.S. Geological Survey modular three-dimensional finite-difference ground-water-flow model developed by McDonald and Harbaugh (1988). The model uses finite-difference methods to obtain approximate solutions to partial-differential equations of ground-water flow. The model incorporates horizontal- and vertical-flow equations, hydrogeologic characteristics of aquifers, and recharge to and discharge from the aquifer system to determine hydraulic heads in the aquifers.

A conceptual model--that is, a qualitative description of the known characteristics and functioning of the aquifer system--was formulated from knowledge of the hydrogeologic setting, aquifer characteristics, distribution and amount of recharge and discharge, and aquifer boundaries. A number of simplifying assumptions about the aquifer system and boundary condition specifications were required to make mathematical representation of the aquifer system possible:

1. The Prairie du Chien-Jordan, St. Peter, and confined-drift aquifers are confined aquifers.

2. The volume of water that moves vertically across the bottom of the Prairie du Chien-Jordan aquifer through the St. Lawrence-Franconia confining unit is small relative to lateral flow; thus, the aquifer bottom is represented as a no-flow boundary.

3. The hydraulic heads at arbitrarily imposed lateral boundaries where the natural hydrologic boundaries lie outside the modeled area are constant during specified time periods. In such instances, specified-head boundaries, adjusted to measured values for the appropriate time periods, are used in the model.

4. The model boundaries corresponding to surface-water divides near the northeast and southwest boundaries of the modeled area are also ground-water-flow divides and are consequently no-flow boundaries. The lateral boundaries for the unconfined-drift aquifer, which are determined by the physical limits of the Anoka Sand Plain and the Mississippi River valley, are no-flow boundaries.

5. The Mississippi River is a head-dependent flow boundary. Leakage between the river and the underlying aquifer is simulated in the model as head-dependent flux nodes (McDonald and Harbaugh, 1988).

6. The unconfined-drift aquifer is hydraulically connected to the Mississippi River. The Prairie du Chien-Jordan, St. Peter, and confined-drift aquifers are hydraulically connected to the unconfined-drift aquifer in the Mississippi River valley.

7. Recharge to the unconfined-drift aquifer is by infiltration of precipitation and leakage from surface water. Recharge to the unconfined-drift aquifer by infiltration of precipitation represents the net difference between precipitation and evapotranspiration losses occurring above the water table. Evapotranspiration losses occurring above the water table include evapotranspiration from the unsaturated zone and evaporation from soil and plant surfaces. Flow to the confined-drift and St. Peter aquifers occurs by leakage down through overlying deposits.

8. Ground-water evapotranspiration--evaporation from the water table where it is at or near land surface plus transpiration from plants whose roots extend to the water table--is a linear function of the depth of the water table below land surface. Ground-water evapotranspiration is maximum where the water table is at land surface and decreases linearly to zero where the water table is at 7-ft below land surface. Discharge by ground-water evapotranspiration occurs from the unconfined-drift aquifer only.

9. Ground-water flow is horizontal in the aquifers and vertical in the confining units. Ground-water storage occurs only in the aquifers; the confining units release no water from storage to wells.

The model is intended to simulate ground-water flow in the greatest detail near the Minneapolis Water Works. The area modeled is large to include ground-water withdrawals from areas that may affect hydraulic heads near the Minneapolis Water Works and to encompass natural hydrogeologic boundaries where possible.

The study area was subdivided into rectangular finite-difference grid cells within which the aquifer properties are assumed to be uniform (fig. 23). The center of a grid cell is referred to as a node and represents the location for which the hydraulic head is computed by the model. Aquifer properties and stresses are assigned to the cells and are assumed to represent average conditions within grid cells. The variably spaced finite-difference grid used to spatially discretize the study area has 54 rows and 41 columns. Notation of the form (36,23), where the first number in parentheses indicates the row and the second number indicates the column, is used to refer to the location of an individual cell within the grid. The dimensions of the grid cells, ranging from 200 to 20,000 ft on a side, increase toward the edges of the study area; therefore, hydrologic properties assigned to the outer cells are averaged over much larger areas than for cells near the center of the modeled area. The smallest cells are near the Minneapolis Water Works in the central part of the grid, where the most detailed hydrogeologic information is available and desired.

The aquifer system in the study area was subdivided into model layers corresponding to generally horizontal hydrogeologic units. The thickness of a cell representing an aquifer unit is equal to the average saturated thickness of the aquifer within the area represented by the cell and is incorporated in the transmissivity term for the cell. Transmissivity is the product of the horizontal hydraulic conductivity and the saturated thickness. Hydraulic conductivity and transmissivity are a measure of the ability of an aquifer to transmit water. Confining units are not represented in the ground-water-flow model as discrete layers. The thickness and vertical hydraulic conductivity of confining units is incorporated into leakage terms that simulate leakage of water between aquifers for each cell. Ranges in values of thickness and horizontal hydraulic conductivity for the hydrogeologic units in the study area were given in table 3.

Ground-Water-Flow Model

A two-phase process was used to construct and calibrate the numerical ground-water-flow model. During the first phase, a preliminary two-layer ground-water-flow model was developed to (1) simulate regional ground-water flow under steady-state conditions, (2) determine leakage between the principal bedrock aquifer (Prairie du Chien-Jordan) and the overlying bedrock (St. Peter) and confined-drift aquifers, and (3) evaluate and refine the boundary conditions. During the second phase, a surficial unconfined-drift aquifer layer was added to simulate the outwash-alluvial aquifer that underlies the Mississippi River valley and the Anoka Sand Plain. The surficial layer was needed to improve simulation of the aquifer system and the simulation of existing and proposed ground-water withdrawals near the Minneapolis Water Works. The confined-drift aquifer and the St. Peter aquifer are simulated as a single aquifer (confined-drift and St. Peter aquifers) in the numerical ground-water-flow model. The confined-drift aquifer occupies the bedrock valleys that dissect the St. Peter and Prairie du Chien-Jordan aquifers in the study area. Winter and Pfannkuch (1976) report a good hydraulic connection between the bedrock aquifers and the drift filling a bedrock valley in the northern part of the Twin Cities Metropolitan Area. The potentiometric surfaces for the confined-drift aquifer and the St. Peter aquifer are similar in the study area.

Model Design

The hydrogeologic units represented in the two-layered ground-water-flow model are (1) the confined-drift and St. Peter aquifers (layer 1) and (2) the Prairie du Chien-Jordan aquifer (layer 2) (fig. 24). The hydrogeologic units represented in the three-layered ground-water-flow model are (1) the unconfined-drift aquifer consisting of outwash and alluvial deposits underlying the Anoka Sand Plain and the Mississippi River valley (model layer 1), (2) the confined-drift and St. Peter aquifers (model layer 2), and (3) the Prairie du Chien-Jordan aquifer (model layer 3). Where the St. Peter aquifer is present, cells in the model layer for the confined-drift and St. Peter aquifers were assigned the hydrogeologic properties of the St. Peter aquifer. In the northern part of the study area and in bedrock valleys where the St. Peter aquifer is absent, cells in the model layer for the confined-drift and St. Peter aquifers were assigned the hydrogeologic properties of the drift. The confined-drift and St. Peter aquifers model layer does not include the overlying drift in areas where the St. Peter aquifer is present; in these areas the overlying drift is considered a confining unit.

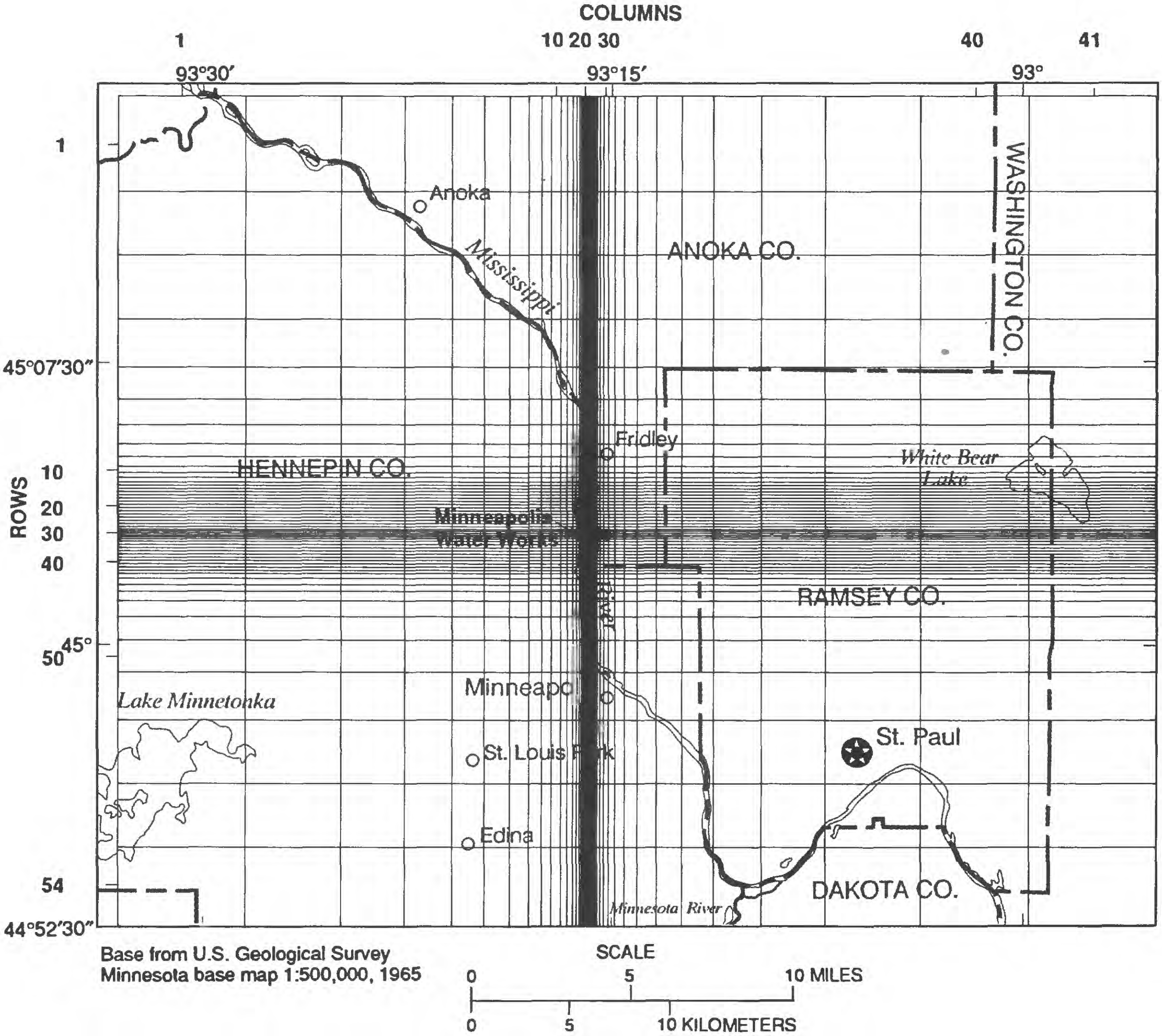


Figure 23.--Grid for the finite-difference ground-water-flow model.

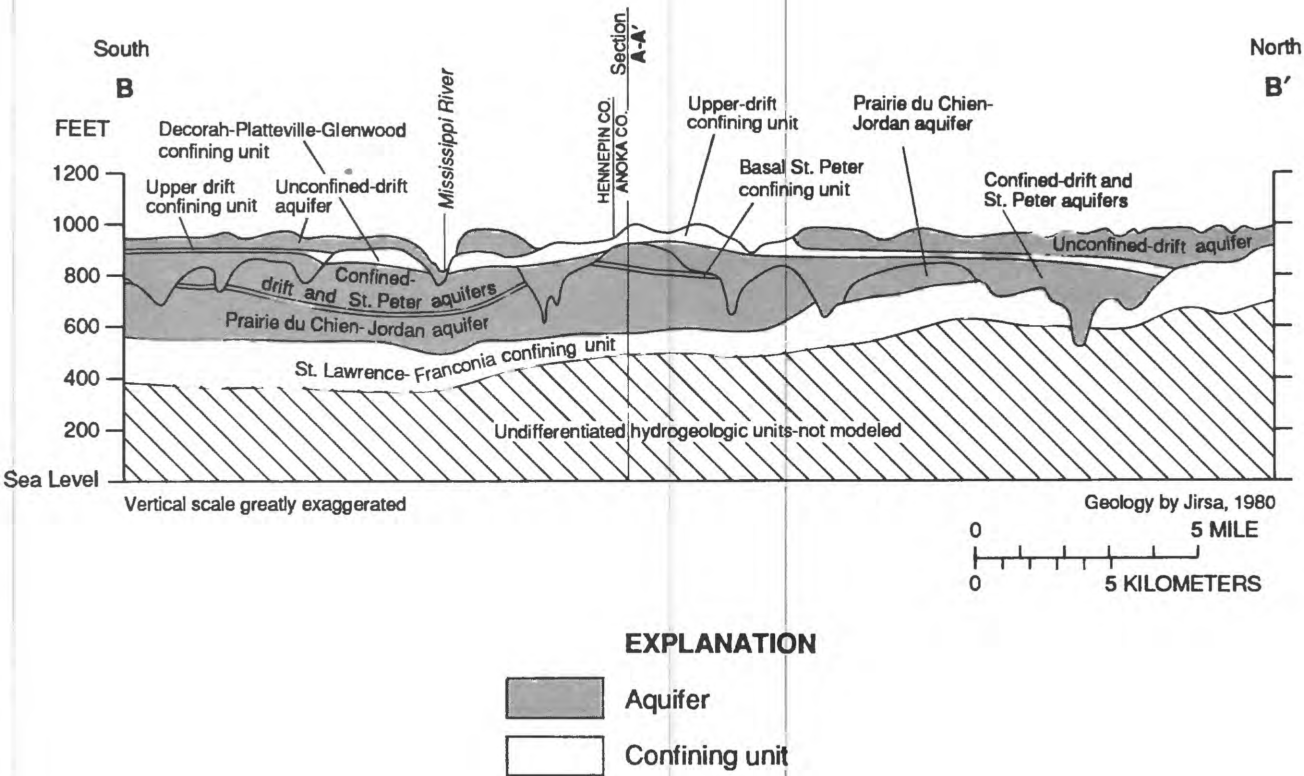


Figure 24.--Generalized south-to-north schematic hydrogeological section through model area showing model hydrogeologic units (trace of section shown in figure 2).

The basal St. Peter Sandstone and clayey, silty layers in the drift, where present, act as a confining unit that impedes the flow of water between the Prairie du Chien-Jordan aquifer, and overlying confined-drift and St. Peter aquifers. The basal St. Peter confining unit and basal-drift confining unit together comprise the lower confining unit as represented in the finite-difference model. A layer of silt, clay, and till varying in thickness and composition underlies the surficial sand and gravel deposits and acts as a confining unit that retards the flow of water between the unconfined-drift aquifer and the underlying confined-drift and St. Peter aquifers. In the southern part of the study area, the Decorah-Platteville-Glenwood confining unit hydraulically separates the unconfined-drift aquifer from the St. Peter aquifer. The upper drift confining unit and Decorah-Platteville-Glenwood confining unit together comprise the upper confining unit. The effect of the confining units on ground-water flow within the aquifer system is represented in the model by a leakage term that incorporates the thickness and vertical hydraulic conductivity of the confining unit.

Ideally, all model boundaries should be located at the physical limits of the aquifer system or at other hydrogeologic boundaries, such as a major river. Practical considerations, such as limitations concerning the size of the area modeled, however, may necessitate the use of arbitrarily imposed model boundaries where the natural hydrologic boundaries lie outside the model area. The western model boundary and southern part of the eastern boundary in the model layer for the Prairie du Chien-Jordan aquifer and the northern boundary in the model layer for the unconfined-drift aquifer are arbitrarily imposed boundaries where the natural hydrologic boundaries lie beyond the practical limits of the model.

The boundaries in the model layers for the confined-drift and St. Peter aquifers and Prairie du Chien-Jordan aquifer represent regional hydrogeologic boundaries in the Prairie du Chien-Jordan aquifer where possible (fig. 25). The northern and western boundaries in the model layer for the confined-drift and St. Peter aquifers were extended beyond the physical limits of the St. Peter aquifer in order to include several large-capacity wells that withdraw water from the confined-drift aquifer for public supply. Current and potential ground-water withdrawals from the confined-drift aquifer in these areas may affect ground-water flow in the study area and hydraulic heads near the Minneapolis Water Works. The northern and western boundaries in the model layer for the confined-drift and St. Peter aquifers were made to coincide with those in the model layer for the Prairie du Chien-Jordan aquifer because no hydrogeologic boundary for the confined-drift aquifer is present within a practical distance to the north and west of the study area. Also, the distribution of confined sand and gravel aquifer units within the drift is poorly known. The northern model boundary in both model layers represents the approximate lateral extent of the Prairie du Chien-Jordan aquifer. A specified-head boundary, where hydraulic head is specified as a function of position and time, was used in the model layer for the Prairie du Chien-Jordan aquifer rather than a no-flow boundary because (1) the areal extent of the Prairie du Chien-Jordan aquifer is not well defined in detail because of limited data and the presence of bedrock valleys and (2) the Prairie du Chien-Jordan aquifer receives lateral inflow of ground water from the drift to the north of the model boundary. A specified-flux boundary was not used because the available information is not sufficient to calculate fluxes across the boundaries. A specified-head boundary was also used in the model layer for the confined-drift and St. Peter aquifers. The hydraulic head at these boundary cells was held constant because historical data indicate that long-term and seasonal changes in ground-water levels are not significant in these areas. The western model boundary and southern part of the eastern boundary in both model layers were also represented using a specified-head boundary. Hydraulic heads in the confined-drift and St. Peter aquifers and the Prairie du Chien-Jordan aquifer near these model boundaries vary over time, however, and the heads were specified to reflect hydraulic head measured in the aquifers during the appropriate time period. Approximately the northern half of the eastern model boundary and the western part of the southern model boundary coincide with ground-water-flow divides, which are represented as no-flow boundaries because flow of ground water across these boundaries is not significant under equilibrium conditions. The western part of the southern model boundary coincides with a ground-water-flow divide between the Mississippi River and the Minnesota River, which flows from west to east to the south of the model boundary. Ground water along the southwestern model boundary flows to the east toward the Mississippi River; flowpaths are parallel to the model boundary (figs. 13 and 14). Ground water to the south of the model boundary flows to the south and southeast toward the Minnesota River. Ground-water-flow divides may change in position or disappear when stresses are introduced. However, seasonal potentiometric maps for the Twin Cities Metropolitan Area indicate that the ground-water-flow divides in the study area have been persistent and remained in about the same position for unstressed conditions (1885-1930) and with current (1980's) levels of ground-water withdrawals. The eastern part of the southern model boundary is represented by a no-flow boundary because the Mississippi River is the regional discharge point for the bedrock aquifers.

The model boundaries and boundary conditions for the unconfined-drift aquifer are shown in figure 26. All except the northern boundary represent the physical limits of the aquifer and are represented in the model as no-flow boundaries. The northern boundary is represented as a specified-head boundary because no hydrogeologic boundary is present within a practical distance to the north of the study area. The physical boundary of the Anoka Sand Plain is about 50 miles north of the Twin Cities Metropolitan Area. Based on historical data, no significant long-term change in ground-water levels in the unconfined-drift aquifer has occurred in the study area.

The affect of the use of specified-head boundary conditions on hydraulic heads near the Minneapolis Water Works was investigated by using no-flow boundaries in place of specified-head boundaries for steady-state conditions prior to major ground-water withdrawals (1885-1930) and comparing the results. Changing from a specified-head boundary to a no-flow boundary (1) in the model layer for the confined-drift and St. Peter aquifers resulted in declines in hydraulic heads near the Minneapolis Water Works of less than 0.2 ft, (2) in the model layer for the Prairie du Chien-Jordan aquifer resulted in declines in hydraulic heads near the Minneapolis Water Works of less than 1.0 ft, (3) in the model layers for the confined-drift and St. Peter aquifers and the Prairie du Chien-Jordan aquifer resulted in declines in hydraulic heads near the Minneapolis Water Works of about 20 ft, and (4) in the model layers for the confined-drift and St. Peter aquifers and the Prairie du Chien-Jordan aquifer for the northern boundary only resulted in declines in hydraulic heads near the Minneapolis Water Works of less than 2.5 ft in both the two-layer and three-layer models. Changing from a specified-head to a no-flow boundary in the model layers for the confined-drift and St. Peter aquifers and the Prairie du Chien-Jordan aquifer for the northern boundary only resulted in small declines in hydraulic heads because boundary inflow to the model from the northern boundary was only about 12 percent of the total boundary inflow. Boundary inflow from the western and southeastern boundaries accounts for about 88 percent of the total boundary inflow. Changing from a specified-head boundary to a no-flow boundary in the model layer for the unconfined-drift aquifer resulted in no change in hydraulic heads near the Minneapolis Water Works in the three-layer model. In summary, the type of boundary condition used for the northern boundary in the model layers for the confined-drift and St. Peter aquifers and the Prairie du Chien-Jordan aquifer and the northern boundary in the model layer for the unconfined-drift aquifer has a minimal affect on hydraulic heads near the Minneapolis Water Works under non-stressed conditions.

A specified-flux boundary is used to represent recharge by the infiltration of precipitation to the unconfined-drift aquifer and leakage from overlying deposits to the confined-drift and St. Peter aquifers. Leakage to the confined-drift and St. Peter aquifers is specified only for the area outside the boundaries of the unconfined-drift aquifer in the three-layer model.

Geologic data from maps prepared by the Minnesota Geological Survey (1980) were used to assign hydrogeologic characteristics to each cell in the two-layer model. Initial values for hydraulic conductivity for each hydrogeologic unit and leakage to the confined-drift and St. Peter aquifers from the overlying deposits were the same as those used by Stark and Hult (1985) and Schoenberg (1990) (table 4). Stark and Hult (1985) report that a leakage rate of 2.0 in/yr to the St. Peter aquifer produced the best match between simulated and measured hydraulic heads in the Prairie du Chien-Jordan aquifer in Hennepin County in the western part of the Twin Cities Metropolitan Area for steady-state conditions prior to significant ground-water withdrawals (prior to 1930). The recharge rate of 2.0 in/yr is less than the recharge rate of about 3.5 in/yr to the underlying Prairie du Chien-Jordan aquifer reported by Larson-Higdem and others (1975) for Hennepin County during a period of significant ground-water withdrawals (1970's) because the lowering of hydraulic heads in the confined-drift and St. Peter aquifers and the Prairie du Chien-Jordan aquifer has resulted in greater leakage from overlying deposits. No additional estimates of leakage rates to the St. Peter and confined-drift aquifers in the Twin Cities Metropolitan Area are available in the literature.

Initial values for horizontal hydraulic conductivity and aquifer-bottom elevations for the unconfined-drift aquifer (simulated by the three-layer model) underlying the Anoka Sand Plain were obtained from Helgesen and Lindholm (1973). Initial values for horizontal and vertical hydraulic conductivity of the unconfined-drift aquifer and drift confining units in the Mississippi River valley south of the Anoka Sand Plain were estimated from values reported by Norvitch and others (1974), Ranney Company (1978), and RMT, Inc. (1987). The bottom of the unconfined-drift aquifer in the Mississippi River valley south of the Anoka Sand Plain was assumed to be at an elevation equal to the land-surface elevation minus 30 ft, the average thickness of the unconfined-drift aquifer as estimated from available drillers' logs. Helgesen and Lindholm (1973) estimated recharge to the unconfined-drift aquifer underlying the Anoka Sand Plain to be 11.1 in/yr on the basis of hydrograph analysis. Recharge to the unconfined-drift aquifer underlying the Mississippi River valley was assumed to be similar. Leakage was applied directly to the model layer for the confined-drift and St. Peter aquifers in the three-layer model in areas outside the boundaries of the unconfined-drift aquifer.

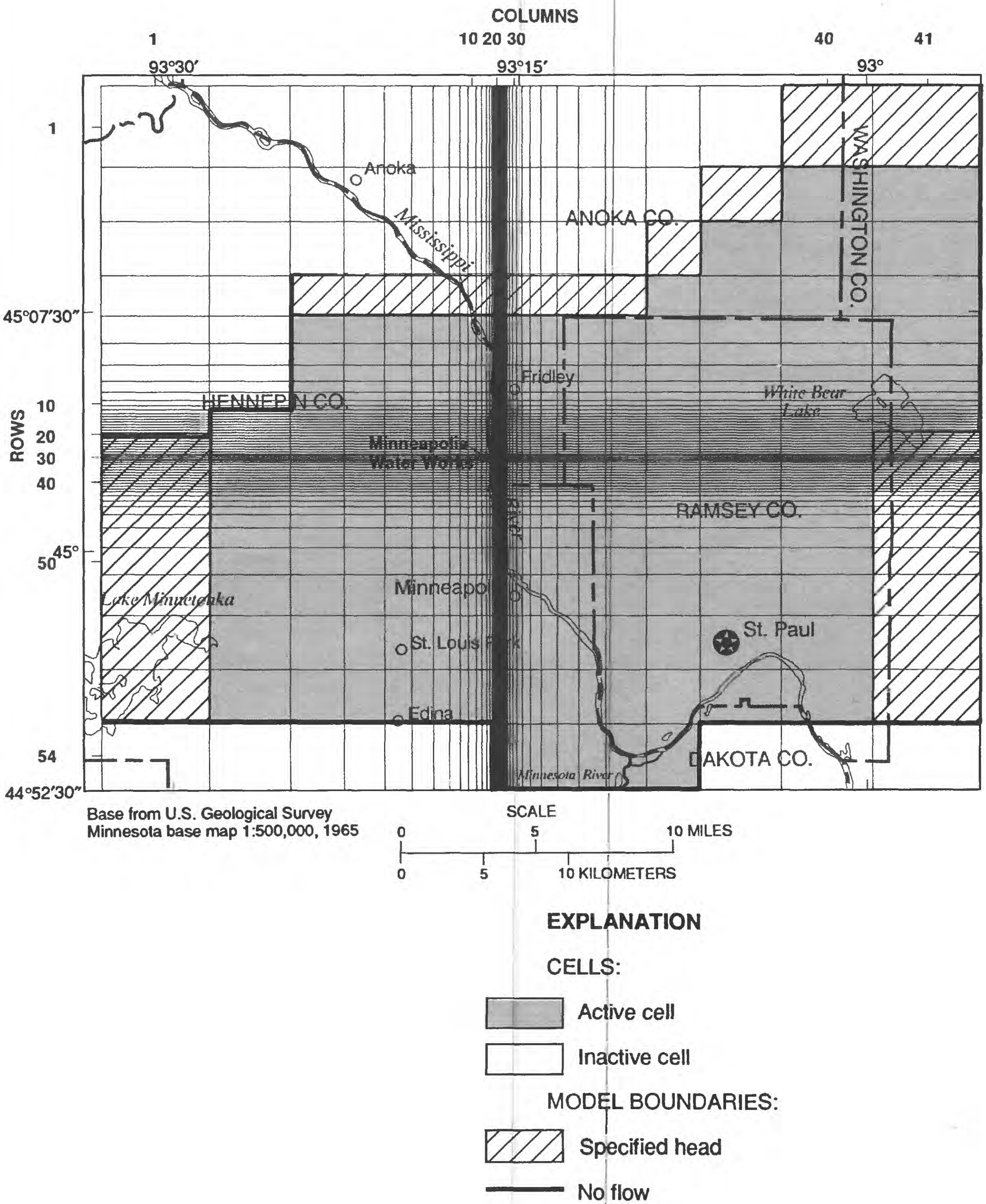


Figure 25.--Finite-difference grid showing model boundaries for the confined-drift and St. Peter aquifers and the Prairie du Chien-Jordan aquifer.

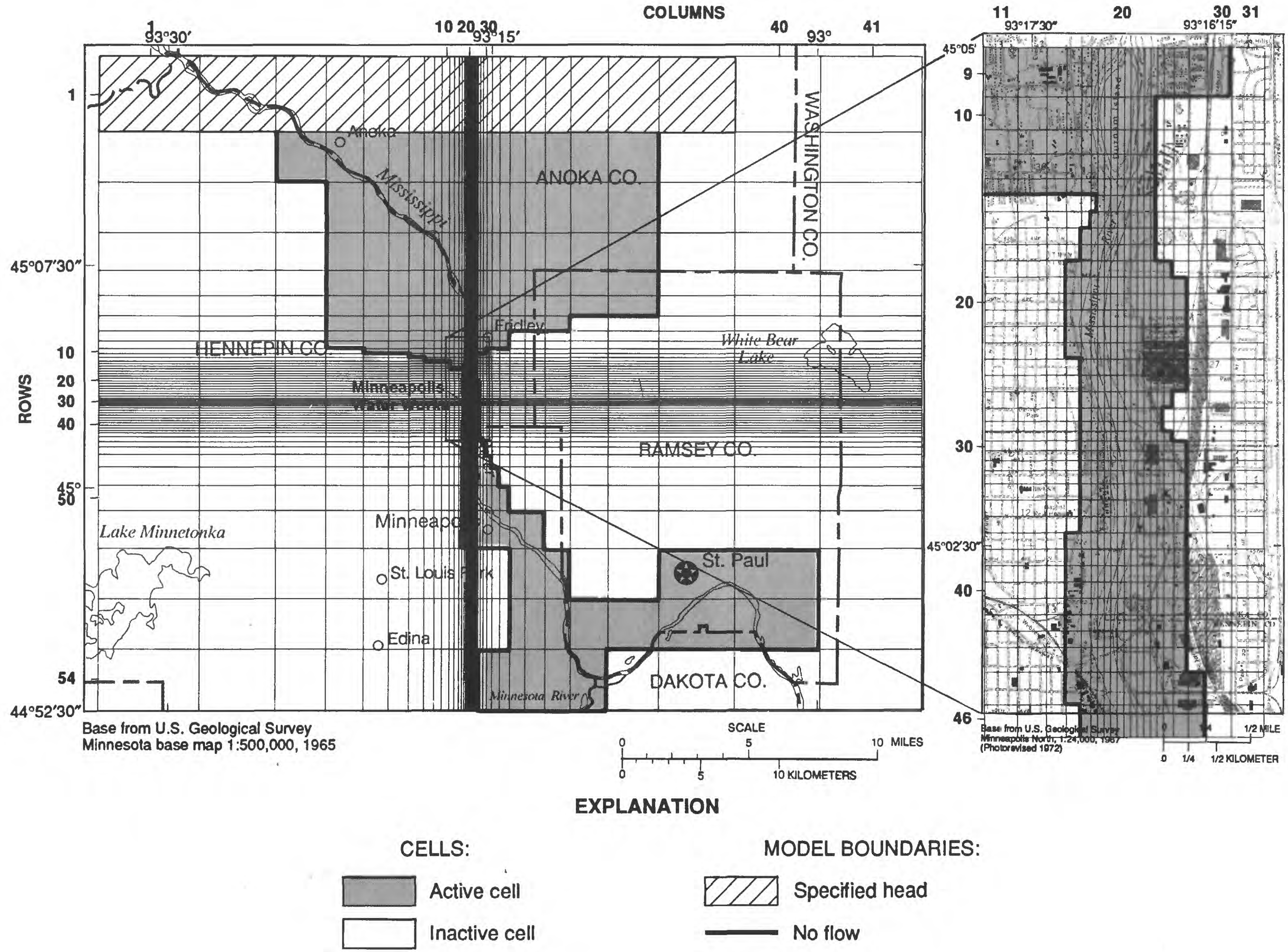


Figure 26.--Finite-difference grid showing model boundaries for the unconfined-drift aquifer.

Table 4.--*Initial values of hydraulic properties and fluxes in the two-layer steady-state simulation for 1885-1930*

[ft/d, feet per day; ft^2/d, feet squared per day; in/yr, inches per year; --, not applicable]

Hydrogeologic unit	Horizontal hydraulic conductivity (ft/d)	Transmissivity (ft^2/d)	Vertical hydraulic conductivity (ft/d)	Leakage (in/yr)
Confined-drift aquifer	40	0-5,000	--	2.0
St. Peter aquifer	20	0-3,000	--	2.0
Basal-drift confining unit	--	--	1.0×10^{-2}	--
Basal St. Peter confining unit	--	--	1.5×10^{-3}	--
Prairie du Chien-Jordan aquifer	40	0-10,000	--	--
Mississippi riverbed	--	--	1.0	--

Discharge of water from the drift aquifers to the Mississippi River was simulated with head-dependent flux nodes (McDonald and Harbaugh, 1988, Chapter 6). Discharge of water to the Mississippi River was simulated from the confined-drift and St. Peter aquifers in the two-layer model and from the unconfined-drift aquifer in the three-layer model. The river was divided into reaches, each of which is completely contained in a single cell. Leakage through a reach of riverbed is approximated by Darcy's law as

$$QRIV = KLW\ (HRIV-HAQ)/M,$$

where

QRIV is leakage through the reach of the riverbed (L^3/t),

K is vertical hydraulic conductivity of the riverbed (L/t),

L is length of the reach (L),

W is width of the river (L),

M is thickness of the riverbed (L),

HAQ is head in the aquifer (L), and

HRIV is head in the river (L).

The length of the riverbed in each cell was measured from U.S. Geological Survey 7.5-minute topographic quadrangle maps. The average width of the streambed, measured at streamflow gaging stations within the model area, is about 750 ft. The thickness of the riverbed was assumed to be equal to the average thickness of the unconfined aquifer, about 30 ft, for the preliminary two-layer model. The thickness of the riverbed was arbitrarily assumed to be

1 ft for the three-layer model because the lower limit of the riverbed is poorly defined and not easily measurable. Published values for vertical hydraulic conductivity of riverbed material for streams in glacial terrain commonly range from 0.5 to 10 ft/d [Norris and Fidler (1969), Jorgensen and Ackroyd (1973), and Prince and others (1987)].

Water is also discharged from the unconfined-drift aquifer in the three-layer model by ground-water evapotranspiration. The model simulates evapotranspiration from the water table only; it does not simulate evapotranspiration of soil water in the unsaturated zone. The assumption was made that evaporation from lakes was a reasonable estimate of the maximum ground-water evapotranspiration rate that occurs when the water table is at the land surface. A commonly accepted estimate for lake evaporation rates is about 75 percent of the observed class A pan-evaporation rates (National Oceanic and Atmospheric Administration, 1982). In the Twin Cities Metropolitan Area, the mean annual pan-evaporation rate is about 40 in/yr, which corresponds to an estimated average annual lake-evaporation rate of 30 in/yr. The initial maximum ground-water-evapotranspiration rate specified in the model, therefore, was 30 in/yr. The ground-water evapotranspiration rate in the model decreases linearly with depth below land surface and becomes zero at the "extinction depth." As the depth to the water table increases, fewer plants have roots that extend deep enough to extract water from the water table and the evapotranspiration rate, therefore, decreases. The extinction depth corresponds to a depth below land surface minimally greater than the rooting depth of the plants present. The plausible range for evapotranspiration extinction depth was assumed to be 5 to 10 feet with a most likely average value of 7 ft. The elevation of the land surface for each cell was determined from U.S. Geological Survey 7.5-minute topographic quadrangle maps.

Model Calibration

Model calibration is the process in which initial estimates of aquifer properties and boundary conditions are adjusted until simulated hydraulic heads and ground-water flows adequately match measured water levels and flows. Aquifer properties were also adjusted to produce an adequate match between the simulated ground-water discharge to the Mississippi River and that estimated from measured streamflows (110 ft^3/s). Reliable quantitative estimates of ground-water flows into or through the aquifer system in the study area, other than recharge from infiltration of precipitation and leakage to the confined-drift and St. Peter aquifers and the Prairie du Chien-Jordan aquifer from overlying deposits, are not available. Calibration and evaluation of the two-layer ground-water-flow model was conducted for steady-state (equilibrium) conditions for approximately 1885-1930, a period before significant ground-water withdrawals took place. No storage terms or ground-water withdrawals are included in the steady-state simulation. Under steady-state conditions, the amount of water entering the aquifer system equals the amount of water leaving the aquifer system, and the long-term change in storage is zero.

Calibration and evaluation of the three-layer ground-water-flow model were conducted for two steady-state conditions and two transient conditions. The steady-state conditions simulated are (1) conditions before significant ground-water withdrawals (1885-1930) and (2) average-winter conditions in the aquifer system during 1970-79, a period of large annual ground-water withdrawals. Seasonal variations in ground-water withdrawals during 1970-79 produced large seasonal fluctuations in hydraulic heads in the Prairie du Chien-Jordan aquifer; however, after the heavy summer ground-water withdrawals subsided, hydraulic heads returned to an adjusted steady-state level each fall with no significant long-term change during the 1970's (fig. 18).

Transient simulations incorporate the storage properties of the aquifers and are time dependent. Changes in storage in the aquifers occur when the amount of water entering the aquifer system and the amount of water leaving the system are not equal. Water-level fluctuations in wells generally reflect short-term imbalances in recharge and discharge and resulting changes in storage in the aquifer and (or) the confining units; however, if ground-water withdrawals exceed recharge to the aquifer system over a period of time, water is withdrawn from storage in the aquifers and (or) the confining units and long-term declines in hydraulic heads occur. Transient conditions simulated in the three-layer model include (1) drawdowns resulting from an aquifer test conducted at the Minneapolis Water Works and (2) seasonally variable ground-water withdrawals during 1987, for which changes in potentiometric surfaces with time were documented.

Steady-state simulations

Steady-state simulation for 1885-1930.--Measured hydraulic heads in the Prairie du Chien-Jordan aquifer for the period 1885-1930 were used to define boundary conditions and calibrate the model in the steady-state simulation for 1885-1930. Although these data do not represent a single point in time, they reflect water levels before significant ground-water withdrawals occurred; thus, they are presumed to represent steady-state conditions.

Few hydraulic-head data are available for the confined-drift and St. Peter aquifers for 1885 through 1930. Hydraulic heads in the confined-drift and St. Peter aquifers were assumed to be approximately equal to those in the Prairie du Chien-Jordan aquifer at the same location because (1) the few available data indicate that the difference in hydraulic heads in the two aquifers was less than 2 ft and (2) near the boundaries of the modeled area, where the Prairie du Chien-Jordan aquifer is not affected by pumping stress, water levels measured in the St. Peter aquifer presently are within 2 ft of water levels in the Prairie du Chien-Jordan aquifer. Although a downward vertical hydraulic gradient across the basal St. Peter confining unit may have existed before significant ground-water withdrawals, the vertical hydraulic-head difference between the confined-drift and St. Peter aquifers and the Prairie du Chien-Jordan aquifer probably was small; flow within the aquifers was essentially horizontal except in recharge and discharge areas.

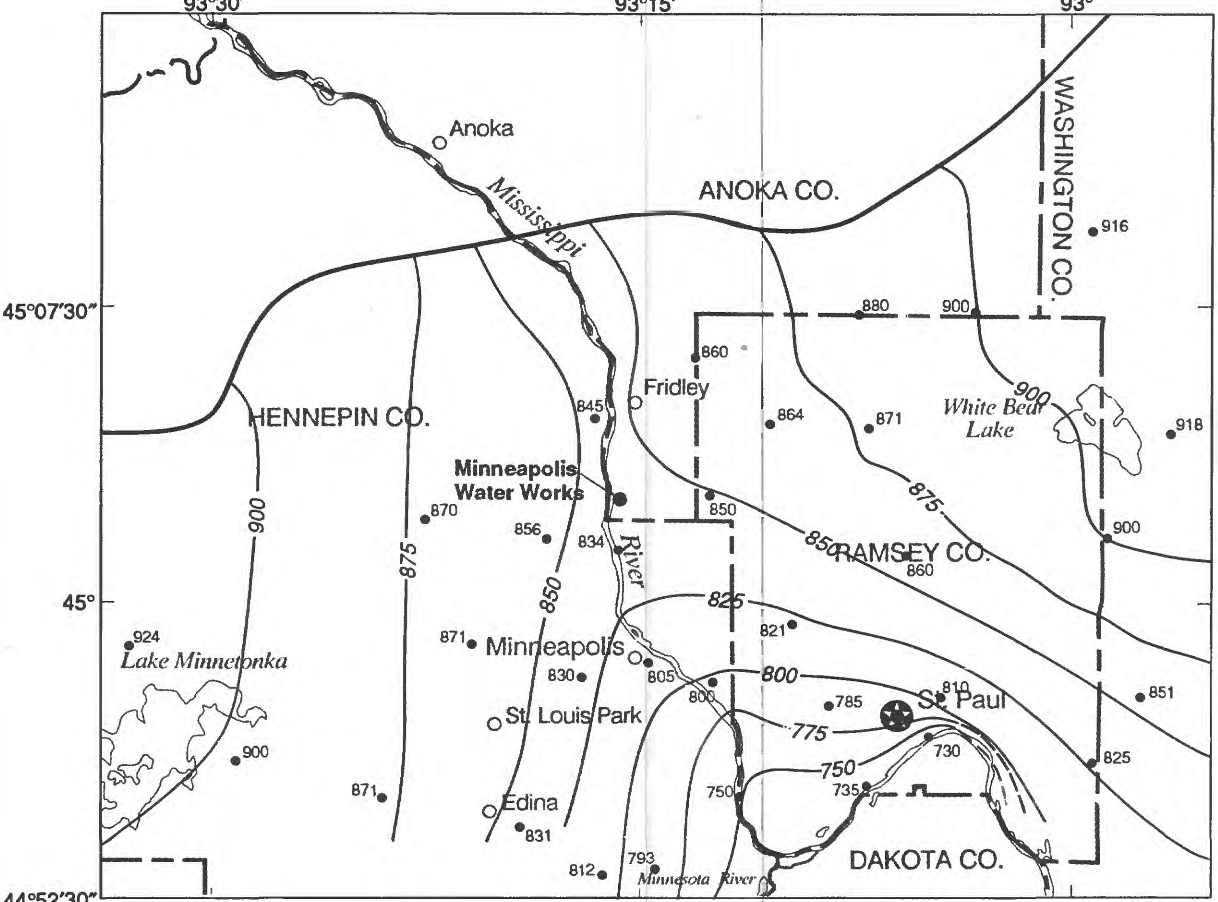
The initial values of hydrologic properties used in the two-layer model are listed in table 4. The two-layer model was calibrated by varying the values of hydraulic properties of the aquifer system (horizontal and vertical hydraulic conductivity) and leakage to the confined-drift and St. Peter aquifers until simulated hydraulic heads and ground-water discharge to the Mississippi River acceptably matched measured water levels and estimated ground-water discharge to the river. The values of hydrologic properties resulting in the best fit between measured water levels and simulated hydraulic heads are listed in table 5. The values of transmissivities of the confined-drift and St. Peter aquifers, vertical hydraulic conductivity of the basal St. Peter confining unit and Mississippi riverbed, and recharge to the confined-drift and St. Peter aquifers were the same as the initial values. Transmissivities for the Prairie du Chien-Jordan aquifer were uniformly increased by 50 percent and the assumed riverbed thickness was increased from 30 ft to 50 ft to improve the match between measured water levels and simulated hydraulic heads. Also, vertical hydraulic conductivity of the basal-drift confining unit was lowered from 0.01 to 0.005 ft/d. The simulated hydraulic heads for the Prairie du Chien-Jordan aquifer (model layer 2) were generally within about 10 ft of measured water levels in wells for which predevelopment (1885-1930) water-level data were available (fig. 27). Simulated hydraulic heads for the confined-drift and St. Peter aquifers (model layer 1) were similar to those for the Prairie du Chien-Jordan aquifer in each cell.

Table 5.--*Final adjusted values of hydraulic properties and fluxes in the two-layer steady-state simulation for 1885-1930*

[ft/d, feet per day; ft^2/d, feet squared per day; in/yr, inches per year; --, not applicable]

Hydrogeologic unit	Horizontal hydraulic conductivity (ft/d)	Transmissivity (ft^2/d)	Vertical hydraulic conductivity (ft/d)	Leakage (in/yr)
Confined-drift aquifer	40	0-5,000	--	2.0
St. Peter aquifer	20	0-3,000	--	2.0
Basal-drift confining unit	--	--	5.0×10^{-3}	--
Basal St. Peter confining unit	--	--	1.5×10^{-3}	--
Prairie du Chien-Jordan aquifer	60	0-15,000	--	--
Mississippi riverbed	--	--	1.0	--

A steady-state simulation has many solutions that would result in the same distribution of hydraulic heads unless either recharge, discharge, or the hydraulic properties of one of the aquifers is known. The same or similar distribution of hydraulic heads in the aquifer system can be produced by proportionately adjusting hydraulic conductivities in all layers and recharge to the aquifer system. The solutions to the steady-state simulations discussed in this report are considered to be unique solutions because (1) the hydraulic conductivity of the St. Peter aquifer is known within a relatively small range of values and (2) reasonable estimates of the only major discharges from the aquifer system in the study area, ground-water discharge to the Mississippi River and ground-water withdrawals by wells, are available.



Base from U.S. Geological Survey Minnesota base map 1:500,000, 1965

SCALE

0 5 10 MILES

0 5 10 KILOMETERS

EXPLANATION

——— Generalized aquifer boundary

—*800*— Simulated potentiometeric contour--Dashed where approximate. Contour interval 25 feet. Datum is sea level.

•830 Observation well--Number shown is elevation of water level measured in well.

Figure 27.--Water levels measured in wells completed in the Prairie du Chien-Jordan aquifer, 1885-1930, and simulated potentiometric surface of the Prairie du Chien-Jordan aquifer (model layer 2), two-layer steady-state simulation.

A model-sensitivity analysis, wherein a single hydrologic property is varied while all other properties are held constant, was done to identify the relative effect of adjustments of hydrologic properties on simulated hydraulic heads. The degree to which the hydrologic properties of the aquifers and confining units can be adjusted is related to the uncertainty associated with each property. Adjustments were kept within reported or plausible ranges of values (table 6). Hydraulic head was found to be most sensitive to changes in the hydrologic properties controlling the discharge of water from the aquifers to the river--the vertical hydraulic conductivity and thickness of the deposits underlying the river. Leakage of water from the underlying aquifers to the river was the only major discharge of water from the aquifer system in the study area before large ground-water withdrawals occurred and therefore the amount of leakage strongly influenced hydraulic heads in the aquifers. Varying the vertical hydraulic conductivity or thickness of the riverbed resulted in about a 20- to 35-ft average difference in hydraulic heads in both layers. Increasing the riverbed thickness would have the same affect on hydraulic heads as decreasing the vertical hydraulic conductivity, and decreasing the riverbed thickness would have the same affect as increasing the vertical hydraulic conductivity. Variations in the transmissivities of the Prairie du Chien-Jordan aquifer and leakage to the confined-drift and St. Peter aquifers resulted in about a 3.5- to 6-ft average difference in hydraulic heads. Hydraulic head is relatively insensitive to changes in the values of other properties.

The simulated water budget is shown in table 7. Leakage to the confined-drift and St. Peter aquifers accounts for about 72 percent of the sources of water to the aquifer system, whereas boundary inflow accounts for about 28 percent. About 99 percent of the discharge from the aquifer system is to the Mississippi River, and about 1 percent is outflow along the northern boundary west of the Mississippi River where the direction of ground-water flow is toward the river.

During the second phase of the model construction and calibration, a third layer was added to the ground-water-flow model. As for the two-layer model, the three-layer model was used to simulate conditions for 1885-1930, before significant ground-water withdrawals took place. Hydraulic heads in the confined-drift and St. Peter aquifers were assumed to be approximately equal to those in the Prairie du Chien-Jordan aquifer at any given location. Hydraulic heads in the unconfined-drift aquifer were assumed to be approximately equal to current heads because the aquifer is little used as a source of water and no significant long-term changes in the water table are apparent from available water-level measurements. The initial values of hydrologic properties in the three-layer steady-state model for 1885-1930 are listed in table 8. An initial value of 1.0 ft/d for vertical hydraulic conductivity of the Mississippi River streambed (from the two-layer model) was used in the three-layer model.

The three-layer steady-state model was calibrated by varying the values of hydrologic properties of the aquifer system until simulated hydraulic heads and ground-water discharge to the Mississippi River acceptably matched measured water levels and discharge to the river. The match between measured water levels and simulated hydraulic heads was improved by (1) changing hydraulic conductivity for the unconfined-drift aquifer from a uniform distribution to an areally variable distribution with values ranging from 150 to 300 ft/d, (2) decreasing the vertical hydraulic conductivity of the upper confining unit, and (3) changing leakage to the confined-drift and St. Peter aquifers from a single uniform rate to two zones with rates of 1.0 and 2.3 in/yr. The lower leakage rate of 1.0 in/yr was applied to model rows 1 to 6 in the northeastern part of the study area because the drift in this area is clayey with a lower vertical hydraulic conductivity than in other areas. Also, the hydraulic head difference between the water table and the underlying aquifers is less in the northeastern part of the study area. The recharge rate to the unconfined-drift aquifer was reduced from the initial value of 11.0 in/yr to 6.5 in/yr. The sensitivity analysis indicated that hydraulic heads in all three model layers are relatively insensitive to the rate of recharge to the unconfined-drift aquifer; however, variations in the recharge rate to the unconfined-drift aquifer result in significant variations in the magnitude of leakage to the Mississippi River. Hydraulic heads in the unconfined-drift aquifer are strongly influenced by river stage and most of any increase in recharge to the aquifer flows through the aquifer and is discharged to the river. The rate of recharge to the unconfined-drift aquifer was varied until an acceptable match was obtained between the simulated leakage to the river and the long-term average gain in streamflow (about 110 ft^3/s) in the Mississippi River between gaging stations at Anoka and St. Paul. Values of hydrologic properties resulting in the best fit between measured and simulated water levels are listed in table 9. The simulated hydraulic heads for the Prairie du Chien-Jordan aquifer (layer 3) were generally within about 10 ft of measured water levels available for the predevelopment period (1885-1930) (fig. 28). Simulated hydraulic heads for the confined-drift and St. Peter aquifers (layer 2) were similar to those for the Prairie du Chien-Jordan aquifer in each cell. Simulated hydraulic heads for the unconfined-drift aquifer were similar to recently measured winter-water levels in wells completed in the unconfined-drift aquifer; however, such measurements are areally limited to 30 wells near the Minneapolis Water Works and 3 wells in the Anoka Sand-Plain area.

A model-sensitivity analysis was done to identify the relative effects of adjustments of hydrologic properties on simulated hydraulic heads (table 10). Hydraulic head was found to be most sensitive to changes in the vertical hydraulic conductivity of the upper confining unit. The vertical hydraulic conductivity of the upper confining unit controls the vertical flow of water to the unconfined-drift aquifer from the confined-drift and St. Peter aquifers and the Prairie du Chien-Jordan aquifer and, ultimately, discharge of this flow to the Mississippi River. Variation of the vertical hydraulic conductivity of the upper confining unit resulted in about a 25-ft average difference in hydraulic heads in the confined-drift and St. Peter aquifers and the Prairie du Chien-Jordan aquifer. Variations in the horizontal hydraulic conductivity of the Prairie du Chien-Jordan aquifer, vertical hydraulic conductivity of the lower confining unit, and recharge to the confined-drift and St. Peter aquifers resulted in average differences in hydraulic heads of about 4 to 10 ft. Hydraulic head is relatively insensitive to changes in the values of other properties.

Table 6.--*Sensitivity of hydraulic heads in the Prairie du Chien-Jordan aquifer (model layer 2) to changes in values of hydraulic properties and fluxes in the two-layer steady-state simulation for 1885-1930*

[Mean deviation of hydraulic heads from values calculated by best-match simulation; deviation calculated at 24 cells in Prairie du Chien-Jordan model layer where field data are available. Numbers in parentheses show number of cells with positive or negative deviations. -- indicates all deviations are positive or all deviations are negative]

Hydrologic Property or condition	Multiplied by factor of:	Mean deviation of hydraulic heads (feet)	Maximum deviation (feet)	Minimum deviation (feet)
Leakage to layer 1	1.25	+ 3.5 (24) --	+5.2 --	+1.0 --
Leakage to layer 1	.75	-- - 3.5 (24)	-- +5.1	-- -1.0
Horizontal hydraulic conductivity of layer 1	1.50	+ 1.7 (6) - 1.1 (18)	+3.3 -2.2	+ .8 - .1
Horizontal hydraulic conductivity of layer 1	.50	+ 1.9 (18) - 1.6 (6)	+3.0 -3.6	+ .4 - .4
Horizontal hydraulic conductivity of layer 2	1.50	+ 4.1 (12) - 2.5 (12)	+9.9 -4.7	+1.0 - .2
Horizontal hydraulic conductivity of layer 2	.50	+ 5.9 (13) - 5.2 (11)	+10.7 -13.7	+ .5 - .5
Vertical hydraulic conductivity of confining layer	10.00	+ .2 (3) - 1.2 (21)	+ .5 -4.9	0 - .1
Vertical hydraulic conductivity of confining layer	.10	+ 3.2 (20) - 1.8 (4)	+8.1 -3.1	0 -2.1
Vertical hydraulic conductivity of riverbed material	10.00	-- -19.2 (24)	-- -69.9	-- -1.0
Vertical hydraulic conductivity of riverbed material	.10	+36.2 (24) --	+87.4 --	+1.3 --

Table 7.--*Simulated water budget for the two-layer steady-state simulation*

[Numbers in parentheses are percentages of total sources or percentages of total discharges]

Budget component	Source (cubic feet per second)	Discharge (cubic feet per second)
Leakage to layer 1	59.6 (72.2)	--
River leakage	--	81.6 (98.8)
Constant head		
Layer 1	4.6 (5.5)	0.3 (.4)
Layer 2	18.4 (22.3)	0.7 (.8)
Subtotal	23.0 (27.8)	1.0 (1.2)
Total	82.6	82.6
Leakage between model layers through confining units		
Layer 1	53.7	36.0
Layer 2	36.0	53.7
Total	89.7	89.7

Table 8.--*Initial values of hydraulic properties and fluxes in the three-layer steady-state simulation for 1885-1930*

[ft/d, feet per day; ft^2/d, feet squared per day; in/yr, inches per year; - -, not applicable]

Hydrogeologic unit	Horizontal hydraulic conductivity (ft/d)	Transmissivity (ft^2/d)	Vertical hydraulic conductivity (ft/d)	Recharge and leakage (in/yr)
Unconfined-drift aquifer	200	--	--	11.0
Upper drift confining unit	--	--	2.0×10^{-3}	--
Decorah-Platteville-Glenwood confining unit	--	--	3.5×10^{-4}	--
Confined-drift aquifer	40	0-5,000	--	2.0
St. Peter aquifer	20	0-3,000	--	2.0
Basal-drift confining unit	--	--	5.0×10^{-3}	--
Basal St. Peter confining unit	--	--	1.5×10^{-3}	--
Prairie du Chien-Jordan aquifer	60	0-15,000	--	--
Mississippi riverbed	--	--	1.0	--

Table 9.--*Final adjusted values of hydraulic properties and fluxes in the three-layer steady-state simulation for 1885-1930*

[ft/d, feet per day; ft^2/d, feet squared per day; in/yr, inches per year; --, not applicable]

Hydrogeologic unit	Horizontal hydraulic conductivity (ft/d)	Transmissivity (ft^2/d)	Vertical hydraulic conductivity (ft/d)	Recharge and leakage (in/yr)
Unconfined-drift aquifer	150-300	--	--	6.5
Upper drift confining unit	--	--	1.0×10^{-3}	--
Decorah-Platteville-Glenwood confining unit	--	--	1.0×10^{-4}	--
Confined-drift aquifer	40	0-5,000	--	1.0 and 2.3
St. Peter aquifer	20	0-3,000	--	1.0 and 2.3
Basal-drift confining unit	--	--	2.5×10^{-3}	--
Basal St. Peter confining unit	--	--	1.5×10^{-3}	--
Prairie du Chien-Jordan aquifer	60	0-15,000	--	--
Mississippi riverbed	--	--	1.0	--

The simulated water budget is shown in table 11. Recharge to the unconfined-drift aquifer (layer 1) accounts for about 46 percent of the sources of water to the aquifer system, whereas leakage to the confined-drift and St. Peter aquifers accounts for about 27 percent and boundary inflow accounts for about 26 percent. The discharge from the aquifer system consists of discharge to the Mississippi River (about 88 percent of the total), ground-water evapotranspiration from the unconfined-drift aquifer (about 9 percent of the total), and boundary outflow (about 3 percent of the total).

Steady-state simulation for 1970-79.-- The three-layer model was used to simulate average winter conditions in the aquifer system during 1970-79, a period of large annual ground-water withdrawals, to further refine and improve the steady-state calibration. The period 1970-79 was chosen because (1) hydraulic head and water-use data were available, and (2) no significant change, other than seasonal fluctuations, occurred in hydraulic heads in the aquifer system from 1970 through 1979. The differences between predevelopment (1885-1930) hydraulic heads and 1970-79 average winter hydraulic heads were used to calibrate the steady-state model for 1970-79. Average annual ground-water withdrawals for 1970-79 were used in the simulations (fig. 29 and 30). The simulated pumpage was about 30.5 billion gallons per year from high-capacity wells within the modeled area. About 94 percent of the water was withdrawn from the Prairie du Chien-Jordan aquifer, about 6 percent was withdrawn from the confined-drift and St. Peter aquifers and only about 0.1 percent was withdrawn from the unconfined-drift aquifer. Simulated pumpage from wells open to more than one model layer was divided in relation to the transmissivities of the open intervals in each layer.

Table 10.--*Sensitivity of hydraulic heads in the Prairie du Chien-Jordan aquifer (model layer 3) to changes in values of hydraulic properties and fluxes in the three-layer steady-state simulation for 1885-1930*

[Mean deviation of hydraulic heads from values calculated by best-match simulation; deviation calculated at 24 cells in Prairie du Chien-Jordan model layer where field data are available. Numbers in parentheses show number of cells with positive or negative deviations. --indicates all deviations are positive or all deviations are negative.]

Hydrologic property or condition	Multiplied by factor of	Mean deviation of hydraulic heads (feet)	Maximum deviation (feet)	Minimum deviation (feet)
Recharge to layer 1	1.083	+ 0.1 (24) --	+0.2 --	0.0 --
Recharge to layer 1	.917	-- - .1 (24)	-- - .3	-- 0
Horizontal hydraulic conductivity of layer 1	1.50	-- - 1.2 (24)	-- -5.3	-- 0
Horizontal hydraulic conductivity of layer 1	.50	+ 2.0 (13) - 1.2 (11)	+6.0 -2.5	+ .2 - .1
Horizontal hydraulic conductivity of layer 2	1.50	+ 1.2 (3) - 5.1 (21)	+3.0 -10.9	0 -1.7
Horizontal hydraulic conductivity of layer 2	.50	+ 2.3 (20) - 1.5 (4)	+8.8 -1.9	+ .6 -1.0
Horizontal hydraulic conductivity of layer 3	1.50	+ 2.1 (6) - 4.7 (18)	+5.0 -10.4	+ .4 - .3
Horizontal hydraulic conductivity of layer 3	.50	+ 5.2 (9) - 9.4 (15)	+12.8 -21.6	+1.1 -1.6
Vertical hydraulic conductivity of upper confining layer	10.00	+ 2.7 (1) -24.5 (23)	-- -77.0	-- - .5
Vertical hydraulic conductivity of upper confining layer	.10	+23.3 (24) --	+65.9 --	+1.5 --
Vertical hydraulic conductivity of lower confining layer	10.00	+ 7.6 (19) - 2.8 (5)	+23.3 -5.7	+ .9 -1.3
Vertical hydraulic conductivity of lower confining layer	.10	+ 9.7 (19) - 2.2 (5)	+26.0 -5.5	+ .8 - .5
Vertical hydraulic conductivity of riverbed material	10.00	-- - .5 (24)	-- -1.2	-- 0
Vertical hydraulic conductivity of riverbed material	.10	+ 3.0 (24) --	+6.8 --	+0.1 --
Ground-water evapotranspiration rate	1.49	+ .1 (24) --	+ .2 --	0 --
Ground-water evapotranspiration rate	.76	-- - .2 (24)	-- - .5	-- 0
Ground-water evapotranspiration extinction depth	1.50	-- - .1 (24)	-- - .1	-- 0
Ground-water evapotranspiration extinction depth	.50	+ .1 (24) --	+ .2 --	0 --
Leakage to layer 2	1.50-1.22	+ 3.9 (24) --	+5.8 --	+ .8 --
Leakage to layer 2	.50- .78	-- - 3.9 (24)	-- -5.8	-- - .9

Table 11.--*Simulated water budget for the steady-state simulation for 1885-1930*

[Number in parentheses is percentage of total sources or percentage of total discharges]

Budget Component	Source (cubic feet per second)	Discharge (cubic feet per second)
Recharge to layer 1	77.5 (46.5)	--
Leakage to layer 2	44.6 (26.8)	--
Subtotal	122.1 (73.3)	--
River leakage	1.2 (.7)	146.1 (87.7)
Constant head		
Layer 1	4.7 (2.8)	--
Layer 2	13.4 (8.0)	2.4 (1.4)
Layer 3	25.1 (15.1)	3.1 (1.9)
Subtotal	43.2 (25.9)	5.5 (3.3)
Ground-water evapotranspiration (from layer 1)	--	14.9 (9.0)
Total	166.5	166.5
Leakage between model layers through confining units		
Layer 1	79.1	1.4
Layer 2		
Through upper confining unit	1.4	79.1
Through lower confining unit	53.1	31.0
Layer 3	31.0	53.1
Total	164.6	164.6

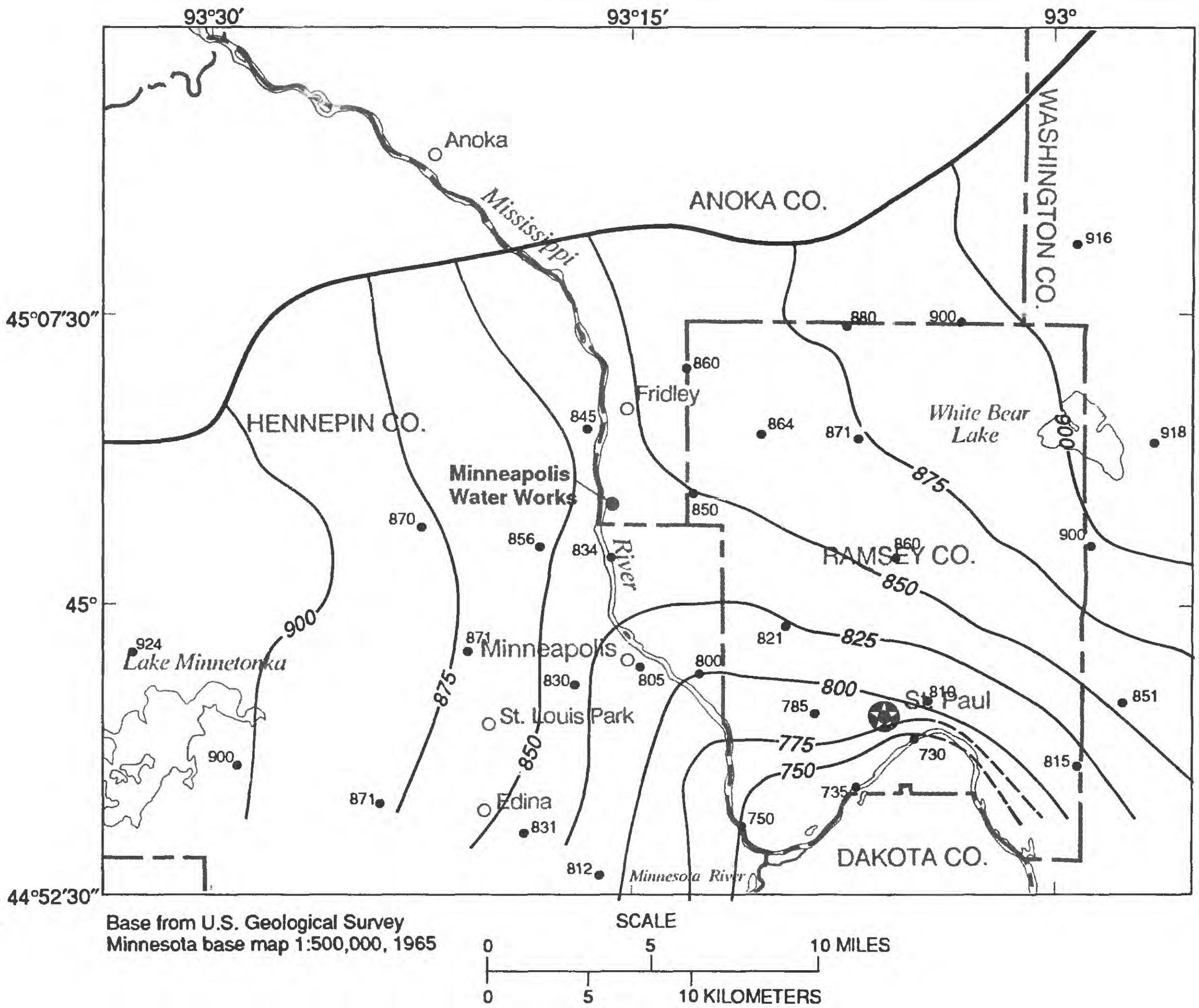
The principle of superposition was used in the simulation of 1970-79 average winter conditions. The principle of superposition means that, for linear systems, the solution to a problem involving multiple inputs or stresses is equal to the sum of the solutions to the simpler individual problems that form the composite problem (Reilly and others, 1987). For example, two different potentiometric distributions resulting from two separate stresses in a confined aquifer can be added together to obtain the potentiometric distribution resulting from the sum of the two stresses. In ground-water problems involving a linear governing equation, the effects of individual changes (or stresses) can be evaluated without consideration of the other concurrent stresses on the system. In using superposition to solve ground-water-flow problems, the appropriate quantities are changes in hydraulic head and changes in flow rather than absolute values of head and flow. The natural hydrologic boundaries and the initial conditions must be represented in models in terms of changes rather than in terms of the observed values.

Defining the boundary conditions in a simulation based on superposition means representing the change in head or flow that will occur at these boundaries. Constant-head and specified-head boundaries are represented as zero-potential boundaries corresponding to zero drawdown or no change in hydraulic head. If the absolute value of hydraulic head does not change at these boundaries in the natural system, the superposition model represents these boundaries as having no drawdown or buildup of hydraulic head. If a change in hydraulic head occurs at one of these boundaries, then the absolute value of this change in head becomes the new value of constant head in the superposition model. For the 1970-79 steady-state superposition model, (1) the northern boundary for all three layers was represented as a zero-potential boundary, and (2) parts of the eastern and western boundaries were assigned a negative constant head corresponding to the difference (drawdown) between predevelopment (1885-1930) and 1970-79 average winter hydraulic heads. Leakage across a confining unit from a specified-head source is represented in superposition by maintaining the source at zero drawdown, or zero change in hydraulic head. As a result, the flow through the confining unit in the superposition model represents the change in flow through the unit in the natural system due to the stress. River stage in each node was maintained at a constant zero potential.

Stresses are represented in superposition models in a manner similar to the representation of boundaries--only changes in stress are represented. In superposition models, constant-flux boundaries are represented by zero change in flow (zero-flux boundaries) because the assumption that flow across these boundaries remains constant implies that change in flow is zero. If, for example, the assumption is made that natural recharge to the geohydrologic system does not change in response to ground-water withdrawals from the aquifers, then the boundary at which recharge occurs is represented as a no-flow (zero-flux) boundary. In the steady-state superposition model for 1970-79, leakage was applied to the confined-drift and St. Peter aquifers (layer 2) in areas where ground-water withdrawals had resulted in declines in hydraulic heads in the Prairie du Chien-Jordan aquifer from the predevelopment period (1885-1930) to the 1970's. The applied leakage represents an increase in leakage to the confined-drift and St. Peter aquifers caused by changes in vertical and horizontal hydraulic gradients, which in turn result from the general lowering of hydraulic heads caused by pumping of wells.

The average annual ground-water withdrawals for 1970-79 represent the change in stress (compared to predevelopment conditions) on the aquifer system to be simulated by the steady-state superposition model for 1970-79. Drawdowns in response to these ground-water withdrawals are determined by the model through superposition.

The assumption is made that evapotranspiration does not change as a result of the change in pumpage from wells and that the evapotranspiration rate in the superposition model, therefore, is zero. The initial hydraulic head distribution in the superposition model is taken as zero in all aquifers and represents zero change in head or drawdown.



EXPLANATION

Generalized aquifer boundary

—800— Simulated potentiometeric contour--Dashed where approximate. Contour interval 25 feet. Datum is sea level.

•815 Observation well--Number shown is elevation of water level measured in well.

Figure 28.--Water levels measured in wells completed in the Prairie du Chien-Jordan aquifer, 1885-1930, and simulated potentiometric surface of the Prairie du Chien-Jordan aquifer (model layer 3), three-layer steady-state simulation, 1885-1930.

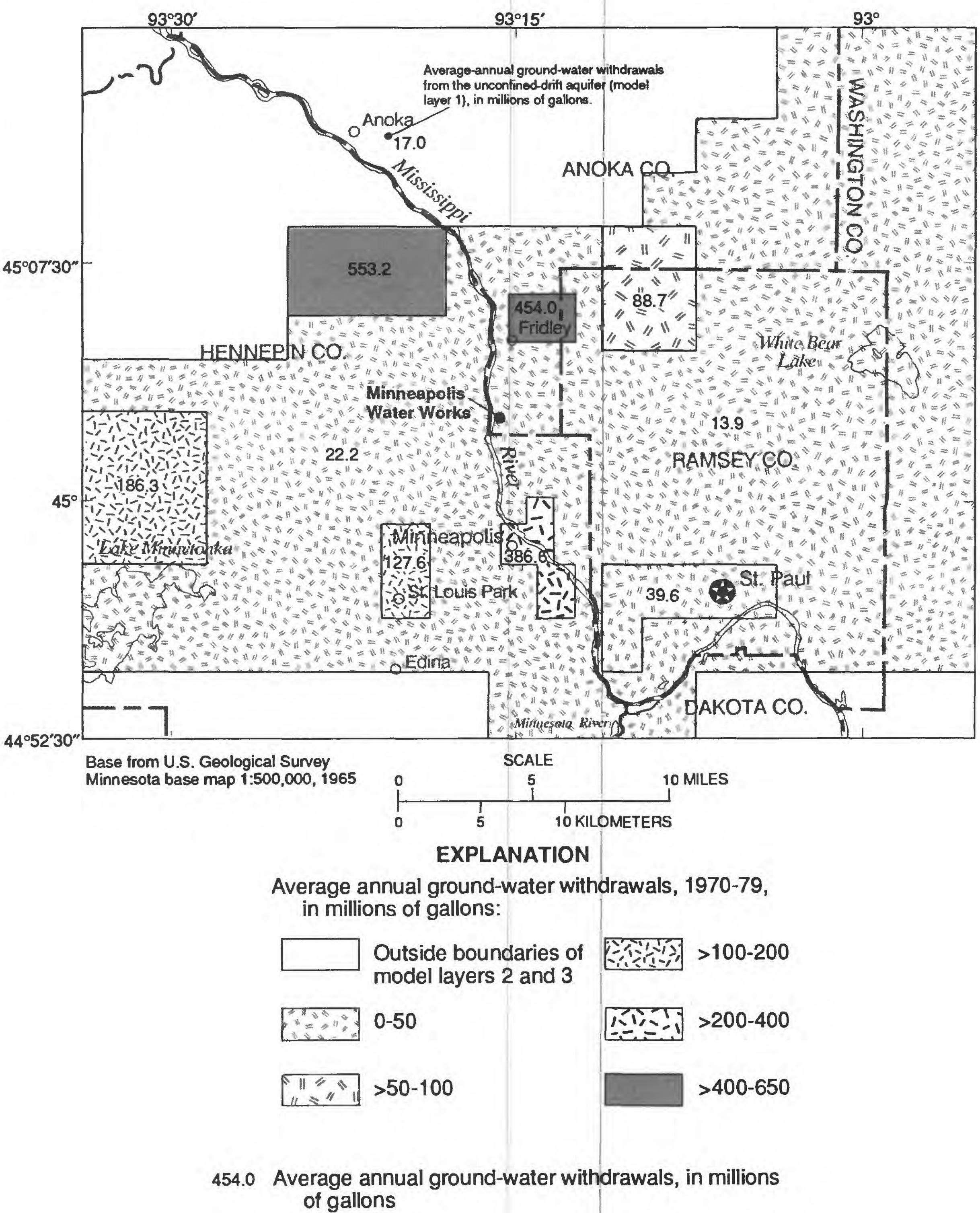


Figure 29.--Distribution of average-annual ground-water withdrawals from high-capacity wells in the unconfined-drift aquifer (model layer 1) and confined-drift and St. Peter aquifer (model layer 2), 1970-79.

An important constraint in the use of superposition in ground-water problems is that the governing differential equation and boundary conditions must be linear. In general, flow in confined aquifers is described by linear differential equations, whereas flow in unconfined aquifers is described by nonlinear differential equations. The principle of superposition may be used, however, if the regional drawdown in an unconfined aquifer is small relative to the full saturated thickness of the aquifer (as a rule of thumb, 10 percent or less) (Reilly and others, 1987). For the unconfined-drift aquifer in the study area, no significant long-term change (drawdown) in hydraulic head has occurred. Therefore, in the steady-state superposition model for 1970-79, the unconfined-drift aquifer is simulated as a confined aquifer with a constant, areally variable transmissivity.

The initial values for the hydrologic properties used in the steady-state superposition model for 1970-79 were the same as the calibrated best-fit values from the steady-state model for 1885-1930 (table 9). Stark and Hult (1985) report an increase in recharge from 1885 to 1970-77 of 3.5 in/yr to the St. Peter aquifer in the St. Louis Park area because of increased ground-water withdrawals and the general lowering of hydraulic head in the pumped aquifers. An areally uniform increased leakage rate of 3.5 in/yr was initially applied to the confined-drift and St. Peter aquifers (model layer 2). Increased recharge to the unconfined-drift aquifer was zero (zero-flux boundary) because hydraulic heads in the aquifer were relatively unaffected by the ground-water withdrawals.

A detailed analysis was conducted of available drillers' logs and previous reports in the area surrounding the Minneapolis Water Works. Estimates of hydrologic properties, including aquifer and confining-unit thicknesses, were refined, and the improved estimates were incorporated in the model.

The steady-state superposition model was calibrated by adjusting selected values of hydrologic properties of the aquifer system until the average deviation between simulated and measured drawdowns was minimized. Early in the calibration process, an areally uniform rate of increased leakage to the confined-drift and St. Peter aquifers did not adequately simulate hydraulic heads in the aquifers. To improve the match between simulated and measured drawdowns, increased leakage was varied areally on the basis of the magnitude of ground-water withdrawals, drawdown in the Prairie du Chien-Jordan aquifer, and the areally variable leakage areas reported by Larson-Higdem and others (1975). The highest increased leakage rates were applied to areas where ground-water withdrawals and drawdown were the greatest. The areally variable increased leakage rates range from 0 to 3.0 in/yr (fig. 31). The increased leakage is an additional source of water needed to simulate the observed drawdowns caused by ground-water withdrawals. The assumption was made for the ground-water-flow-model simulations that the confining layers release no water from storage to wells. Water released from storage in clay beds (confining units) in and adjacent to the aquifers, however, may be an important contributing source to the water released from storage to pumping wells (Jacob, 1940). Part of the additional water simulated in the model as increased leakage to the confined-drift and St. Peter aquifers may actually be derived from water released from storage in confining units, which is not simulated in the model. The magnitude and affect on hydraulic heads of the release of water from storage in confining units in the study area is not known. The affect of not accounting for storage in confining units in the simulations with ground-water withdrawals may be an overestimation of the magnitude of other sources of water, such as leakage, to pumped wells. The increased leakage rates, however, are within the reported range in values. Larson-Higdem and others (1975) estimate that increased leakage to the Prairie du Chien-Jordan aquifer from overlying deposits because of increased summer ground-water withdrawals ranges from 0 to about 1.5 in/yr for most of the Twin Cities Metropolitan Area, but is as much as 6 in/yr in some areas. Increased leakage to the confined-drift and St. Peter aquifers is assumed to be similar to that for the Prairie du Chien-Jordan aquifer. Stark and Hult (1985) report a leakage rate of 5.5 in/yr to the St. Peter aquifer in Hennepin County in the western part of the study area for the period 1970-77, an increase of 3.5 in/yr compared to the rate of 2.0 in/yr for the period prior to significant ground-water withdrawals (prior to 1930). In addition to adjustments to leakage, the transmissivities of the Prairie du Chien-Jordan aquifer and vertical hydraulic conductivities of the upper and lower confining units were adjusted within reported ranges to improve the match between measured and simulated drawdowns. The transmissivities of the Prairie du Chien-Jordan aquifer were uniformly increased by a factor of 1.17 (horizontal hydraulic conductivity was increased from 60 to 70 ft/d). The vertical hydraulic conductivity of the upper drift confining unit was decreased from 0.001 to 0.0002 ft/d in the southern part of the model area. A value of 0.1 ft/d was specified for the vertical hydraulic conductivity of the drift north of the Minneapolis Water Works where the upper drift confining unit is absent. Norvitch and others (1974) report a value of 0.175 for the drift that fills bedrock valleys in the Twin Cities Metropolitan Area. The vertical hydraulic conductivity of the lower confining unit was increased to 0.025 ft/d in the northern part of the model area and decreased to 0.00005 ft/d in the southern part. The vertical hydraulic conductivity of the lower confining unit varies greatly between the northern and southern parts of the model area because the composition of the unit differs in the two parts. In the northern part, the lower confining unit consists of the basal St. Peter confining unit, which is discontinuous, and the basal-drift confining unit and has a relatively high vertical hydraulic conductivity. In the southern part, the basal St. Peter confining unit comprises the lower confining unit and is generally continuous with a relatively low vertical hydraulic conductivity. Simulated drawdowns were generally within 10 ft of measured drawdowns for the confined-drift and St. Peter aquifers (fig. 32) and the Prairie du Chien-Jordan (fig. 33) aquifer. The average difference between simulated and measured drawdowns was 5.1 ft in the confined-drift and St. Peter aquifers (7 wells measured) and 5.9 ft in the Prairie du Chien-Jordan aquifer (30 wells measured). Drawdowns in the unconfined-drift aquifer (model layer 1) were generally about 3 ft or less; however, in areas where the upper confining unit is absent or discontinuous, drawdowns were as much as 10 ft. Values of hydrologic properties used in the model for the best-fit simulation are listed in table 12.

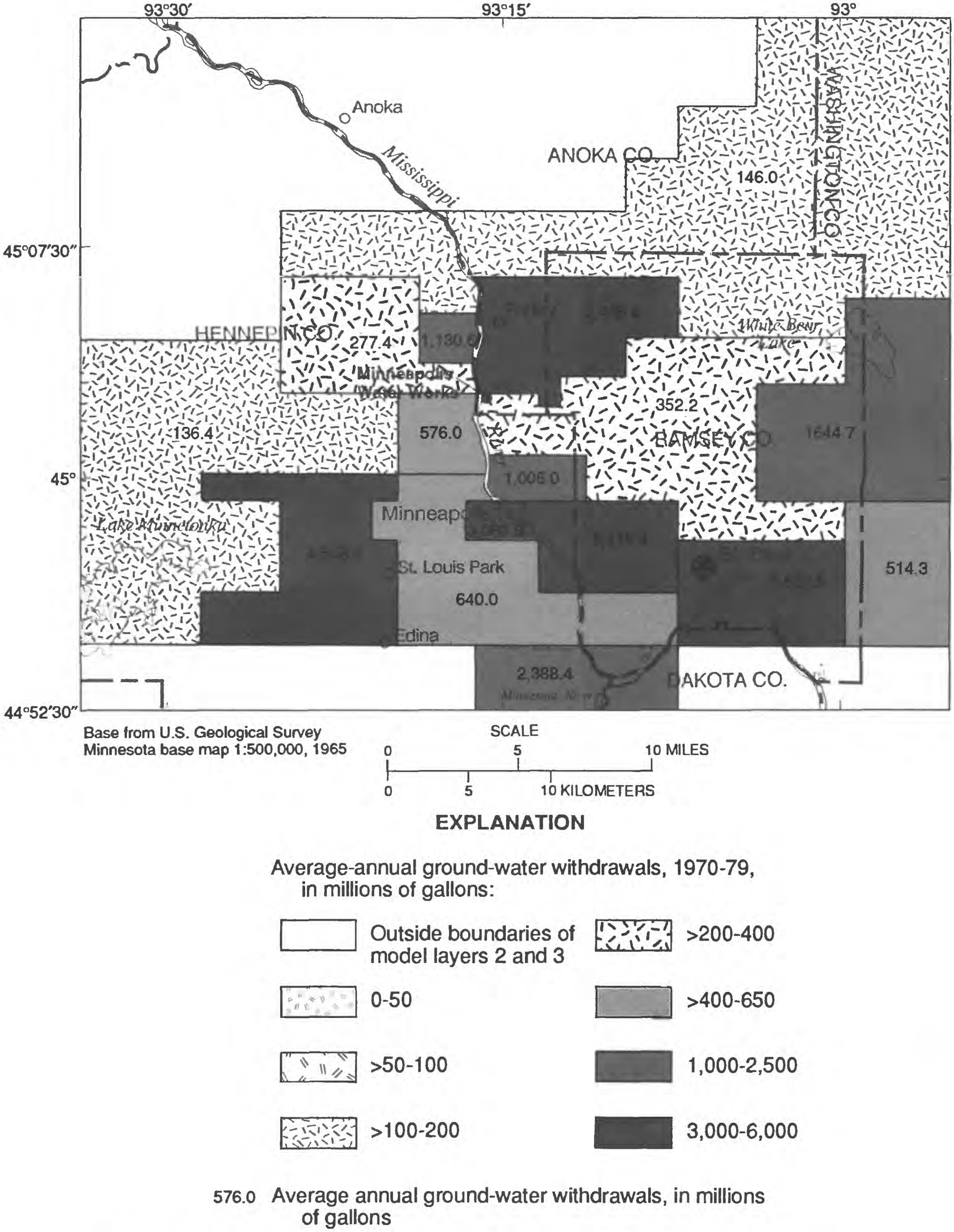
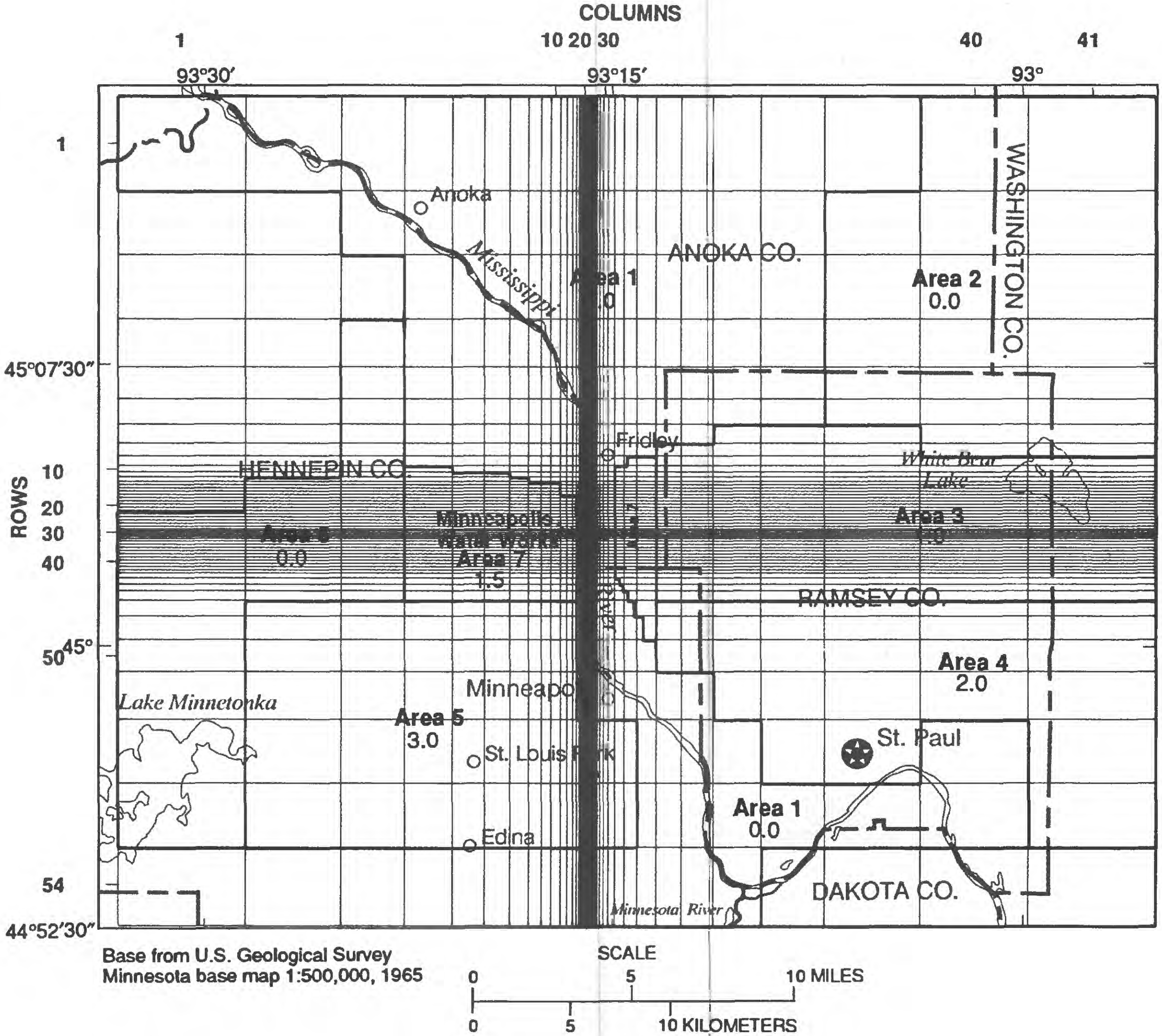


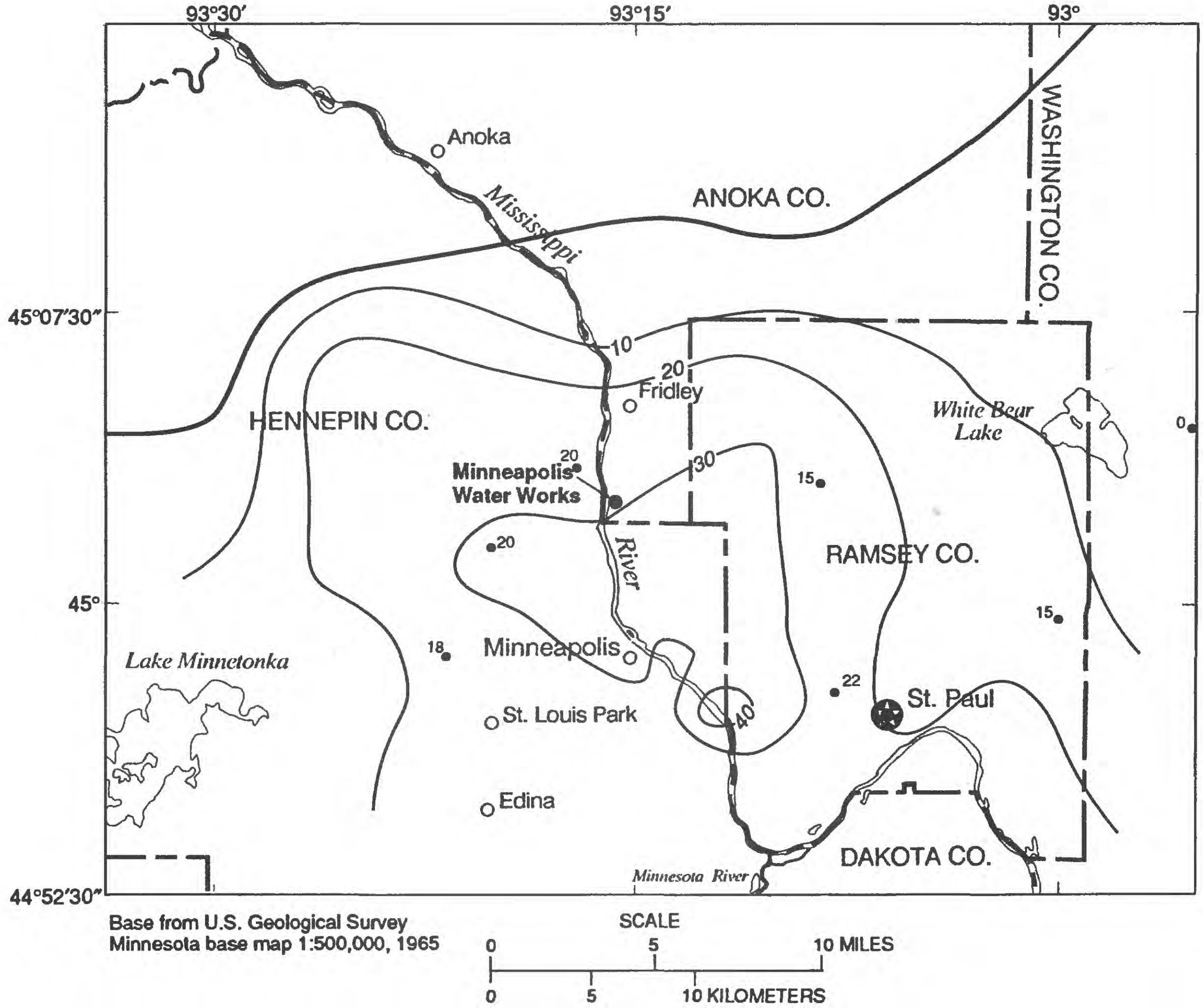
Figure 30.--Distribution of average-annual ground-water withdrawals from high-capacity wells in the Prairie du Chien-Jordan aquifer (model layer 3), 1970-79.



EXPLANATION

2.0 Simulated increase in recharge, in inches per year

Figure 31.--Simulated increase in recharge to the unconfined-drift aquifer (model layer 1; area 1) and leakage to the confined-drift and St. Peter aquifers (model layer 2; areas 2-7) in the steady-state simulation, 1970-79, as compared to predevelopment (1885-1930) steady-state recharge.



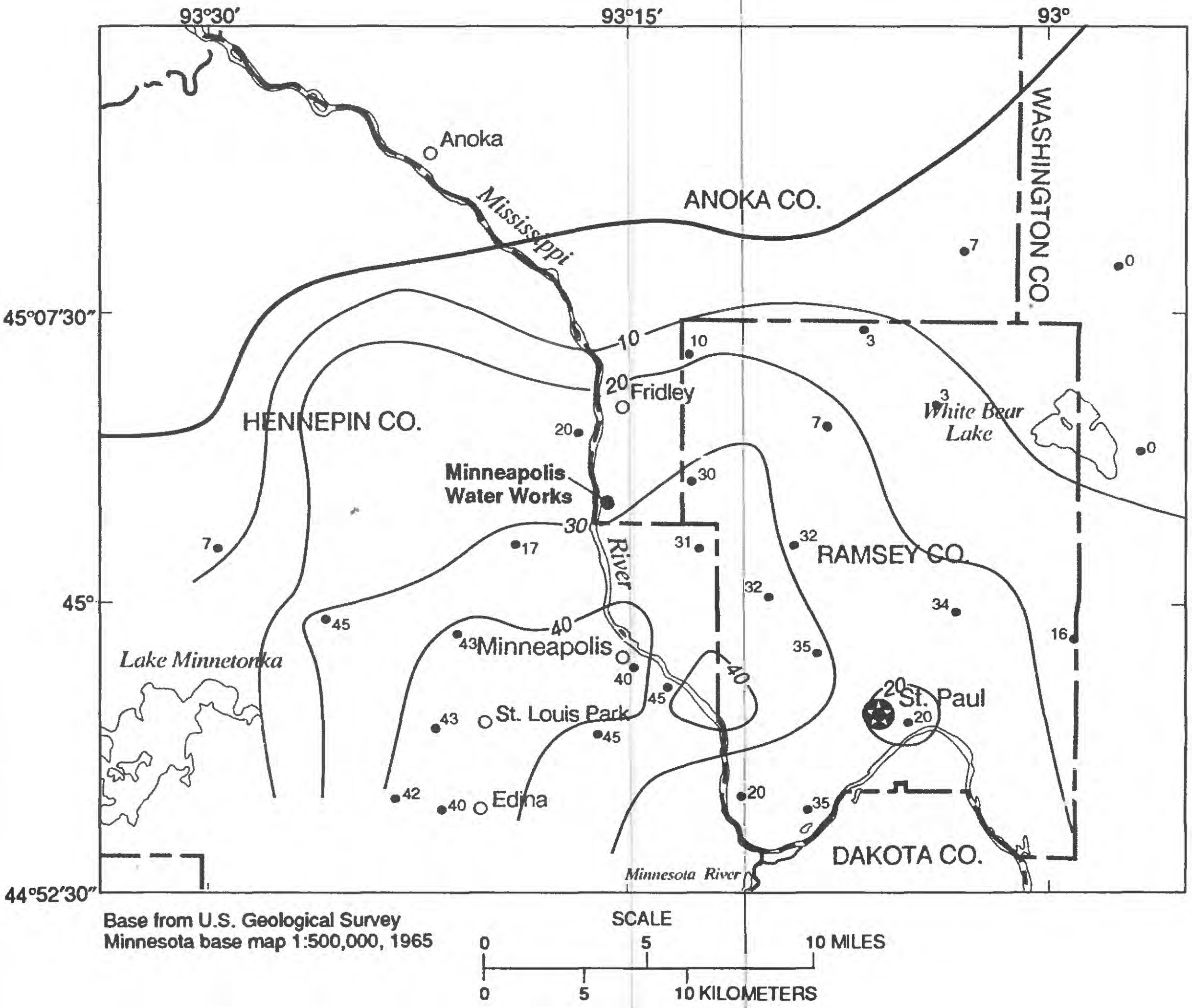
EXPLANATION

——— Generalized aquifer boundary

—20— Line of equal simulated drawdown in the confined-drift and St. Peter aquifers--Interval 10 feet.

18• Observation well--Number shown is decline in water level measured in well.

Figure 32.--Measured hydraulic head declines in the confined-drift and St. Peter aquifers, 1885-1930 and through the 1970's, and simulated drawdowns in the confined-drift and St. Peter aquifers (model layer 2), steady-state simulation, 1970-79.



EXPLANATION

—— Generalized aquifer boundary

—20— Line of equal simulated drawdown in the Prairie du Chien-Jordan--Interval 10 feet.

17• Observation well--Number shown is decline in water level measured in well.

Figure 33.--Measured hydraulic head declines in the Prairie du Chien-Jordan aquifer, 1885-1930 and through the 1970's, and simulated drawdowns in the Prairie du Chien-Jordan aquifer (model layer 3), steady-state simulation, 1970-79.

Table 12.--*Values of hydraulic properties and fluxes in the three-layer steady-state simulation for 1970-79*

[ft/d, feet per day; ft^2/d, feet squared per day; in/yr, inches per year; --, not applicable]

Hydrogeologic unit	Horizontal hydraulic conductivity (ft/d)	Transmissivity (ft^2/d)	Vertical hydraulic conductivity (ft/d)	Recharge and leakage (in/yr)
Unconfined-drift aquifer	200	0-14,000	--	0
Upper-drift confining unit	--	--	Variable, 1.0×10^{-3} to 2.0×10^{-4}	--
Decorah-Platteville-Glenwood confining unit	--	--	1.0×10^{-4}	--
Confined-drift aquifer	40	0-5,600	--	Variable, 0-3
St. Peter aquifer	20	0-3,000	--	Variable, 0-3
Basal-drift confining unit	--	--	$2.5\ 10^{-2}$	--
Basal St. Peter confining unit	--	--	5.0×10^{-5}	--
Prairie du Chien-Jordan aquifer	70	0-17,500	--	--
Mississippi riverbed	--	--	1.0	--

A model-sensitivity analysis was done to identify the relative effect of adjustments of hydrologic properties on simulated drawdowns (table 13 and 14). Tables 13 and 14 also show differences in the simulated drawdown for cell (30,23) which represents part of the Minneapolis Water Works site. Drawdown was found to be most sensitive to changes in ground-water withdrawals, decrease in the vertical hydraulic conductivity of the upper confining unit, and decrease in the vertical hydraulic conductivity of the lower confining unit. Doubling the ground-water withdrawals resulted in additional drawdowns in the confined-drift and St. Peter aquifers (model layer 2) and Prairie du Chien-Jordan aquifer (model layer 3) of about 25 to 30 ft; whereas, decreasing ground-water withdrawals by 50 percent resulted in a decrease in drawdowns of about 12 to 15 ft. Variations in recharge to the confined-drift and St. Peter aquifers and the hydraulic conductivity of the Prairie du Chien-Jordan aquifer resulted in average differences in hydraulic heads of about 3 to 7 ft in both model layers 2 and 3. Drawdown is relatively insensitive to changes in the values of other hydrologic properties. Other than ground-water withdrawals, variations in the vertical hydraulic conductivity of the upper confining unit resulted in the greatest difference in simulated drawdowns in model layers 2 and 3 for cell (30,23).

Table 13.--*Sensitivity of hydraulic heads in the confined-drift and St. Peter aquifers (model layer 2) to changes in values of hydraulic properties and fluxes in the steady-state simulation for 1970-79*

[Mean deviation of drawdowns from values calculated by best-match simulation; deviation calculated at 13 cells in confined-drift and St. Peter aquifers model layer where field data are available. Numbers in parentheses show number of cells with positive or negative deviations. -- indicates all deviations are positive or all deviations are negative.]

Hydrologic property or condition	Multiplied by factor of	Mean deviation of drawdowns (feet)	Deviation at node (30,23)	Maximum deviation (feet)	Minimum deviation (feet)
Leakage to layer 2	1.50	+ 5.2 (13) --	+ 3.0	+19.5 --	+0.1 --
Leakage to layer 2	.50	-- - 5.3 (13)	- 3.1	-- -19.8	-- + .1
Horizontal hydraulic conductivity of layer 1	1.50	+ .2 (13) --	+ .6	+ .6 --	0 --
Horizontal hydraulic conductivity of layer 1	.50	-- - .4 (13)	- 1.0	-- -1.0	-- 0
Horizontal hydraulic conductivity of layer 2	1.50	+ 1.2 (13) --	+ 1.3	+2.3 --	0 --
Horizontal hydraulic conductivity of layer 2	.50	+ .8 (1) - 1.7 (12)	- 2.0	-- -2.9	-- + .1
Horizontal hydraulic conductivity of layer 3	1.50	+ 2.6 (13) --	+ 1.8	+6.8 --	0 --
Horizontal hydraulic conductivity of layer 3	.50	-- - 5.1 (13)	- 3.2	-- -14.8	-- - .1
Vertical hydraulic conductivity of upper confining layer	10.00	+ 6.4 (13) --	+ 6.4	+12.9 --	0 --
Vertical hydraulic conductivity of upper confining layer	.10	-- -17.4 (13)	-15.4	-- -43.1	-- - .1
Vertical hydraulic conductivity of lower confining layer	10.00	+ .4 (10) - 2.2 (3)	+ .6	+ .8 -5.3	0 - .3
Vertical hydraulic conductivity of lower confining layer	.10	+16.0 (2) - 4.1 (11)	- 5.2	+28.4 -7.3	+3.6 - .1
Vertical hydraulic conductivity of riverbed material	10.00	+ 0.5 (13) --	+ 1.1	+1.1 --	0 --
Vertical hydraulic conductivity of riverbed material	.10	-- - .6 (13)	- 1.1	-- -1.1	-- 0
Pumpage	2.00	-- -25.5 (13)	-21.7	-- -58.1	-- - .4
Pumpage	.50	+12.7 (13) --	+10.7	+28.8 --	+ .2 --

Table 14.--*Sensitivity of hydraulic heads in the Prairie du Chien-Jordan aquifer (model layer 3) to changes in values of hydraulic properties and fluxes in the steady-state simulation for 1970-79*

[Mean deviation of drawdowns from values calculated by best-match simulation; deviation calculated at 39 cells in Prairie du Chien-Jordan model layer where field data are available. Numbers in parentheses show number of cells with positive or negative deviations. -- indicates all deviations are positive or all deviations are negative.]

Hydrologic property or condition	Multiplied by factor of	Mean deviation of drawdowns (feet)	Deviation at node (30,23)	Maximum deviation (feet)	Minimum deviation (feet)
Leakage to layer 2	1.50	+ 4.7 (39) --	+ 3.2	+14.5 --	+0.3 --
Leakage to layer 2	.50	-- - 4.7 (39)	- 3.2	-- -13.9	-- - .3
Horizontal hydraulic conductivity of layer 1	1.50	+ .2 (39) --	+ .6	+ .6 --	0 --
Horizontal hydraulic conductivity of layer 1	.50	-- - .4 (39)	- 1.0	-- -1.0	-- 0
Horizontal hydraulic conductivity of layer 2	1.50	+ 1.5 (39) --	+ 1.3	+2.9 --	+ .1 --
Horizontal hydraulic conductivity of layer 2	.50	-- - 1.9 (39)	- 1.9	-- -4.1	-- - .1
Horizontal hydraulic conductivity of layer 3	1.50	+ 3.7 (39) --	+ 1.8	+9.5 --	+ .1 --
Horizontal hydraulic conductivity of layer 3	.50	+ .2 (1) - 7.5 (38)	- 3.3	-- -21.3	-- - .3
Vertical hydraulic conductivity of upper confining layer	10.00	+ 7.5 (39) --	+ 6.3	+18.3 --	+ .2 --
Vertical hydraulic conductivity of upper confining layer	.10	-- -20.4 (39)	-15.4	-- -51.5	-- - .5
Vertical hydraulic conductivity of lower confining layer	10.00	+ 1.2 (39) --	+ .9	+3.2 --	0 --
Vertical hydraulic conductivity of lower confining layer	.10	-- -11.6 (39)	- 8.7	-- -30.5	-- - .2
Vertical hydraulic conductivity of riverbed material	10.00	+ .4 (39) --	+ 1.1	+1.2 --	0 --
Vertical hydraulic conductivity of riverbed material	.10	-- - .4 (39)	- 1.0	-- -1.2	-- 0
Pumpage	2.00	-- -31.1 (39)	-22.3	-- -67.6	-- -1.4
Pumpage	.50	+15.5 --	+11.1	+33.8 --	+ .7 --

Simulated changes in fluxes are shown in table 15. Leakage of water from the river to the unconfined-drift aquifer accounts for about 47 percent of the water withdrawn from the aquifers by pumpage, whereas boundary inflow accounts for about 30 percent and leakage to the confined-drift and St. Peter aquifers (in areas where the unconfined-drift aquifer is absent) accounts for about 23 percent. Nearly 75 percent of the boundary inflow is to the Prairie du Chien-Jordan aquifer. The increased boundary inflow is caused by the lowering of hydraulic heads in the aquifers caused by ground-water withdrawals and the resulting increase in hydraulic gradients across the boundaries. Ground-water withdrawals near the boundaries are generally minimal and declines in hydraulic heads therefore relatively small, with the exception of the southeast boundary. In the superposition simulation, the water-budget sources represent the changes in fluxes resulting from the simulated ground-water withdrawals. The simulated leakage of water from the Mississippi River to the unconfined-drift aquifer represents a reduction in the natural discharge of ground water to the river.

Table 15.--*Simulated changes in fluxes for the steady-state simulation for 1970-79*

[Numbers in parentheses are percentages of total sources or percentages of total discharges; --, not applicable]

Budget component	Source (cubic feet per second)	Discharge (cubic feet per second)
Recharge to layer 1	--	--
Leakage to layer 2	30.2 (23.4)	--
Subtotal	30.2 (23.4)	--
River leakage	60.6 (46.8)	--
Constant head		
Layer 1	.6 (.4)	--
Layer 2	10.6 (8.2)	--
Layer 3	27.4 (21.2)	--
Subtotal	38.6 (29.8)	--
Evapotranspiration	--	--
Pumpage		
Layer 1	--	.1 (0.1)
Layer 2	--	7.4 (5.7)
Layer 3	--	121.9 (94.2)
Subtotal	--	129.4
Total	129.4	129.4
Leakage between model layers through confining units		
Layer 1	.9	62.0
Layer 2		
Through upper confining unit	62.0	.9
Through lower confining unit	2.4	96.9
Layer 3	96.9	2.4
Total	162.2	162.2

Transient simulations

The numerical model was tested with limited transient data to refine values of hydrologic properties and review model sensitivity to aquifer storage. These transient simulations are used to establish the reliability of the numerical model to predict short-term drawdowns caused by stresses, such as seasonal changes in ground-water withdrawals.

Aquifer-test transient simulation.--Data from an aquifer test conducted by Ranney Company (1978) were used to improve and refine model values for the hydrologic properties of the aquifer system, particularly the vertical hydraulic conductivity of the Mississippi riverbed material and the upper confining unit in the immediate vicinity of the Minneapolis Water Works. The well pumped during the aquifer test was completed in the lower sand-and-gravel unit of the drift[1] filling the buried bedrock valley that traverses the Minneapolis Water Works site. The well was pumped at a rate of 1,500 gal/min (gallons per minute) for 72 hours. Drawdown was measured in six observation wells located from 58 to 200 ft away from the pumped well (fig. 34). Three of the wells were located along a line perpendicular to the nearby Mississippi River and three were located along a line parallel to the river. The pumped well and all six observation wells were located within a 200 ft by 300 ft area represented by cell (36,23) in the model grid. The large scale of the model grid and the location of the pumped well away from the center of the model cell make possible only a rough approximation of the aquifer test; however, the results of the simulation are valuable for checking and refining the model values for hydrologic properties. The principle of superposition was used in the aquifer-test simulation. The discharge of water from the pumped well represents the change in stress on the system simulated. The initial potential distribution, recharge, and evapotranspiration were zero. Values of hydrologic properties for the aquifers and confining units used in the calibrated best-fit steady-state superposition simulation for 1970-79 (table 12) were used as initial values in the aquifer-test simulation.

At the end of 72 hours of pumping, the measured drawdown in the pumped well was 65.6 ft. The measured drawdown in the observation well closest to the Mississippi River along the line of wells perpendicular to the river was 4.3 ft. Drawdowns in the wells had not stabilized at the end of the aquifer test, but were considered sufficiently stabilized for analysis (Ranney Company, 1978). An acceptable simulated drawdown in the confined-drift aquifer (model layer 2) for cell (36,23) was estimated to range from 15 to 20 ft on the basis of measured drawdowns shown in figure 34. The acceptable range of simulated drawdown was determined by estimating the approximate area of the model cell within each contoured drawdown interval and calculating an area-weighted averaged drawdown in the cell.

The initial value of specific yield for the unconfined-drift aquifer was 0.25, as reported by Helgesen and Lindholm (1973). The initial values of storage coefficients for the confined-drift and St. Peter aquifers and the Prairie du Chien-Jordan aquifer were average values given in published reports (table 3). The initial storage coefficients for the St. Peter aquifer

[1]This unit is represented by layer 2 of the three-layer model.

and the Prairie du Chien-Jordan aquifer were 1×10^{-4} and 6.5×10^{-4}, respectively. On the basis of values reported by the Ranney Company (1978) (table 3), a uniform storage coefficient of 3.7×10^{-4} was assigned to the confined-drift aquifer in the buried bedrock valley beneath the Minneapolis Water Works.

The aquifer-test model was calibrated by adjusting the vertical hydraulic conductivities of the Mississippi riverbed and upper confining unit in the immediate vicinity of the Minneapolis Water Works site until the simulated drawdown for model cell (36,23) for the confined-drift and St. Peter aquifers (model layer 2) was within 15 to 20 ft. The best-fit simulation produced drawdowns of 16.8 ft for cell (36,23) and 10.6 ft for cell (36,22). Calibration to the best-fit simulation required increases in the vertical hydraulic conductivity of the Mississippi riverbed material (from 1.0 to 2.25 ft/d) and of the upper confining unit in the vicinity of cell (36,23) to allow an increase in leakage of water from the Mississippi River downward to the confined-drift aquifer. The aquifer-test simulation was found to be relatively insensitive to variations in specific yield for the unconfined-drift aquifer and storage coefficients for the confined-drift and St. Peter aquifers and Prairie du Chien-Jordan aquifer. Values of specific yield and storage coefficients were maintained at their initial values.

The simulated changes in flow resulting from the simulated ground-water withdrawals are shown in table 16. At the end of 72 hours, about 49 percent of the pumped water is derived from river leakage, and about 51 percent is derived from aquifer storage. About 70 percent of the water released from storage is from the unconfined-drift aquifer; only about 6 percent is from the confined-drift and St. Peter aquifers (model layer 2).

Transient simulation for 1980-87.--The three-layer model was used to simulate seasonally variable ground-water withdrawals and the resulting fluctuations in potentiometric surfaces during 1987. Actual potentiometric surfaces, boundary conditions, and stresses on the aquifer system were used for this simulation rather than changes in these hydrologic conditions, as used in the steady-state simulation for 1970-79 and the aquifer-test simulation. A transient simulation for 1980-86 was done with seven annual stress periods to establish initial conditions for 1987. The simulated hydraulic heads at the end of the simulation for 1980-86 were used as the initial heads in the simulation for 1987.

Reported annual ground-water withdrawals by high-capacity wells within the model area were compiled and used in the transient simulation. The hydraulic heads from the steady-state superposition simulation for 1970-79, calculated as predevelopment hydraulic heads minus simulated drawdown through 1970-79, were used as starting heads in the transient simulation for 1980-86. Values for the regional hydrologic properties of the aquifer system from the calibrated steady-state superposition model for 1970-79 were used as initial values in the 1980-86 transient simulation (table 12). Values for the hydrologic properties of the aquifer system near the Minneapolis Water Works were the same as those from the calibrated aquifer-test transient simulation. Initial values of specific yield and storage coefficients were the same as the initial values used in the aquifer-test transient simulation. The initial value for recharge to the unconfined-drift aquifer was 7.0 in/yr. The greater recharge to the unconfined-drift aquifer used in the transient simulation for 1980-86 as compared to the three-layer steady-state simulation for 1885-1930 (6.5 in/yr) reflects above-normal precipitation during 1980-86. Initial values for leakage to the confined-drift and St. Peter aquifers (model layer 2) were the sums of recharge from the steady-state simulation for 1885-1930 and the steady-state superposition simulation for 1970-79. The initial spatially variable values for leakage to the confined-drift and St. Peter aquifers ranged from 1 to 5.3 in/yr.

Table 16.--*Simulated changes in fluxes for the transient aquifer-test simulation*

[Numbers in parentheses are percentages of total sources and percentages of total discharges; --, not applicable]

Budget component	Source (cubic feet per second)	Discharge (cubic feet per second)
River leakage	1.6 (48.5)	--
Constant head		
Layer 1	0	--
Layer 2	0	--
Layer 3	0	--
Subtotal	0	--
Storage		
Layer 1	1.2 (36.4)	--
Layer 2	.1 (3.0)	--
Layer 3	.4 (12.1)	--
Subtotal	1.7 (51.5)	--
Pumpage (layer 2)	--	3.3
Total	3.3	3.3
Leakage between model layers through confining units		
Layer 1	0	2.7
Layer 2		
Through upper confining unit	2.7	0
Through lower confining unit	.7	.1
Layer 3	.1	.7
Total	3.5	3.5

The transient simulation for 1980-86 was calibrated by adjusting the transmissivities of the confined-drift and St. Peter and Prairie du Chien-Jordan aquifers and leakage to the confined-drift and St. Peter aquifers within reported ranges until the simulated hydraulic heads at the end of the simulation acceptably matched water levels measured in wells during January and February of 1987 and 1988[1]. The transmissivities of the confined-drift and St. Peter aquifers were uniformly decreased by a factor of 2 (horizontal hydraulic conductivity of the St. Peter aquifer decreased from 20 ft/d to 10 ft/d) and those of the Prairie du Chien-Jordan aquifer were uniformly increased by a factor of about 2 (horizontal hydraulic conductivity increased from 70 ft/d to 150 ft/d). The transmissivities (the horizontal hydraulic conductivity) of the Prairie du Chien-Jordan aquifer were increased to improve the match between measured and simulated hydraulic heads near the Minneapolis Water Works; in effect, increasing the transmissivities resulted in an additional source of water to the central part of the model area. A possible additional source of water to the aquifer system may be water released from storage in confining units, which is not simulated in the model. The best fit value for hydraulic conductivity of the Prairie du Chien-Jordan aquifer may be too high if water released from storage in confining units is a major source of water to pumped wells in the study area. The best fit value, however is well within the range of reported values (25 to 210 ft/d, table 3). Another possible source of water to the Prairie du Chien-Jordan aquifer in the Mississippi River valley may be the upward leakage of water from underlying aquifers through the St. Lawrence-Franconia confining unit. The calibrated, best-fit values of recharge to the confined-drift and St. Peter aquifers in the transient simulation for 1980-86 ranged from 1.0 to 5.1 in/yr (fig. 35). The leakage values given on fig. 35 are average values for 1980-86. Average values for 1980-86 were used in the simulation rather than annual values because the simulation was not calibrated for annual hydraulic heads, but only for heads at the end of the simulation. The areally variable leakage values for each area (fig. 35) are based on the magnitude of ground-water withdrawals, drawdown in the Prairie du Chien-Jordan, and confined-drift and St. Peter aquifers, and the areally variable leakage reported by Larson-Higdem and others (1975). Simulated hydraulic heads at the end of the transient simulation for 1980-86 were generally within 10 ft of water levels measured in wells during January and February of 1987 and 1988 (fig. 36).

Sensitivity analysis indicated that transient simulations were not greatly affected by variations in values of aquifer storage coefficients because equilibrium conditions were approached quickly after each summer pumping season. Sensitivity analysis also indicated that the transient simulation for 1980-86 was not greatly affected by variations in values of recharge to the unconfined-drift aquifer, other than the affect on ground-water discharge to the Mississippi River, as explained previously.

A 1-year transient simulation was done to further refine values of hydrologic properties and test the reliability of the model for seasonally variable conditions. Seasonally variable ground-water withdrawals and the resulting fluctuations in hydraulic heads for 1987 were simulated. The year 1987 was chosen because water-use and seasonal hydraulic-head data were available and because significant seasonal fluctuations of about 40 ft in hydraulic heads had been observed.

[1]Water levels measured in wells during January and February of 1988 were used in conjunction with water levels measured in 1987 because few water-level data were available for 1987. Water levels measured during January and February in 1987 and 1988 were similar each year in those wells that were measured both years.

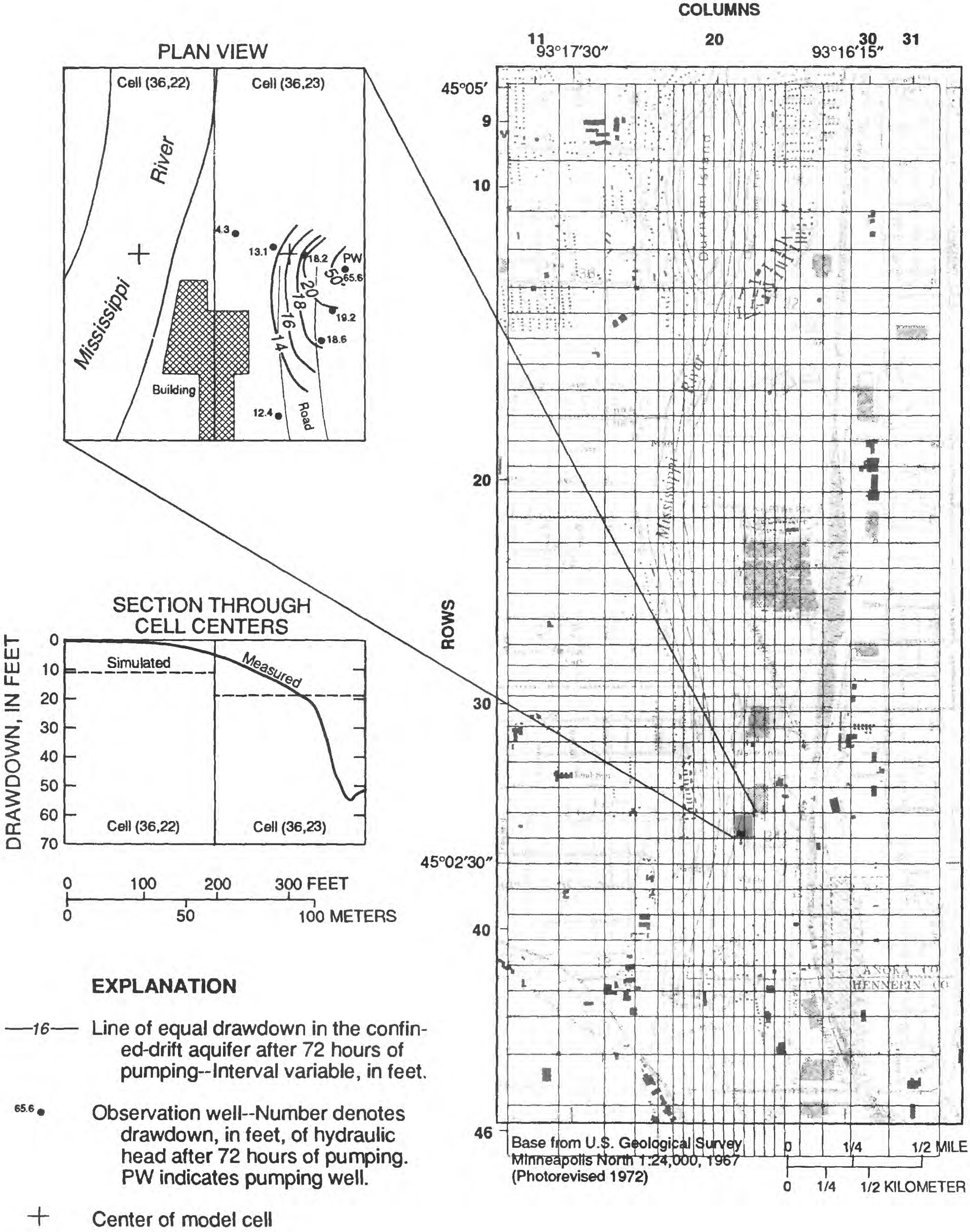
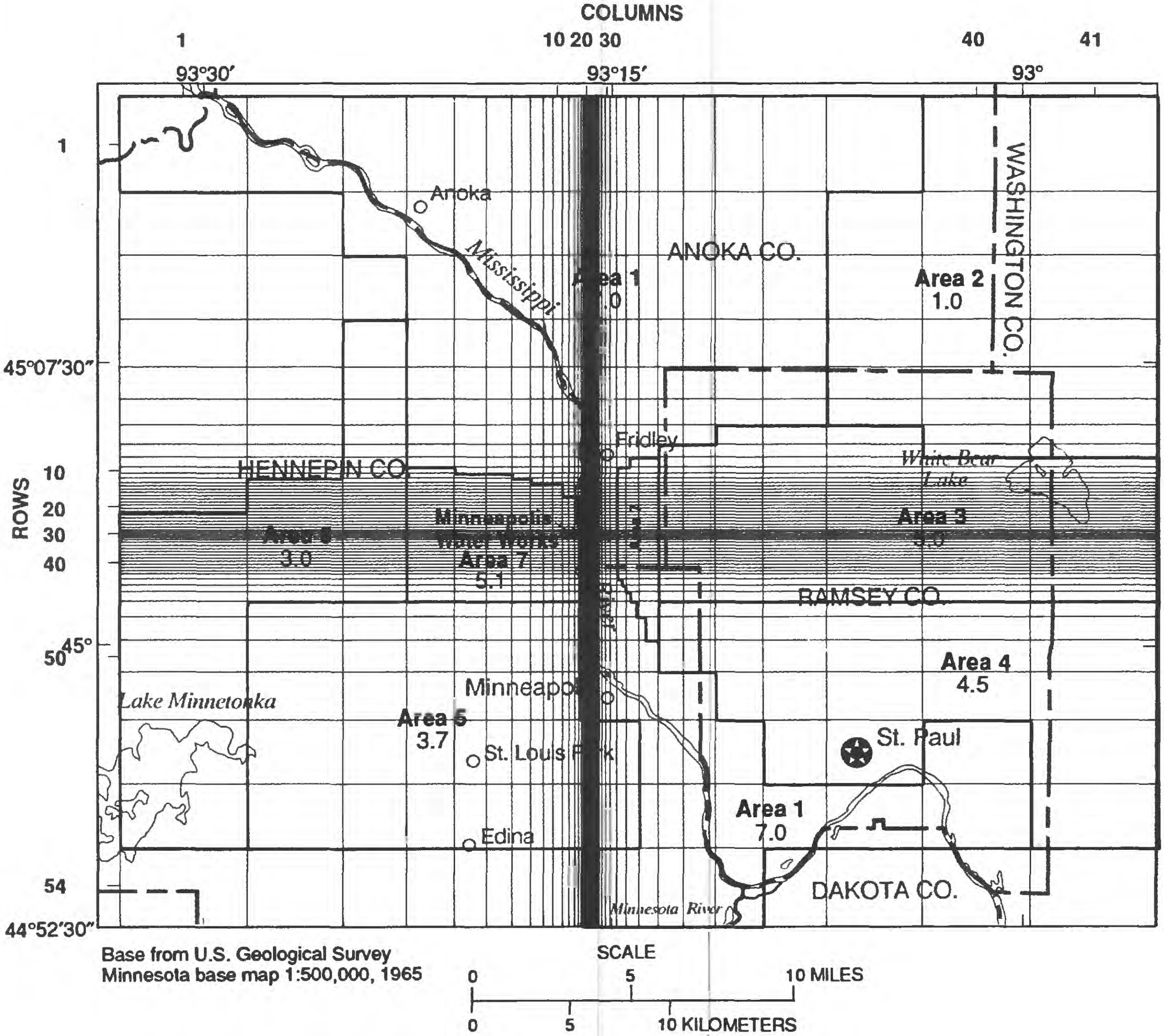


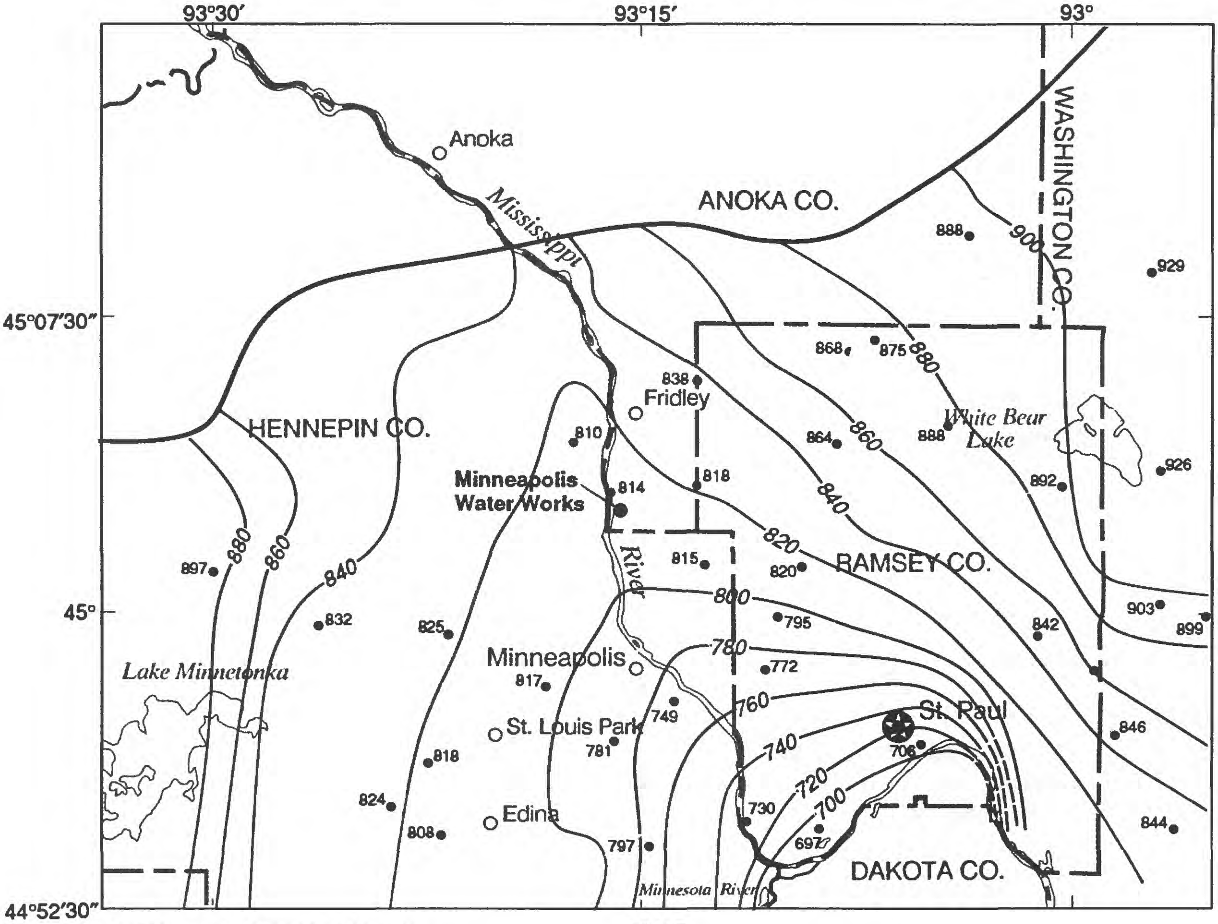
Figure 34.--Aquifer-test site and measured and simulated drawdowns in the confined-drift aquifer (model layer 2) after 72 hours of pumping.



EXPLANATION

3.0 Simulated recharge, in inches per year

Figure 35.--Simulated recharge to the unconfined-drift aquifer (model layer 1; area 1) and leakage to the confined-drift and St. Peter aquifers (model layer 2; areas 2-7), transient simulation, 1980-86.



Base from U.S. Geological Survey
Minnesota base map 1:500,000, 1965

SCALE
0 5 10 MILES
0 5 10 KILOMETERS

EXPLANATION

Generalized aquifer boundary

—800— Simulated potentiometeric contour--Dashed where approximate. Contour interval 20 feet. Datum is sea level.

•832 Observation well--Number shown is elevation of water level measured in well.

Figure 36.--Water levels measured in wells completed in the Prairie du Chien-Jordan aquifer, January and February 1987 and 1988, and simulated potentiometric surface of the Prairie du Chien-Jordan aquifer (model layer 3) at the end of the transient simulation, 1980-86.

To simulate transient conditions during 1987, five stress periods were specified to account for changing pumping rates in the model area. The stress periods specified were "winter" (January-February), "spring" (March-April), "early summer" (May-June), "late summer" (July-September), and "fall" (October-December). Simulated ground-water withdrawals during 1987 for the specified stress periods were: "winter," 92 ft^3/s; "spring," 149 ft^3/s; "early summer," 217 ft^3/s; "late summer," 187 ft^3/s; and "fall," 108 ft^3/s (fig. 37).

Values for hydraulic conductivities of the aquifers and confining units and storage properties of the aquifers from the calibrated transient simulation for 1980-86 were used as initial values in the transient simulation for 1987. Initial values of seasonal recharge to the unconfined-drift aquifer were derived from an analysis of hydrographs for wells completed in the unconfined-drift aquifer near the Minneapolis Water Works. Seasonal recharge rates, calculated as the product of measured water-level rises in wells and a specific yield of 0.25, ranged from 0 to 4.5 in. (inches). Initial values of seasonal leakage to the confined-drift and St. Peter aquifers were derived from the calibrated best-fit 1980-86 average values for the transient simulation for 1980-86 (fig. 35). Downward leakage to the confined-drift and St. Peter aquifers from the overlying deposits is dependent on the vertical hydraulic conductivity and thickness of the deposits and the difference between the hydraulic head in the confined-drift and St. Peter aquifers and the hydraulic head in the overlying deposits (water-table). Seasonal variations in hydraulic head in the confined-drift and St. Peter aquifers are caused largely by ground-water withdrawals from all (but predominantly the Prairie du Chien-Jordan) the aquifers (fig. 37). Hydraulic heads in the confined-drift and St. Peter aquifers approach short-term, seasonal equilibrium or quasi-steady-state levels during a given annual cycle, as shown in figure 37. Therefore, initial seasonal leakage rates to the confined-drift and St. Peter aquifers were estimated from the following approximate relation:

$$\text{LEAK (SEASONAL)} = \text{LEAK (ANNUAL)} \times \frac{\text{PUMP (SEASONAL)}}{\text{PUMP (ANNUAL)}},$$

where

LEAK (SEASONAL) is seasonal leakage rate to the confined-drift and St.Peter aquifers for the transient simulation for 1987,
LEAK (ANNUAL) is annual leakage rate to the confined-drift and St. Peters aquifers for the transient simulation for 1980-86 (fig. 35),
PUMP (SEASONAL) is seasonal ground-water withdrawals from the aquifers during 1987, and
PUMP (ANNUAL) is total ground-water withdrawals from the aquifers during 1987.

The relation assumes that hydraulic head in the deposits overlying the confined-drift and St. Peter aquifers (water-table) is constant. Available measurements indicate that seasonal fluctuations of the water-table during 1987 were about 2 ft.

Evapotranspiration rates also vary seasonally. Reported pan-evaporation rates at St. Paul during 1987 were zero inches for January and February ("winter" stress period), 0.91 in. for March and April ("spring" stress period), 10.44 in. for May and June ("early summer" stress period), 10.87 in. for July to September ("late summer" stress period), and 0.66 in. for October to December ("fall" stress period). The estimated actual seasonal maximum ground-water evapotranspiration rates incorporated in the transient simulation for 1987 were derived from the following relation:

$$\text{EVAPOTRANSPIRATION (SEASONAL)} = \text{PAN EVAP (SEASONAL)} \times \frac{\text{ESTIMATED STEADY-STATE EVAPOTRANSPIRATION RATE (30.0 in/yr)}}{\text{AVERAGE ANNUAL PAN-EVAPORATION RATE (40.0 in/yr)}}$$

The 1987 transient simulation was calibrated by adjusting seasonal recharge and leakage rates until the simulated seasonal hydraulic heads acceptably matched seasonal water levels measured in wells during 1987. Monthly water-level measurements were available for wells in the immediate vicinity of the Minneapolis Water Works; only biannual measurements were available for most of the other wells within the model area. Simulated recharge to the unconfined-drift aquifer varied seasonally and ranged from 0 to 2.3 in. (table 17). Simulated leakage to the confined-drift and St. Peter aquifers varied both seasonally (table 17) and spatially (fig. 38). Table 18 gives the values for the hydraulic properties of the hydrogeologic units resulting in the best fit between measured and simulated hydraulic heads for the 1987 transient simulation. The values given represent the best estimates for the hydraulic properties of the hydrogeologic units in the study area, based on reported values and the results of the calibrations of the model simulations. The simulated hydraulic heads compared closely in trend to 1987 water levels measured in representative wells. Figure 39 shows simulated and measured water levels in wells completed in the unconfined-drift aquifer, and the confined-drift and St. Peter aquifers during 1987. Figures 40 and 41 show simulated and measured water levels in wells completed in the Prairie du Chien-Jordan aquifer during 1987 in the modeled area and in the immediate vicinity of the Minneapolis Water Works, respectively. The transient simulation for 1987 acceptably reproduces measured seasonal fluctuations in hydraulic heads in the aquifers, most reliably near the Minneapolis Water Works.

Table 17.--*Seasonal recharge to the unconfined-drift aquifer (model layer 1) and leakage to the confined-drift and St. Peter aquifers (model layer 2) for the transient simulation for 1987*

[Values in inches per stress period. (L1) indicates recharge to the unconfined-drift aquifer. (L2) indicates leakage to the confined-drift and St. Peter aquifers.]

Recharge or leakage area	Stress period					
	"Winter"	"Spring"	"Early summer"	"Late summer"	"Fall"	Total
1(L1)	0.00	1.20	0.40	1.40	2.30	5.30
2(L2)	.45	.65	.40	.60	.50	2.60
3(L2)	.40	.65	1.30	1.30	.40	4.05
4(L2)	.50	.95	.90	1.45	.90	4.70
5(L2)	.55	.60	.80	1.15	.95	4.05
6(L2)	.40	.65	.90	1.00	.30	3.25
7(L2)	.45	.75	2.10	2.10	.30	5.70

The ability of the simulation to approximate hydraulic heads and seasonal fluctuations in hydraulic heads in the aquifers during 1987 resulting from stresses on the aquifer system indicates that the simulation provides reasonable estimates of hydraulic properties of the hydrogeologic units and ground-water flow during 1987 into (boundary inflow) the model area and between the aquifer units. The specified boundary conditions are considered to be appropriate, and recharge and leakage to the aquifer system are within broad reported ranges. Ground-water withdrawals are known and simulated ground-water discharge to the Mississippi River is within a range of reasonable estimated values. Estimates of ground-water flows in the aquifer system would change with changes in stresses on the system (recharge, leakage, and ground-water withdrawals) and (or) boundary conditions.

A model-sensitivity analysis was done to identify the relative effect of adjustments of hydrologic properties on simulated hydraulic heads at the end of the "early summer" and "fall" pumping seasons (tables 19, 20, 21 and 22). The model was found to be most sensitive to changes in leakage to the confined-drift and St. Peter aquifers, and pumpage; resulting average differences in hydraulic heads in model layers 2 and 3 were about 10 to 20 ft. Variations in the horizontal hydraulic conductivity of the Prairie du Chien-Jordan aquifer (model layer 3) and the vertical hydraulic conductivity of the upper and lower confining units resulted in average differences in hydraulic heads in model layers 2 and 3 of about 2 to 6.5 ft. Hydraulic head is relatively insensitive to changes in the values of other properties. Variations in leakage and pumpage resulted in differences in hydraulic heads at model

Table 18.--*Best estimates for the hydraulic properties of and fluxes to the hydrogeologic units in the study area*

[ft/d, feet per day; ft^2/d, feet squared per day; in/yr, inches per year; --, not applicable]

Hydrogeologic unit	Horizontal hydraulic conductivity (ft/d)	Transmissivity (ft^2/d)	Vertical hydraulic conductivity (ft/d)	Specific yield or storage coefficient	Recharge and leakage (in/yr)
Unconfined-drift aquifer	Variable, 50-300	0-21,000	--	0.25	5.3-7.0
Upper drift confining unit	--	--	Variable, 1.0×10^{-3} to 2.0×10^{-4}	--	--
Decorah-Platteville-Glenwood confining unit	--	--	1.0×10^{-4}	--	--
Confined-drift aquifer	40	0- 5,600	--	3.7×10^{-4}	Variable, 2.6-5.7
St. Peter aquifer	10	0- 1,500	--	1.0×10^{-4}	Variable, 2.6-5.7
Basal-drift confining unit	--	--	2.5×10^{-2}	--	--
Basal St. Peter confining unit	--	--	5.0×10^{-5}	--	--
Prairie du Chien-Jordan aquifer	150	0-33,000	--	6.5×10^{-4}	--
Mississippi riverbed	--	--	1.0	--	--

cell (30,23), which represents part of the Minneapolis Water Works site, that ranged from about 7 to 23 ft. Differences at model cell (30,23) resulting from variations in the horizontal hydraulic conductivity of the Prairie du Chien-Jordan aquifer (model layer 3) and decreasing the vertical hydraulic conductivity of the upper confining unit ranged from about 2.5 to 5 ft. The differences in hydraulic head resulting from variations in hydrologic properties are similar for the "early summer" and "fall" stress periods, except for variations in storage coefficients for model layers 2 and 3 and horizontal hydraulic conductivity for model layer 1. Increasing the storage coefficients of model layers 2 and 3 results in generally positive average differences in hydraulic heads in model layers 2 and 3 at the end of the "early summer" stress period and generally negative average differences in hydraulic heads at the end of the "fall" stress period. Decreasing the storage coefficients of model layers 2 and 3 results in negative average differences at the end of the "early summer" stress period and positive average differences at the end of the "fall" stress period. The trend in average differences in hydraulic heads also differs at the end of the "early summer" and "fall" stress periods for variations in the horizontal hydraulic conductivity of layer 1.

The sensitivity of hydraulic heads in the transient simulation for 1987 to changes in boundary conditions was investigated by reducing the altitude of the specified-head boundary cells by 5 ft for the confined-drift and St. Peter aquifers, and by 10 ft for the Prairie du Chien-Jordan aquifer. The resulting simulated drawdowns in hydraulic heads near the Minneapolis Water Works site are less than 2.5 ft (figs. 42 and 43).

The simulated water budget is shown in table 23. Principal sources of water to the aquifer system were as follows: (1) "winter" stress period--boundary inflow, about 49 percent, recharge and leakage, about 26 percent, and water released from storage about 24 percent; (2) "spring," "late summer," and "fall" stress periods--recharge and leakage, about 55, 49, and 54 percent, respectively, and boundary inflow, about 40, 42, and 44 percent, respectively; and (3) "early summer" stress period--recharge and leakage, about 41 percent, boundary inflow, about 40 percent, and water released from storage, about 19 percent. Most of the boundary inflow is from the southwest and southeast model boundaries, where the hydraulic gradient from areas with comparatively high hydraulic heads toward the Mississippi River and areas of large ground-water withdrawals is the steepest. The amount and percentage of water released from storage is greatest during the "winter" stress period because no recharge occurs to the unconfined-drift aquifer. Precipitation is in the form of snow and remains frozen at the land surface. Nearly all of the water released from storage is derived from the unconfined-drift aquifer and most of the water released leaks downward to the underlying aquifers and is a source of water to pumping wells. Release of water from storage is not as large during the other stress periods because recharge to the unconfined-drift aquifer and leakage to the confined-drift and St. Peter aquifers are much greater than during the "winter" stress period; a greater proportion of the water pumped by wells is derived from the available recharge and leakage and less release of water from storage is required. The amount and contributing percentage of water released from storage is much greater for the "early summer" stress period than for the "spring", "late summer", and "fall" stress periods because ground-water withdrawals are greater and recharge to the unconfined-drift aquifer is less. The principal discharge from the aquifer system is leakage (seepage) from the unconfined-drift aquifer to the river during the "winter" and "fall" stress periods and pumpage during the "spring", "early summer", and "late summer" stress periods. The relatively large reductions in leakage to the river observed during the stress periods with large ground-water withdrawals ("spring", "early summer", and "late summer" stress periods) as compared to leakage to the river during the "winter" stress period indicate ground-water that would otherwise discharge to the river is being captured by pumped wells.

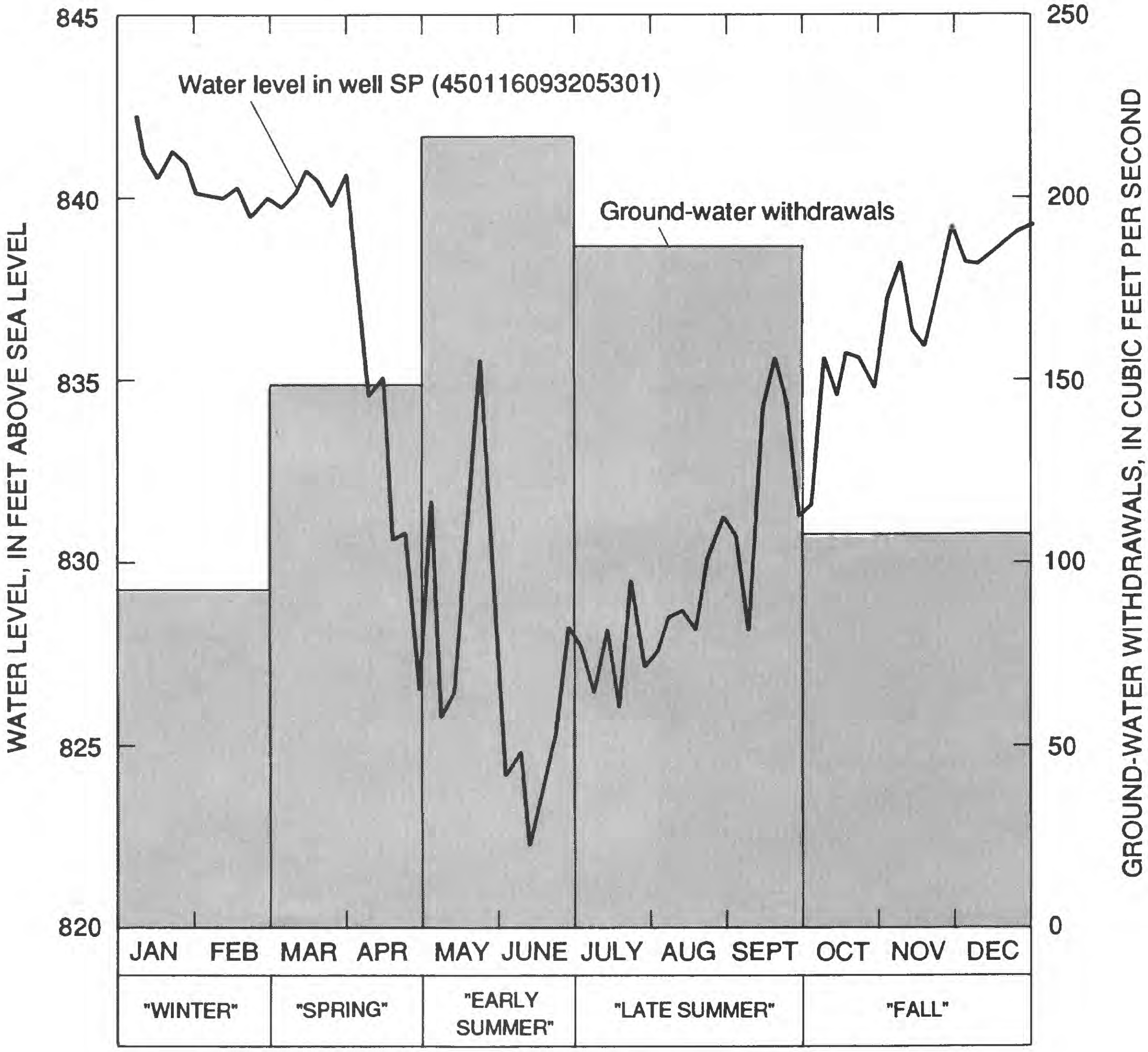
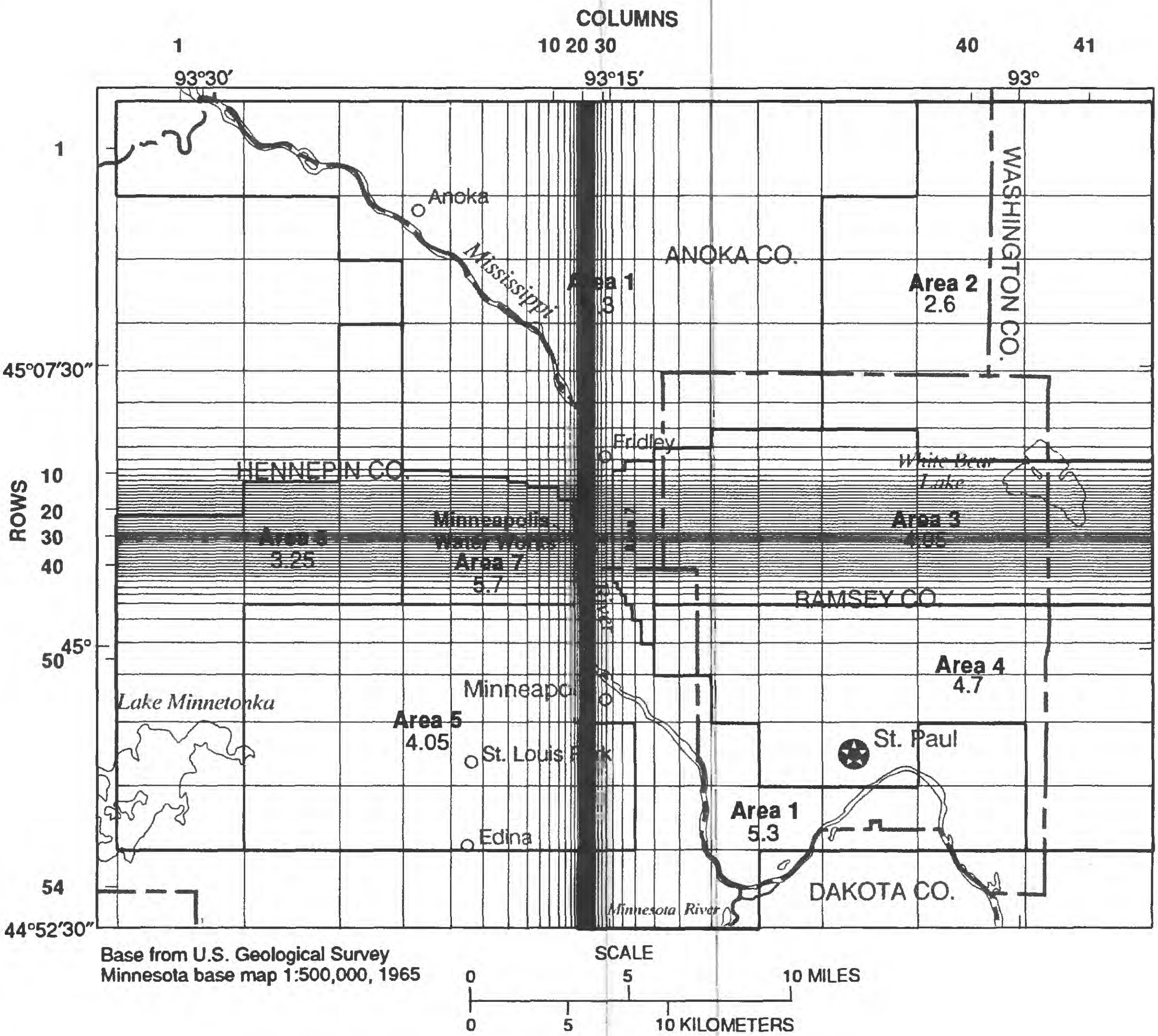


Figure 37.--Water-level fluctuations in well SP completed in the confined-drift and St. Peter aquifers and ground-water withdrawals from the Prairie du Chien-Jordan and overlying aquifers in the model area, 1987 (location of well shown in figure 2).



EXPLANATION

5.0 Simulated recharge, in inches per year

Figure 38.--Simulated recharge to the unconfined-drift aquifer (model layer 1; area 1) and leakage to the confined-drift and St. Peter aquifers (model layer 2; areas 2-7), transient simulation, 1987.

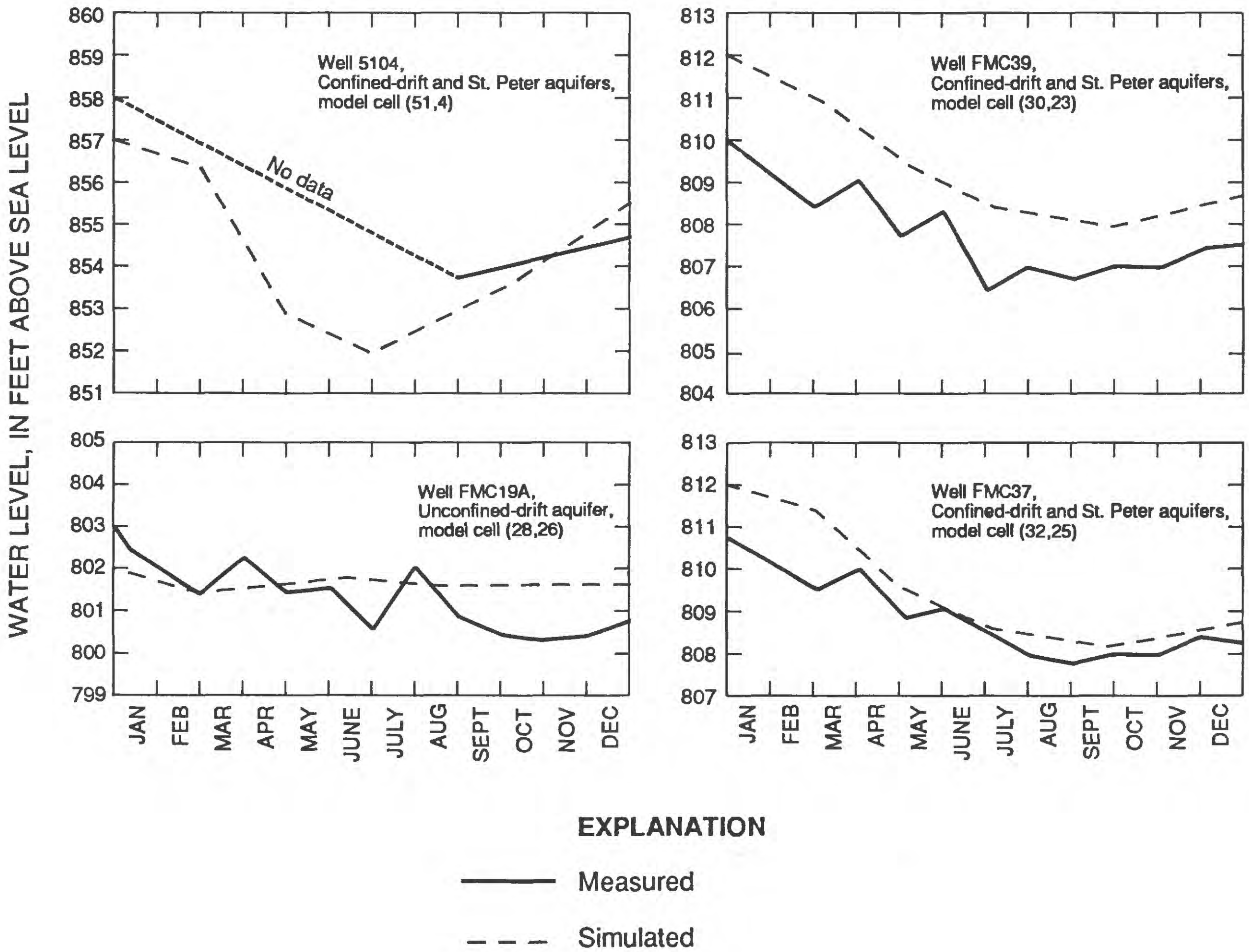


Figure 39.--Water levels measured during 1987 in wells completed in the unconfined-drift aquifer and in the confined-drift and St. Peter aquifers and simulated hydraulic heads for the unconfined-drift aquifer (model layer 1) and confined-drift and St. Peter aquifers (model layer 2), transient simulation, 1987 (locations of wells shown in figure 2 and 6).

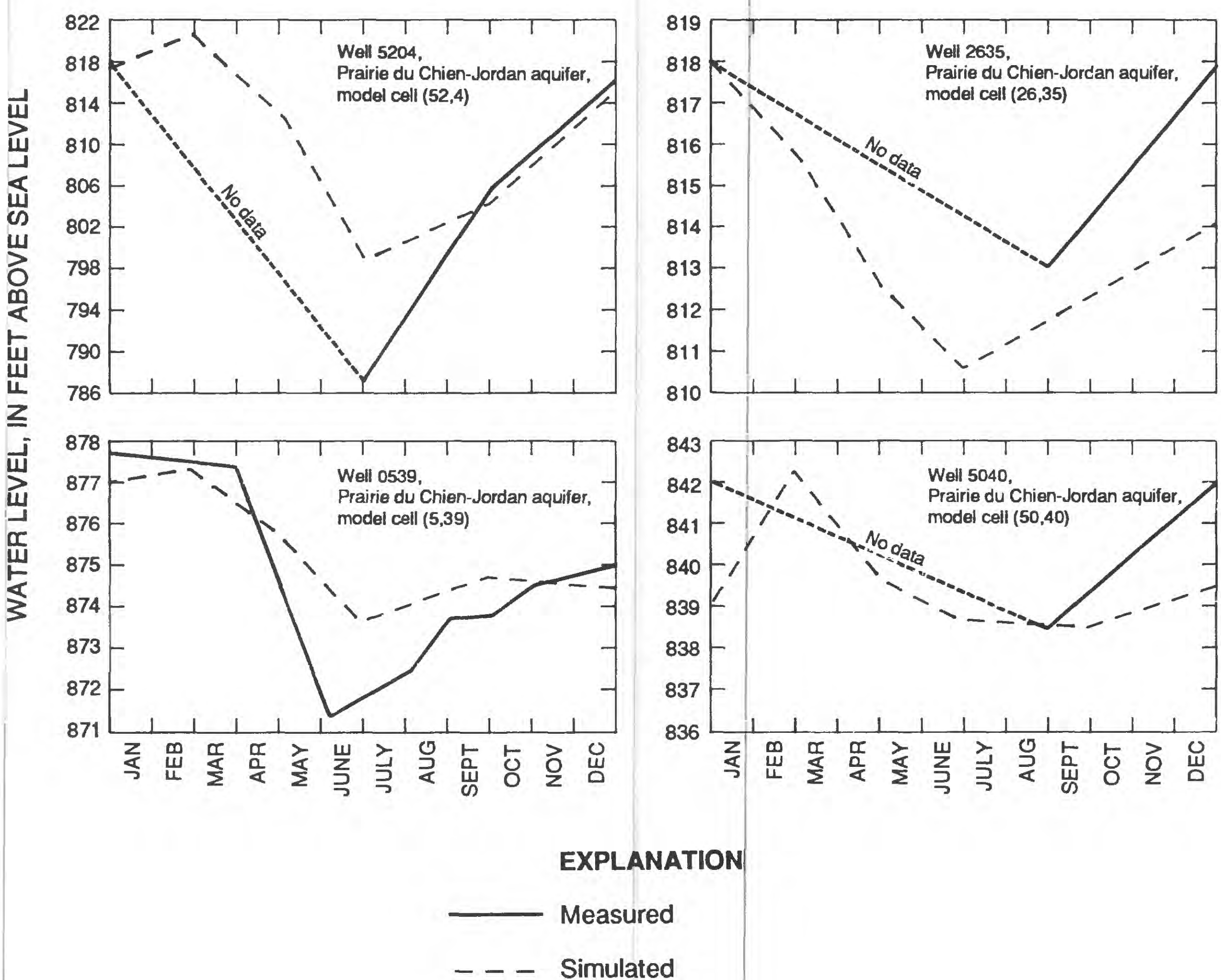


Figure 40.--Water levels measured during 1987 in wells completed in the Prairie du Chien-Jordan aquifer and simulated hydraulic heads for the Prairie du Chien-Jordan aquifer (model layer 3), transient simulation, 1987 (locations of wells shown in figure 2).

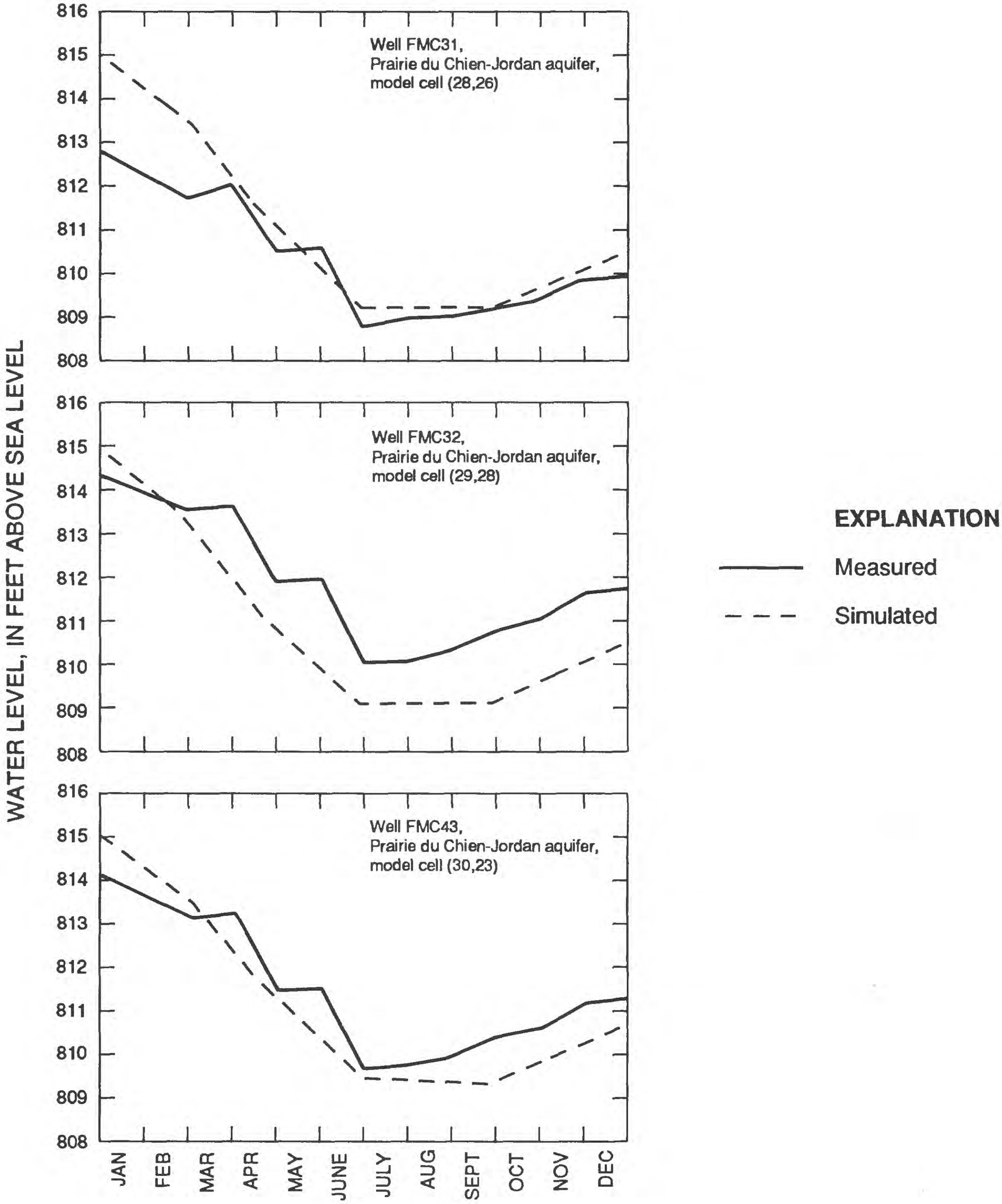
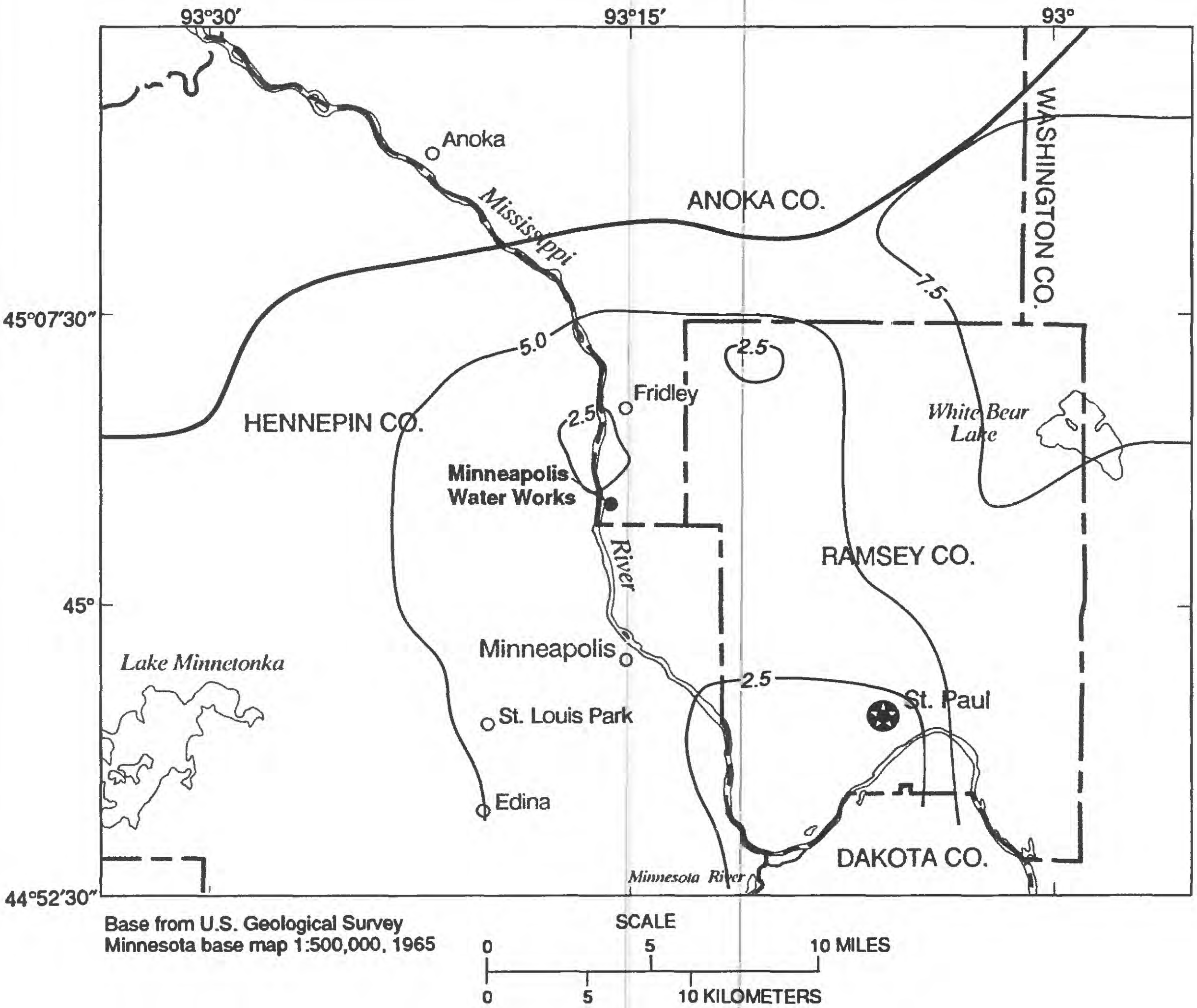


Figure 41.--Water levels measured during 1987 in wells completed in the Prairie du Chien Jordan aquifer near the Minneapolis Water Works and simulated hydraulic heads for the Prairie du Chien-Jordan aquifer (model layer 3), transient simulation, 1987 (locations of wells shown in figure 6).

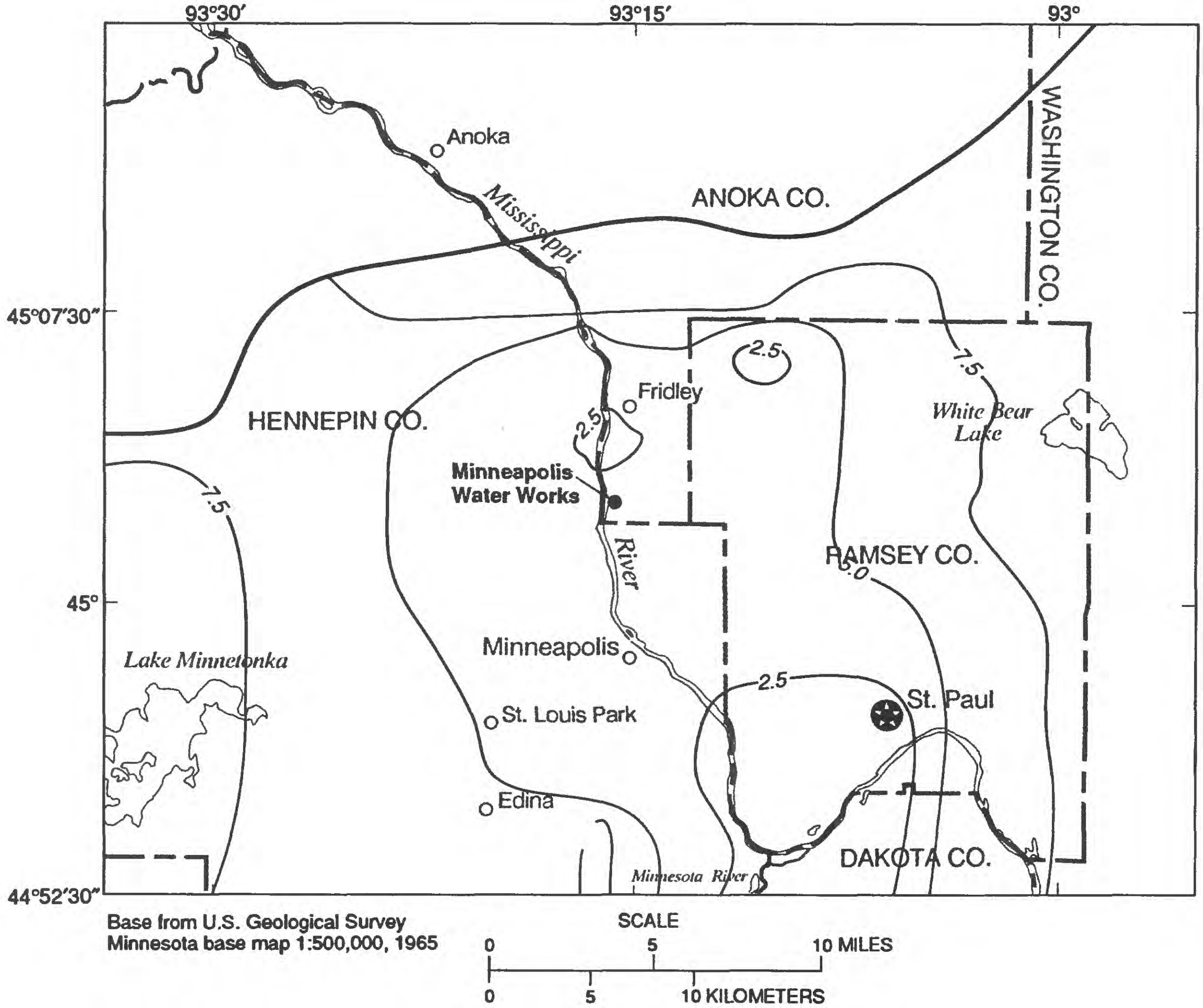


EXPLANATION

——— Generalized aquifer boundary

—5.0— Line of equal simulated drawdown in the confined-drift and St. Peter aquifers-- Interval 2.5 feet.

Figure 42.--Simulated drawdowns in the confined-drift and St. Peter aquifers (model layer 2) resulting from lowering the altitude of the hydraulic heads at specified-head boundaries in the transient simulation, 1987.



EXPLANATION

——— Generalized aquifer boundary

—5.0— Line of equal simulated drawdown in the Prairie du Chien-Jordan aquifer--Interval 2.5 feet.

Figure 43.--Simulated drawdowns in the Prairie du Chien-Jordan aquifer (model layer 3) resulting from lowering the altitude of hydraulic heads at specified-head boundaries in the transient simulation, 1987.

Table 19.--*Sensitivity of hydraulic heads in the confined-drift and St. Peter aquifers (model layer 2) to changes in values of hydraulic properties and fluxes in the transient simulation for 1987, "early summer" stress period*

[Mean positive and negative deviations of hydraulic heads from values calculated by best-fit simulation; deviations calculated at 21 cells in the confined-drift and St. Peter aquifers model layer where field data are available. Numbers in parentheses show number of cells with positive or negative deviations. -- indicates all deviations are positive or all deviations are negative.]

Hydrologic property or condition	Multiplied by factor of	Mean deviation of hydraulic heads (feet)	Deviation at node (30,23)	Maximum deviation (feet)	Minimum deviation (feet)
Recharge and leakage	1.50	+22.5 (21) --	+19.7	+84.3 --	-0.6 --
Recharge and leakage	.50	-- -11.5 (21)	-10.2	-- -42.3	-- - .2
Horizontal hydraulic conductivity of layer 1	1.50	+ .05(17) - .15(4)	+ 0	+ .2 - .3	0 - .1
Horizontal hydraulic conductivity of layer 1	.50	+ .2 (3) - .1 (18)	- .2	+ .3 - .3	+ .1 0
Horizontal hydraulic conductivity of layer 2	2.00	+ .2 (15) - 2.2 (6)	0	+1.1 -12.7	0 - .1
Horizontal hydraulic conductivity of layer 2	.50	+ 1.3 (18) - .3 (3)	+ .3	+16.8 - .5	0 - .2
Horizontal hydraulic conductivity of layer 3	1.33	+ 2.9 (21) --	+ 2.5	+7.1 --	0 --
Horizontal hydraulic conductivity of layer 3	.66	+ .1 (1) - 3.8 (20)	- 3.0	-- -8.6	-- -2.5
Vertical hydraulic conductivity of upper confining layer	10.00	+ .4 (1) - 1.9 (20)	- .7	-- -12.2	-- 0
Vertical hydraulic conductivity of upper confining layer	.10	+ 6.6 (21) --	+ 3.9	+37.9 --	+ .1 --
Vertical hydraulic conductivity of lower confining layer	10.00	-- - 2.5 (21)	- .8	-- -35.8	-- 0

Table 19.--*Sensitivity of hydraulic heads in the confined drift and St. Peter aquifers (model layer 2) to changes in values of hydraulic properties and fluxes in the transient simulation for 1987, "early summer" stress period*
--Continued

Hydrologic property or condition	Multiplied by factor of	Mean deviation of hydraulic heads (feet)	Deviation at node (30,23)	Maximum deviation (feet)	Minimum deviation (feet)
Vertical hydraulic conductivity of lower confining layer	0.10	+ 5.1 (21) --	+ .2	+74.9 --	0.0 --
Vertical hydraulic conductivity of riverbed material	10.00	-- - 0.3 (21)	- 0.2	-- -1.6	-- 0
Vertical hydraulic conductivity of riverbed material	.10	+ 1.2 (21) --	+ .9	+4.6 --	+ .1 --
Pumpage	1.50	-- -16.4 (21)	-16.4	-- -33.1	-- - .2
Pumpage	.50	+15.0 (21) --	+14.4	+32.0 --	+ .3 --
Storage coefficient of layer 1	1.20	+ .3 (21) --	+ .3	+ .4 --	0 --
Storage coefficient of layer 1	.80	-- - .3 (21)	- .4	-- - .5	-- 0
Storage coefficient of layer 2	10.00	+ 1.0 (21) --	+ .8	+4.4 --	+ .1 --
Storage coefficient of layer 2	.10	-- - .1 (21)	- .2	-- - .7	-- 0
Storage coefficient of layer 3	10.00	+ 3.0 (21) --	+ 2.6	+10.1 --	+ .1 --
Storage coefficient of layer 3	.10	-- - .9 (21)	- .9	-- -2.8	-- 0

Table 20.--*Sensitivity of hydraulic heads in the confined-drift and St. Peter aquifers (model layer 2) to changes in values of hydraulic properties and fluxes in the transient simulation for 1987, "fall" stress period*

[Mean positive and negative deviations of hydraulic heads from values calculated by best-fit simulation; deviations calculated at 21 cells in the confined-drift and St. Peter aquifers model layer where field data are available. Numbers in parentheses show number of cells with positive or negative deviations. -- indicates all deviations are positive or all deviations are negative.]

Hydrologic property or condition	Multiplied by factor of	Mean deviation of hydraulic heads (feet)	Deviation at node (30,23)	Maximum deviation (feet)	Minimum deviation (feet)
Recharge and leakage	1.50	+14.8 (21) --	+12.6	+62.2 --	+ 0.3 --
Recharge and leakage	.50	-- - 7.7 (21)	- 6.7	-- -31.2	-- - .1
Horizontal hydraulic conductivity of layer 1	1.50	+ .1 (1) - .1 (20)	- .1	-- - .4	-- 0
Horizontal hydraulic conductivity of layer 1	.50	+ .1 (21) --	+ .1	+ .4 --	0 --
Horizontal hydraulic conductivity of layer 2	2.00	+ .4 (18) - 3.5 (3)	+ .3	+ 1.0 -10.2	0 - .1
Horizontal hydraulic conductivity of layer 2	.50	+ .9 (17) - .2 (4)	0	+13.2 - .4	0 - .1
Horizontal hydraulic conductivity of layer 3	1.33	+ 3.0 (21) --	+ 3.0	+ 6.9 --	0 --
Horizontal hydraulic conductivity of layer 3	.66	-- - 3.9 (21)	- 3.9	-- - 8.4	-- 0
Vertical hydraulic conductivity of upper confining layer	10.00	-- - 3.5 (21)	- 2.3	-- -15.6	-- 0
Vertical hydraulic conductivity of upper confining layer	.10	+11.1 (21) --	+ 8.6	+47.4 --	+ .1 --
Vertical hydraulic conductivity of lower confining layer	10.00	-- - 2.6 (21)	- 1.2	-- -28.6	-- 0
Vertical hydraulic conductivity of lower confining layer	.10	+ 4.5 (21) --	+ 1.0	+57.5 --	0 --

Table 20.--*Sensitivity of hydraulic heads in the confined-drift and St. Peter aquifers (model layer 2) to changes in values of hydraulic properties and fluxes in the transient simulation for 1987, "fall" stress period*--Continued

Hydrologic property or condition	Multiplied by factor of	Mean deviation of hydraulic heads (feet)	Deviation at node (30,23)	Maximum deviation (feet)	Minimum deviation (feet)
Vertical hydraulic conductivity of riverbed material	10.00	-- - 0.5 (21)	- 0.4	-- - 2.0	-- 0.0
Vertical hydraulic conductivity of riverbed material	.10	+ 2.0 (21) --	+ 1.6	+ 7.5 --	0 --
Pumpage	1.50	-- -10.8 (21)	-11.2	-- -21.0	-- - .1
Pumpage	.50	+10.0 (21) --	+10.1	+20.3 --	+ .1 --
Storage coefficient of layer 1	1.20	+ .2 (21) --	+ .2	+ .4 --	0 --
Storage coefficient of layer 1	.80	-- - .2 (21)	- .2	-- - .6	-- 0
Storage coefficient of layer 2	10.00	-- - .4 (21)	- .3	-- - 1.5	-- 0
Storage coefficient of layer 2	.10	+ .03 (21) --	0	+ .3 --	0 --
Storage coefficient of layer 3	10.00	+ .3 (1) - .5 (20)	- .1	-- - 2.5	-- 0
Storage coefficient of layer 3	.10	+ .3 (21) --	+ .3	+ .9 --	0 --

Table 21.--*Sensitivity of hydraulic heads in the Prairie du Chien-Jordan aquifer (model layer 3) to changes in values of hydraulic properties and fluxes in the transient simulation for 1987, "early summer" stress period*

[Mean positive and negative deviations of hydraulic heads from values calculated by best-fit simulation; deviations calculated at 34 cells in Prairie du Chien-Jordan aquifer model layer where field data are available. Numbers in parentheses show number of cells with positive or negative deviations. -- indicates all deviations positive or all deviations are negative.]

Hydrologic property or condition	Multiplied by factor of	Mean deviation of hydraulic heads (feet)	Deviation at node (30,23)	Maximum deviation (feet)	Minimum deviation (feet)
Recharge and leakage	1.50	+20.3 (34) --	+23.5	+41.5 --	+ 0.9 --
Recharge and leakage	.50	-- -10.3 (34)	-12.2	-- -21.1	-- - .5
Horizontal hydraulic conductivity of layer 1	1.50	+ .3 (2) - .1 (32)	0	+ .4 - .4	+ .2 0
Horizontal hydraulic conductivity of layer 1	.50	+ .1 (30) - .25 (2)	0	+ .5 - .6	0 - .1
Horizontal hydraulic conductivity of layer 2	2.00	+ .5 (32) - .2 (2)	0	+ 1.8 - .2	0 - .2
Horizontal hydraulic conductivity of layer 2	.50	+ .05 (14) - .3 (20)	+ .3	+ .3 - .9	0 - .1
Horizontal hydraulic conductivity of layer 3	1.33	+ 4.6 (31) - .3 (3)	+ 3.3	+18.8 - .6	0 - .1
Horizontal hydraulic conductivity of layer 3	.66	+ .4 (6) - 7.1 (28)	- 3.9	+ 1.4 -34.2	+ .1 - .2
Vertical hydraulic conductivity of upper confining layer	10.00	+ 2.2 (12) - 4.8 (22)	+ .1	+14.0 -20.3	0 - .1
Vertical hydraulic conductivity of upper confining layer	.10	+12.0 (30) - 3.8 (4)	+ 4.9	+50.6 - 7.5	+ .1 - .9
Vertical hydraulic conductivity of lower confining layer	10.00	+ .9 (6) - .9 (28)	- 1.2	+ 4.7 - 4.9	0 - .1
Vertical hydraulic conductivity of lower confining layer	.10	+ .6 (26) - 4.0 (8)	+ .6	+ 3.6 - 7.3	.0 - .2

Table 21.--*Sensitivity of hydraulic heads in the Prairie du Chien-Jordan aquifer (model layer 3) to changes in values of hydraulic properties and fluxes in the transient simulation for 1987, "early summer" stress period*--Continued

Hydrologic property or condition	Multiplied by factor of	Mean deviation of hydraulic heads (feet)	Deviation at node (30,23)	Maximum deviation (feet)	Minimum deviation (feet)
Vertical hydraulic conductivity of riverbed material	10.00	-- - 0.5 (34)	- 0.4	-- - 1.6	-- 0.0
Vertical hydraulic conductivity of riverbed material	.10	+ 1.7 (34) --	+ 1.7	+ 6.2 --	0 --
Pumpage	1.50	-- -17.9 (34)	-19.8	-- -58.0	-- - .4
Pumpage	.50	+17.0 (34) --	+17.5	+57.2 --	+ .4 --
Storage coefficient of layer 1	1.20	+ .2 (34) --	+ .4	+ .6 --	0 --
Storage coefficient of layer 1	.80	-- - .3 (34)	- .4	-- - .8	-- 0
Storage coefficient of layer 2	10.00	+ .9 (34) --	+ .9	+ 2.6 --	0 --
Storage coefficient of layer 2	.10	-- - .1 (34)	- .1	-- - .3	-- 0
Storage coefficient of layer 3	10.00	+ 4.3 (34) --	+ 3.3	+14.5 --	+ .1 --
Storage coefficient of layer 3	.10	-- - 1.0 (34)	- 1.0	-- - 3.0	-- 0

Table 22.--*Sensitivity of hydraulic heads in the Prairie du Chien-Jordan aquifer (model layer 3) to changes in values of hydraulic properties and fluxes in the transient simulation for 1987, "fall" stress period*

[Mean positive and negative deviations of hydraulic heads from values calculated by best-fit simulation; deviations calculated at 34 cells in Prairie du Chien-Jordan aquifer model layer where field data are available. Numbers in parentheses show number of cells with positive or negative deviations. -- indicates all deviations positive or all deviations are negative.]

Hydrologic property or condition	Multiplied by factor of	Mean deviation of hydraulic heads (feet)	Deviation at node (30,23)	Maximum deviation (feet)	Minimum deviation (feet)
Recharge and leakage	1.50	+13.9 (34) --	+15.0	+30.2 --	+ 0.6 --
Recharge and leakage	.50	-- - 7.0 (34)	- 7.8	-- -15.3	-- - .2
Horizontal hydraulic conductivity of layer 1	1.50	+ .15(2) - .2 (32)	- .1	+ .2 - .7	+ .1 0
Horizontal hydraulic conductivity of layer 1	.50	+ .2 (33) - .2 (1)	+ .3	+ .7 --	0 --
Horizontal hydraulic conductivity of layer 2	2.00	+ .4 (21) - .2 (13)	0	+ 1.7 - .5	0 - .1
Horizontal hydraulic conductivity of layer 2	.50	+ .2 (26) - .3 (8)	+ .4	+ .4 - .9	0 - .1
Horizontal hydraulic conductivity of layer 3	1.33	+ 3.6 (31) - .3 (3)	+ 3.8	+10.3 - .5	0 - .1
Horizontal hydraulic conductivity of layer 3	.66	+ .4 (8) - 5.7 (26)	- 4.8	+ .8 -19.0	0 - .2
Vertical hydraulic conductivity of upper confining layer	10.00	+ 3.7 (3) - 5.4 (31)	- 2.0	+ 8.5 -25.0	+ .1 0
Vertical hydraulic conductivity of upper confining layer	.10	+15.7 (32) - 1.0 (2)	+ 9.8	+62.6 - 1.5	+ .2 - .4
Vertical hydraulic conductivity of lower confining layer	10.00	+ 1.9 (1) - 1.4 (33)	- 2.1	-- - 7.7	-- 0
Vertical hydraulic conductivity of lower confining layer	.10	+ 1.4 (29) - 2.9 (9)	+ 2.3	+ 4.6 - 4.1	0 - 1.1

Table 22.--*Sensitivity of hydraulic heads in the Prairie du Chien-Jordan aquifer (model layer 3) to changes in values of hydraulic properties and fluxes in the transient simulation for 1987, "fall" stress period*--Continued

Hydrologic property or condition	Multiplied by factor of	Mean deviation of hydraulic heads (feet)	Deviation at node (30,23)	Maximum deviation (feet)	Minimum deviation (feet)
Vertical hydraulic conductivity of riverbed material	10.00	-- - 0.6 (34)	- 0.6	-- - 2.1	-- 0.0
Vertical hydraulic conductivity of riverbed material	.10	+ 2.5 (34) --	+ 2.5	+10.1 --	+ .1 --
Pumpage	1.50	-- -10.5 (34)	-13.0	-- -32.7	-- - .2
Pumpage	.50	+10.2 (34) --	+12.0	+32.2 --	+ .2 --
Storage coefficient of layer 1	1.20	+ .2 (34) --	+ .3	+ .6 --	0 --
Storage coefficient of layer 1	.80	-- - .3 (34)	- .3	-- - .8	-- 0
Storage coefficient of layer 2	10.00	-- - .4 (34)	- .3	-- - 1.0	-- 0
Storage coefficient of layer 2	.10	+ .04(34) --	+ .1	+ .1 --	0 --
Storage coefficient of layer 3	10.00	+ .4 (2) - 1.4 (32)	0	+ .7 - 4.4	+ .1 0
Storage coefficient of layer 3	.10	+ .3 (34) --	+ .4	+ .9 --	0 --

Table 23.--*Simulated water budget, by season, for the transient simulation for 1987*

[Numbers in parentheses are percentages of totals by season]

Budget component	Sources of water, by season (cubic feet per second) "Winter" January-February	"Spring" March-April	"Early summer" May-June	"Late summer" July-September	"Fall" October-December	Total (acre-feet)
Recharge to layer 1	0.00	86.2	28.7	66.8	109.6	46,090
Leakage to layer 2	64.3	94.3	124.0	104.1	57.4	63,410
Subtotal	64.3 (26.2)	180.5 (55.0)	152.7 (40.7)	170.9 (48.7)	167.0 (54.3)	109,500 (46.8)
River leakage to layer 1)	.9 (0.4)	2.3 (.7)	1.5 (.4)	1.3 (.4)	.8 (.2)	950 (.4)
Boundary inflow						
Layer 1	7.9	7.7	8.0	8.0	7.6	5,670
Layer 2	8.0	8.3	10.7	10.2	8.8	6,700
Layer 3	105.3	114.2	132.9	128.4	118.0	87,185
Subtotal	121.2 (49.3)	130.2 (39.6)	151.6 (40.4)	146.6 (41.7)	134.4 (43.7)	99,555 (42.5)
Discharge from storage						
Layer 1	59.0	12.5	66.9	32.2	5.5	23,390
Layer 2	.0	.4	.3	0	0	85
Layer 3	.2	2.5	2.1	0	0	580
Subtotal	59.2 (24.1)	15.4 (4.7)	69.3 (18.5)	32.2 (9.2)	5.5 (1.8)	24,055 (10.3)
Total sources	245.6	328.4	375.1	351.0	307.7	234,060
Leakage to model layers through confining units						
Layer 1	95.7	83.5	70.8	70.0	86.6	58,445
Layer 2	108.2	101.8	98.3	89.9	100.8	71,670
Layer 3	71.6	103.1	135.4	113.1	65.8	69,880
Total	275.5	288.4	304.5	273.0	253.2	199,995

Table 23. -- *Simulated water budget, by season, for the transient simulation for 1987*--Continued

Budget component	"Winter" January-February	"Spring" March-April	"Early summer" May-June	"Late summer" July-September	"Fall" October-December	Total (acre-feet)
	Discharges of water, by season (cubic feet per second)					
River leakage (from layer 1)	141.0 (57.3)	120.9 (36.8)	121.7 (32.4)	141.0 (40.2)	158.1 (51.4)	100,435 (42.9)
Ground-water evapotranspiration (from layer 1)	0 (0)	3.7 (1.1)	33.3 (8.9)	20.8 (5.9)	1.8 (.6)	8,600 (3.7)
Boundary outflow						
Layer 1	0	0	0	0	0	0
Layer 2	1.4	1.3	1.0	1.1	1.2	860
Layer 3	1.2	1.6	.7	.8	.6	675
Subtotal	2.6 (1.1)	2.9 (.9)	1.7 (.4)	1.9 (.5)	1.8 (.6)	1,535 (.6)
Pumpage						
Layer 1	.3	.6	1.2	1.0	.4	510
Layer 2	11.8	16.9	26.3	19.9	13.2	12,645
Layer 3	79.7	131.4	189.4	166.4	94.3	95,715
Subtotal	91.8 (37.3)	148.9 (45.3)	216.9 (57.8)	187.3 (53.3)	107.9 (35.0)	108,870 (46.5)
Recharge to storage						
Layer 1	9.7	52.1	1.9	0	36.9	14,400
Layer 2	.1	.0	0	0	.2	50
Layer 3	.7	.1	0	.2	1.1	330
Subtotal	10.5 (4.3)	52.2 (15.9)	1.9 (.5)	.2 (.1)	38.2 (12.4)	14,780 (6.3)
Total discharges	245.9	328.6	375.5	351.2	307.8	234,220
Leakage from model layers through confining units						
Layer 1	12.6	15.1	17.9	15.7	13.1	10,720
Layer 2	167.3	186.6	206.2	183.1	152.4	128,325
Layer 3	95.6	86.7	80.4	74.2	87.7	60,950
Total	275.5	288.4	304.5	273.0	253.2	199,995
Difference: Sources - discharges	- .3	- .2	- .4	- .2	- .1	- 160

Comparison of simulation results

An analysis of the simulated water budgets for the steady-state simulation for 1885-1930 and the transient simulation for 1987 and the simulated changes in fluxes for the steady-state simulation for 1970-79 indicates the effects of ground-water withdrawals on the amount and direction of ground-water flow through the aquifer system in the study area. Prior to large ground-water withdrawals, water entered the aquifer system mainly by infiltration of precipitation (about 73 percent) and ground-water inflow at the model boundaries (about 26 percent) and was discharged mainly by leakage to the Mississippi River (about 88 percent). The net leakage of water between the unconfined-drift aquifer and the confined-drift and St. Peter aquifers; and net leakage between the confined-drift and St. Peter aquifers and the Prairie du Chien-Jordan aquifer was upward due to discharge to the Mississippi River. The regional pattern of ground-water flow was not changed as a result of development of the ground-water resource and large ground-water withdrawals. The steady-state simulation for 1970-79, however, indicates that leakage to the confined-drift and St. Peter aquifers increased by about 68 percent and boundary inflow by about 89 percent compared to the flows prior to large ground-water withdrawals due to the lowering of hydraulic heads. The amount of water discharging from the aquifer system to the Mississippi River was reduced by about 41 percent. The reduction in discharge to the Mississippi River is the amount of water captured by pumping wells that would otherwise flow toward and discharge to the river. The transient simulation for 1987 indicates that the net ground-water leakage between the confined-drift and St. Peter aquifers and the Prairie du Chien-Jordan aquifer is downward during the periods of large ground-water withdrawals from March to September, in contrast to the net upward leakage prior to large ground-water withdrawals. The general affect of the large ground-water withdrawals was to (1) increase the downward leakage of water to the confined-drift and St. Peter aquifers and the Prairie du Chien-Jordan aquifer from overlying deposits resulting from the lowering of hydraulic heads and (2) decrease the amount of water discharged from the aquifer system to the Mississippi River resulting from the capture of water by pumped wells.

Sensitivity analyses, in which a single hydrologic property is varied while all other properties are held constant, were done for each of the simulations to identify the relative effect of adjustments of hydrologic properties on simulated hydraulic heads. Hydraulic heads in the steady-state simulations were most sensitive to changes in the vertical hydraulic conductivity of the upper drift confining unit. The vertical hydraulic conductivity and thickness of the upper drift confining unit control the leakage of water to the unconfined-drift aquifer from the underlying confined-drift and St. Peter aquifers and the Prairie du Chien-Jordan aquifer in the Mississippi River valley. Leakage of water to the unconfined-drift aquifer and ground-water withdrawals by wells are the only major discharges from the confined-drift and St. Peter aquifers and the Prairie du Chien-Jordan aquifer in the study area. Hydraulic heads in the aquifers are, therefore, greatly influenced by the hydraulic properties of the upper drift confining unit. Hydraulic heads in the aquifers were sensitive to (1) changes in the vertical hydraulic conductivity of the lower confining unit, (2) the hydraulic conductivity of the Prairie du Chien-Jordan aquifer, and (3) leakage to the confined-drift and St. Peter aquifers to a lesser degree. Hydraulic heads were relatively insensitive to changes in (1) the hydraulic conductivity of the unconfined-drift and confined-drift and St. Peter aquifers, (2) the vertical hydraulic conductivity of the Mississippi riverbed, (3) recharge to the unconfined-drift aquifer, and (4) ground-water evapotranspiration rates. Hydraulic heads in the steady-state simulation with large ground-water withdrawals (1970-79) are more sensitive to changes in the vertical hydraulic conductivity of the lower confining unit than are heads in the simulation prior to large ground-water withdrawals (1885-1930) due to the downward leakage of water from the confined-drift and St. Peter aquifers to the Prairie du Chien-Jordan aquifer resulting from ground-water withdrawals.

Hydraulic heads in the transient simulation for 1980-87 were most sensitive to changes in leakage to the confined-drift and St. Peter aquifers, rather than to changes in the vertical hydraulic conductivity of the upper drift confining unit, as was the case in the steady-state simulations. Under steady-state conditions, new recharge-discharge relations can be established, whereas under transient conditions, short-term imbalances may greatly affect hydraulic heads. Hydraulic heads in the aquifers were sensitive to changes in the vertical hydraulic conductivity of the upper drift and lower confining units and the horizontal hydraulic conductivity of the Prairie du Chien-Jordan aquifer to a lesser degree. Hydraulic heads were relatively insensitive to changes in (1) the hydraulic conductivity of the unconfined-drift and confined-drift and St. Peter aquifers, (2) the storage properties (specific yield and storage coefficient) of the aquifers, (3) the vertical hydraulic conductivity of the Mississippi riverbed, (4) recharge to the unconfined-drift aquifer, and (5) ground-water evapotranspiration rates.

Availability of Ground Water

The Minneapolis Water Works has considered developing a ground-water supply of as much as 55 Mgal/d at (or) near their present location. Such a supply could be used to (1) supplement the present surface-water supply, (2) dilute surface water during periods of natural water-quality degradation, or (3) replace, on an emergency basis, a substantial part of the surface-water supply if it should be temporarily threatened by contamination. The numerical ground-water-flow model was developed to help estimate the capacity of the aquifer system to yield water to wells and to estimate the effect of ground-water withdrawals on water levels in wells and the extent to which these withdrawals induce flow from areas of known ground-water contamination. The predictive capabilities of the calibrated ground-water-flow model are only as accurate as the documented aquifer response to stress, but they permit evaluation of the effects of hypothetical pumping scenarios. A series of model simulations was done to evaluate the response of the aquifer system in the study area to a hypothetical increase in ground-water withdrawals of as much as 55 Mgal/d near the Minneapolis Water Works site.

The calibrated models were used to simulate the effects of hypothetical ground-water withdrawals under both steady-state and transient conditions. Under steady-state conditions, recharge-discharge relations change depending on the volume of ground-water withdrawals, location of pumping wells, and natural recharge to and discharge from the aquifers. Ground-water discharge to streams may be diverted to wells because of increased ground-water withdrawals. If ground-water withdrawals continue for a sufficiently long time and do not exceed potential increases in recharge to or potential decreases in discharge from the aquifers, new steady-state hydrologic conditions will occur, new recharge-discharge relations will be established, and the aquifer system will approach a new equilibrium. Under transient conditions, the response of the aquifer system to ground-water withdrawals is also dependent on the storage characteristics of the aquifers.

The accuracy of hypothetical simulations varies depending on the particular conditions being simulated. General factors affecting the accuracy of the simulations include (1) uncertainties in the model calibration, including uncertainties in estimates of recharge, discharge, and aquifer properties, (2) the duration of the simulation period compared to the duration of the calibration period, and (3) the rate of simulated ground-water withdrawals compared to the rate of ground-water withdrawals used in calibration. Assuming the model calibration is accurate, the most accurate hypothetical simulations are possible when the duration and withdrawal rate for the hypothetical simulations are less than, or comparable to, the duration and withdrawal rate for the calibration period. In a transient simulation, if the duration of the hypothetical simulation period is much greater than the duration of the calibration period, errors that accumulate through time can lessen the accuracy of the simulation results. The rate of recharge or discharge, for example, ground-water withdrawals, during the hypothetical simulation period also can affect the accuracy of the simulation results. If all the errors in a model calibration are due to incorrect model response to ground-water withdrawals, then a doubling of the pumping rate in a hypothetical simulation could lead to an approximate doubling of the error in simulated hydraulic heads and simulated ground-water-flows compared with that shown by the calibration. Long simulation periods and high rates of ground-water withdrawal can produce large errors, and special care should be taken in using the results of such simulations.

Transient hypothetical simulations

Transient hypothetical simulations were made to determine the effect additional ground-water withdrawals would have on seasonal fluctuations in hydraulic heads in the aquifers and flow in the Mississippi River. Transient hypothetical simulations were made for periods of 1 and 5 years. The hydrologic properties for the aquifers from the calibrated transient simulation for 1987 (table 18) were used in the transient hypothetical simulations. Simulations were made by varying the rate and distribution of hypothetical ground-water withdrawals from the confined-drift and St. Peter aquifers and the Prairie du Chien-Jordan aquifer near the Minneapolis Water Works. The locations of the cells from which additional ground-water withdrawals were simulated are shown in figure 44. The same seasonal stress periods (five per year) used in the transient simulation for 1987 were also used in the transient hypothetical simulations. The simulated hydraulic heads in the aquifers at the end of the simulation for 1980-86 (initial hydraulic heads in the transient simulation for 1987) were used as the initial hydraulic heads in the 1-year transient hypothetical simulations.

Use of the calibrated model as a management or predictive tool is based on the premise that if historical conditions in the aquifer system can be simulated, then future similar hydrologic conditions can also be simulated. The variation in recharge and discharge occurring during the hypothetical simulation period should be similar to that for the model-calibration period. The accuracy of hypothetical simulation results becomes more uncertain if the variation in recharge and discharge exceeds the range used in calibration.

EXPLANATION

SP5 Model cell from which additional ground-water withdrawals were simulated--Label refers to cell designation used in the text and table 24.

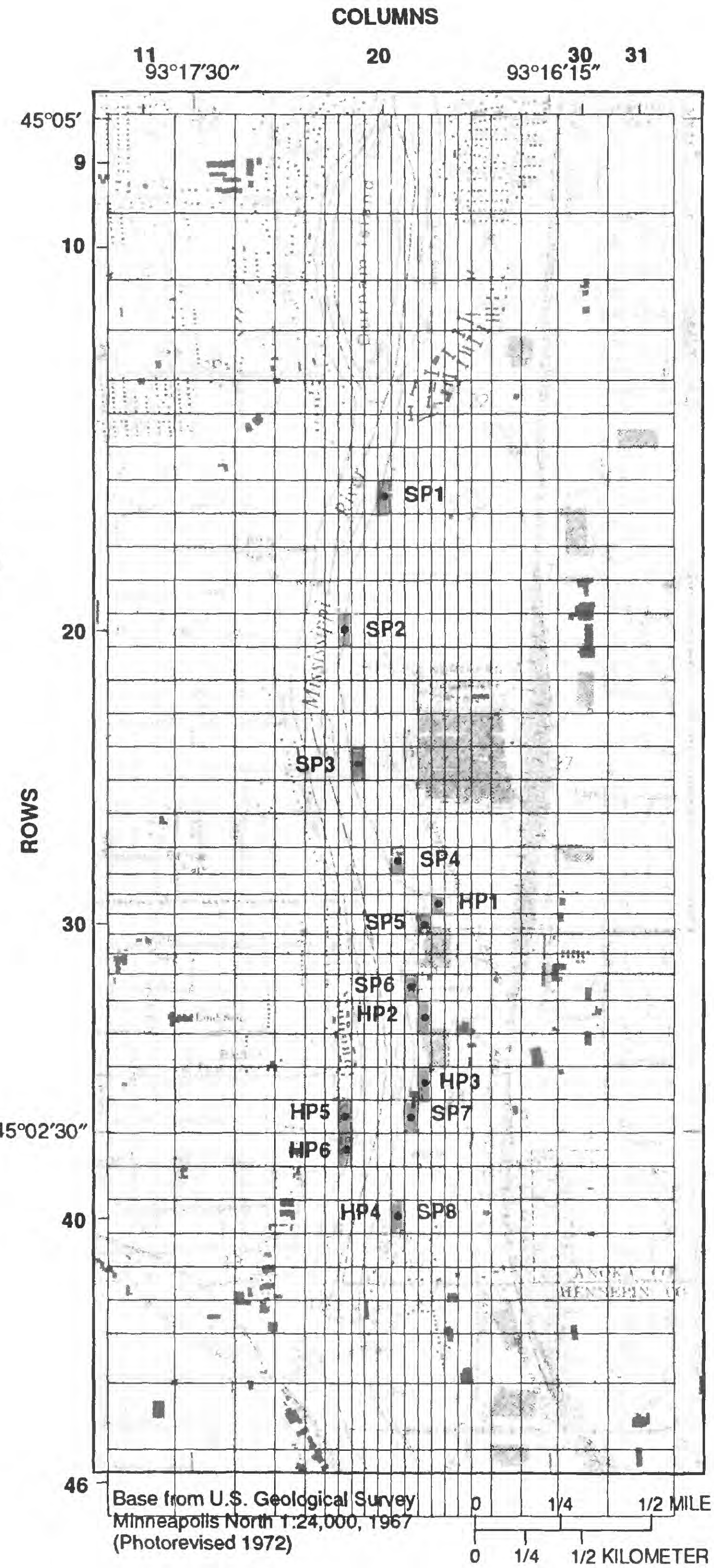


Figure 44.--Locations of model cells from which additional ground-water withdrawals were simulated in the hypothetical simulations.

Two major assumptions producing uncertainty in the results of the hypothetical transient simulations are that (1) recharge to the unconfined-drift aquifer and leakage to the confined-drift and St. Peter aquifers does not change as a result of the increased hypothetical ground-water withdrawals, and (2) hydraulic heads in the aquifers at the specified-head boundaries remain constant during the hypothetical simulations. The assumption that recharge and leakage to the aquifer system does not change is conservative (may lead to overestimation of drawdown) because, as indicated by the steady-state simulation for 1970-79, the drawdowns caused by the increased ground-water withdrawals would probably induce increased leakage to the confined-drift and St. Peter aquifers from the overlying deposits. The assumption that hydraulic heads in the aquifers at the model boundaries remain constant (are not lowered by the ground-water withdrawals during the simulation period) is nonconservative (possibly leading to underestimation of drawdown) because maintaining the heads at current levels could result in unrealistically high boundary inflows to the aquifer system as hydraulic heads in the aquifers within the modeled area are lowered by ground-water withdrawals. Boundary inflow ranged from about 40 to 49 percent of the total simulated sources of water to the aquifer system in the transient simulation for 1987 (table 23). Hydraulic heads for the specified-head model boundaries were maintained at 1987 levels for the hypothetical transient simulations because of (1) uncertainty regarding future changes in hydraulic heads and (2) historical data indicating that long-term and seasonal changes in hydraulic heads have not been significant in the areas where specified heads are used in the model, except for the southeast boundary.

One-year transient simulations were done by adding hypothetical ground-water withdrawals from model cells at or near the Minneapolis Water Works site to the ground-water withdrawals in the transient simulation for 1987. Ground-water withdrawals from specified cells were increased by as much as 10.64 ft^3/s (1/8 of the maximum rate proposed by the Minneapolis Water Works) during the "late summer" stress period. Norvitch and others (1974) report yields as high as 2,765 gal/min for the Prairie du Chien-Jordan aquifer near the Mississippi River and (or) where penetrated by drift filled bedrock valleys. Maximum yields to wells completed in the confined-drift and St. Peter aquifers are about 1,250 gal/min. A reasonable maximum yield to wells completed in the Prairie du Chien-Jordan aquifer from an area the size of a model cell at the Minneapolis Water Work site (200 ft X 200 ft) was assumed to be about 5,000 gal/min, or about 11 ft^3/s, based on well densities in existing municipal well fields in the Twin Cities Metropolitan Area; this corresponds to 2 wells pumping at a rate of 2,500 gal/min. The maximum yield to wells completed in the confined-drift and St. Peter aquifers from a model cell at the Minneapolis Water Works site was assumed to be about 2,500 gal/min. The "late summer" stress period was chosen because flow in the Mississippi River is generally lowest during late summer, and water use during the summer is relatively high compared to other seasons. Seasonal recharge to the unconfined-drift aquifer and leakage to the confined-drift and St. Peter aquifers were maintained at the same rates as for the calibrated transient simulation for 1987. The seasonal maximum ground-water evapotranspiration rates specified in the model were the same as those used for the calibrated transient simulation for 1987.

Hydraulic heads simulated for the confined-drift and St. Peter aquifers and the Prairie du Chien-Jordan aquifer at the end of the "late summer" and "fall" stress periods in the 1-year transient hypothetical simulations were compared to the hydraulic heads simulated for the aquifers at the end of the "late summer" and "fall" stress periods in the calibrated transient simulation for 1987. The difference between the hydraulic heads for the two simulations represents the effect of hypothetical increased ground-water withdrawals on hydraulic heads in the aquifers.

A hypothetical transient simulation was done by adding 10.64 ft^3/s in ground-water withdrawals from the Prairie du Chien-Jordan aquifer to each of four model cells (cells HP1, HP2, HP3, and HP4, fig. 44), for a total additional withdrawal of 42.55 ft^3/s (27.5 Mgal/d), during the "late summer" stress period. The maximum simulated increase in drawdown in the Prairie du Chien-Jordan aquifer at the end of the "late summer" stress period was about 80 ft (in the cells with additional ground-water withdrawals); the maximum increase in drawdown in the confined-drift and St. Peter aquifers was about 60 ft. The increase in simulated drawdowns caused by the additional ground-water withdrawals was less than 35 ft in the Prairie du Chien-Jordan aquifer outside the immediate vicinity of the Minneapolis Water Works (fig. 45). Increases in simulated drawdowns in the confined-drift and St. Peter aquifers were similar to those in the Prairie du Chien-Jordan aquifer. Figure 46 shows the simulated increase in drawdowns in the confined-drift and St. Peter aquifers and Prairie du Chien-Jordan aquifer near the Minneapolis Water Works at the end of the "late summer" stress period. The lesser drawdowns simulated for the confined-drift and St. Peter aquifers to the north of the Minneapolis Water Works are caused by (1) the greater thickness of the confined-drift aquifer in the northern part of the area as compared to the southern part and (2) the smaller thickness of the upper drift confining unit in the northern part of the area as compared to the southern part. Near the 10-ft contour line, the upper drift confining unit is not present. The greater transmissivity of the confined-drift aquifer and greater downward leakage from the unconfined-drift aquifer (to the north as compared to the south) result in less drawdown to the north. A comparison of the simulated hydraulic heads at the end of the "fall" stress period for the calibrated transient simulation for 1987 and hypothetical 1-year transient simulation indicated that hydraulic heads rebound to about the same altitude whether or not the additional ground-water is withdrawn. Hydraulic heads in the confined-drift and St. Peter aquifers and Prairie du Chien-Jordan aquifer near the Minneapolis Water Works at the end of the "fall" stress period were about 2.5 ft lower than they were at the beginning of the simulation (fig 47). The water supplying the additional ground-water withdrawals (42.55 ft^3s) was derived from changes in (1) leakage between the Mississippi River and the unconfined-drift aquifer, (2) storage of ground water in the aquifers, and (3) boundary inflow to and boundary outflow from the model area. Direct leakage of water from the Mississippi River to the unconfined-drift aquifer contributed about 9.5 percent and the capture of ground water that would otherwise discharge to the river about 24.5 percent of the additional water withdrawn. The reduction in flow in the Mississippi River would be about 14.4 ft^3/s, which is relatively small in comparison to streamflows in the river, even under conditions of drought (about 1,000 ft^3/s). The additional ground-water withdrawals simulated, therefore, would not have a measurable affect on streamflows in the river. Water released from storage in the aquifers contributed about 29 percent of the additional water withdrawn and a reduction in the amount of water

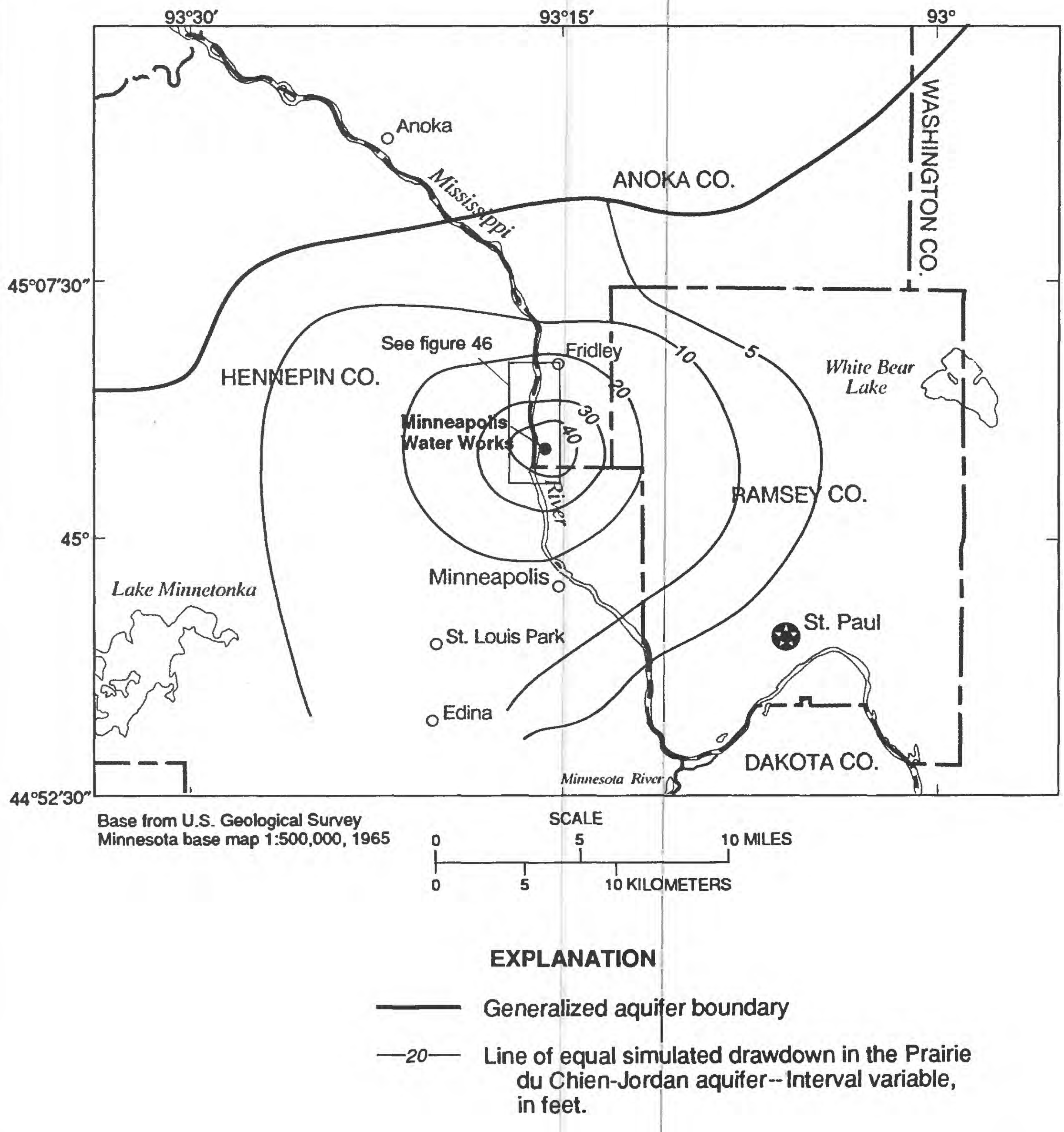


Figure 45.--Simulated drawdowns in the Prairie du Chien-Jordan aquifer at the end of the "later summer" stress period for hypothetical 1-year transient simulation of four model cells (HP1, HP2, HP3, and HP4) with additional ground-water withdrawals totaling 42.55 cubic feet per second from the Prairie du Chien-Jordan aquifer.

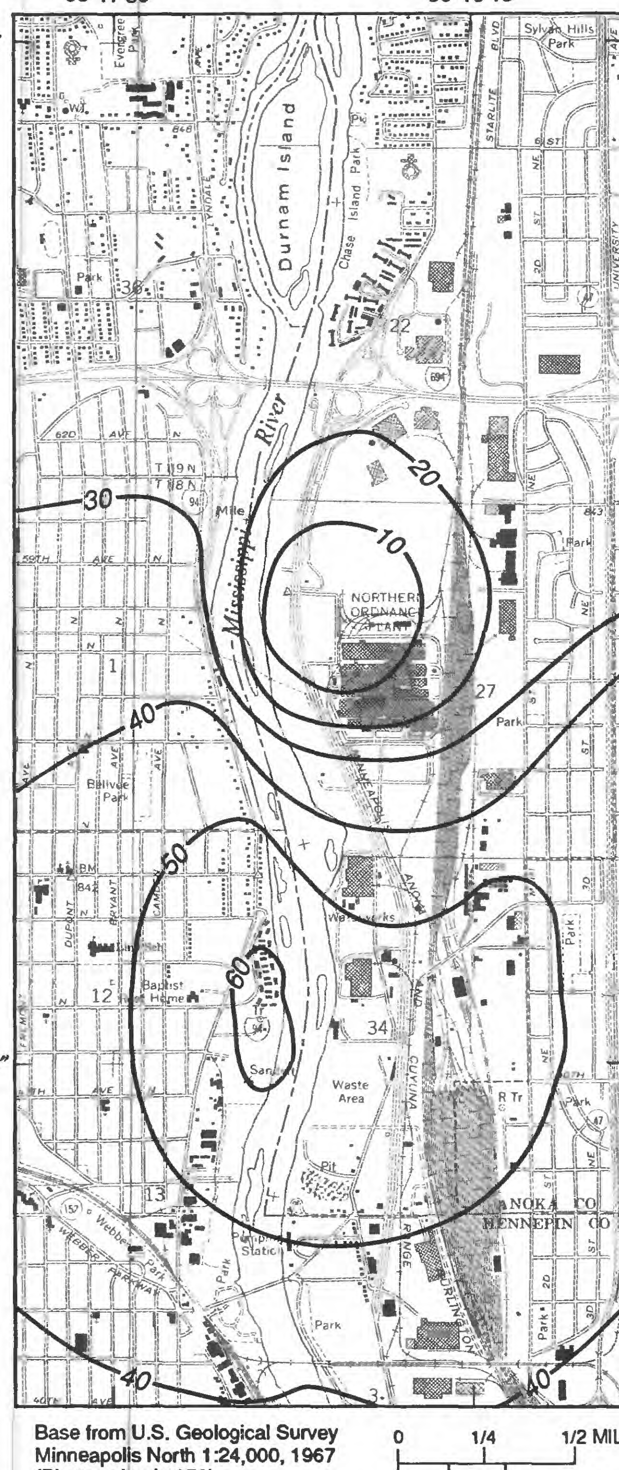
returned to storage another 0.5 percent. About 89 percent of the additional water derived from storage was released from storage in the unconfined-drift aquifer and subsequently leaked through confining units to the underlying confined aquifers. Downward leakage of water through the upper drift confining unit increased by about 99 percent (nearly doubled) compared to that observed for the calibrated 1987 transient simulation. Downward leakage of water through the lower confining unit increased by about 18 percent and the upward leakage of water through both confining units in discharge areas near the river decreased by about 12 percent. Ground-water inflow from areas beyond the model boundaries contributed about 34.5 percent of the additional water withdrawn, with about 92 percent being derived from the Prairie du Chien-Jordan aquifer. Most of the additional ground-water inflow entered through the southwestern and southeastern boundaries, with a much smaller amount entering from the northern boundary. Ground-water inflow from the northern boundary of the unconfined-drift aquifer did not change as a result of the additional ground-water withdrawals. A reduction in boundary outflow accounted for about 2 percent of the additional ground-water withdrawals.

A second hypothetical transient simulation was done by using a constant-flux boundary in place of a specified- (constant-) head boundary to investigate the effects of a more conservative assumption on hydraulic heads in the aquifers. A constant-flux boundary maintains the flow of water across the boundary to or from the aquifer system at a specified rate. The flow rate remains constant as hydraulic heads in the aquifers are lowered by ground-water withdrawals, in contrast to the increased flow rates that may result from increased hydraulic gradients when a specified-head (constant-head) boundary is used. The simulation was done with additional ground-water withdrawals from the Prairie du Chien-Jordan aquifer of 10.64 ft^3/s in each of four cells (cells HP1, HP2, HP3, and HP4, fig. 44) during the "late summer" stress period, as for the previous simulation. The simulated fluxes for the specified-head (constant-head) boundary cells in the transient simulation for 1987 were used as the specified fluxes for the constant-flux boundary cells. Use of constant-flux boundaries lowered hydraulic heads in the confined-drift and St. Peter aquifers and Prairie du Chien-Jordan aquifer at the end of the "late summer" stress period an additional 3.0 to 4.5 ft near the Minneapolis Water Works, as compared to heads from the simulation with specified-head (constant-head) boundaries. The results of this simulation indicate that the specified-head boundaries influence the seasonal drawdowns caused by additional ground-water withdrawals at the Minneapolis Water Works site. If hydraulic heads at the specified-head boundaries were to decline below 1987 levels due to future ground-water withdrawals, actual seasonal drawdowns would be greater than those projected by these simulations; an additional 3.0 to 4.5 ft near the Minneapolis Water Works assuming the hydraulic gradient at the boundaries did not change.

A third hypothetical transient simulation was done by adding 10.64 ft^3/s in ground-water withdrawals from the Prairie du Chien-Jordan aquifer to each of four model cells (cells HP2, HP3, HP5, and HP6, fig. 44) during the "late summer" stress period. Two of the cells are located on the western side of the Mississippi River and two on the eastern side. The maximum simulated increase in drawdown in the Prairie du Chien-Jordan aquifer at the end of the "late summer" stress period was about 90 ft in the cells with additional ground-water withdrawals; the maximum increase in drawdown in the confined-drift and St. Peter aquifers was about 85 ft. The increase in simulated

EXPLANATION

—*30*— Line of equal simulated drawdown--
Interval 10 feet.

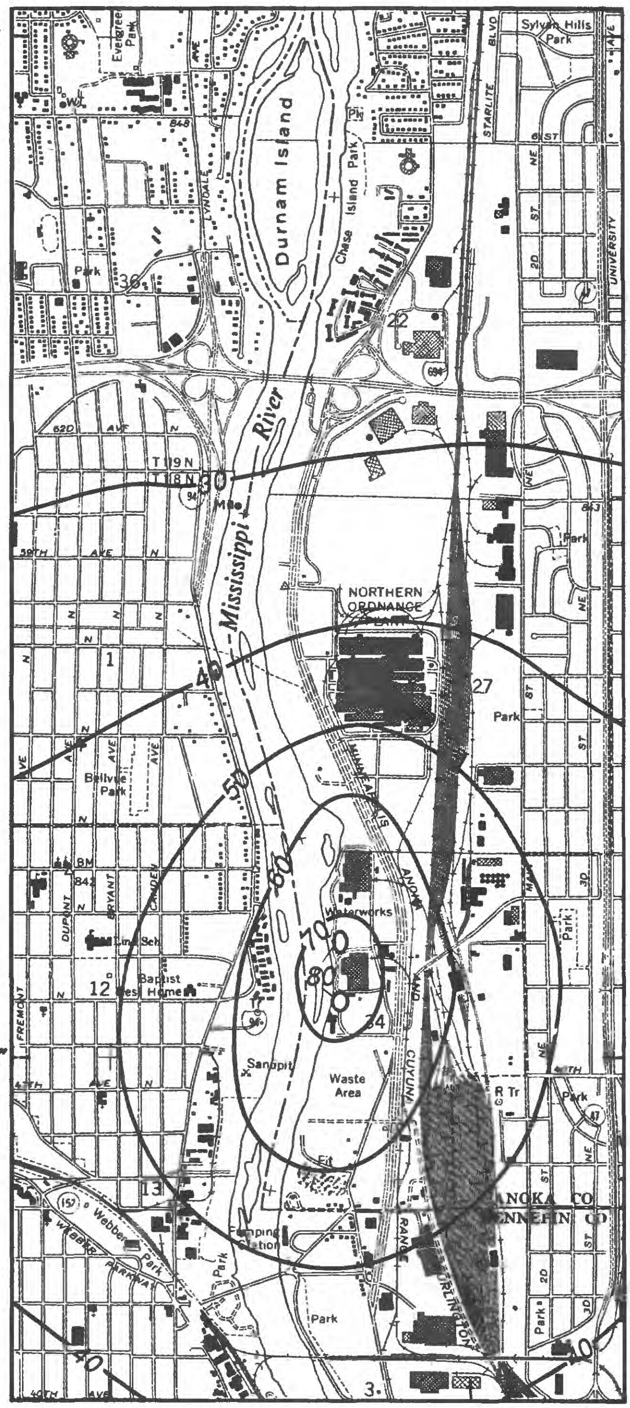


Base from U.S. Geological Survey
Minneapolis North 1:24,000, 1967
(Photorevised 1972)

0 1/4 1/2 MILE
0 1/4 1/2 KILOMETER

CONFINED-DRIFT AND ST. PETER AQUIFERS

Figure 46.--Simulated drawdowns in the confined-drift and St. Peter aquifers and the end of the "late summer" stress period for hypothetical 1-year transient ground-water withdrawals totaling 42.55 cubic feet



Base from U.S. Geological Survey
Minneapolis North 1:24,000, 1967
(Photorevised 1972)

0 1/4 1/2 MILE

0 1/4 1/2 KILOMETER

PRAIRIE DU CHIEN-JORDAN AQUIFER

in the Prairie du Chien-Jordan aquifer near the Minneapolis Water Works at simulation of four model cells (HP1, HP2, HP3, and HP4) with additional per second from the Prairie du Chien- Jordan aquifer.

drawdowns due to the additional ground-water withdrawals was less than 40 ft in the Prairie du Chien-Jordan aquifer outside the immediate vicinity of the Minneapolis Water Works (fig. 48). Increases in simulated drawdowns in the confined-drift and St. Peter aquifers were similar to those in the Prairie du Chien-Jordan aquifer. Drawdowns are similar to those for the preceding simulation with 4 cells with additional ground-water withdrawals located on the eastern side of the river only (compare fig. 48 to figs. 45 and 46). Drawdowns on the west side of the river and to the south and west of the Minneapolis Water Works are somewhat greater for this simulation, however, because of the additional withdrawals on the west side of the river. The water supplying the additional ground-water withdrawals (42.55 ft^3/s) was derived from (1) direct leakage of water from the Mississippi River to the unconfined-drift aquifer (9.2 percent) and the capture of ground water that would otherwise discharge to the river (24.7 percent), (2) increased boundary inflow (34.8 percent), (3) water released from storage in the aquifers (29.0 percent), and (4) a reduction in water returned to storage and in boundary outflow (2.3 percent). The contributing percentages for each source of water are similar to those for the preceding simulation, but with a small decrease in the percentage of water derived from direct leakage of water from the river and small increases in the capture of ground water that would otherwise discharge to the river and in boundary inflow. Downward leakage of water through the upper drift confining unit nearly doubled (increased by 98 percent) and through the lower confining unit increased by about 17 percent. Upward leakage of water through both confining units decreased by about 12 percent.

A fourth hypothetical transient simulation was done by adding 5.4 ft^3/s in ground-water withdrawals from the confined-drift and St. Peter aquifers to each of four model cells (cells SP1, SP2, SP3, and SP4, fig. 44), for a total additional withdrawal of 21.6 ft^3/s (14.0 Mgal/d) during the "late summer" stress period. The maximum simulated increase in drawdown in the confined-drift and St. Peter aquifers at the end of the "late summer" stress period was about 118 ft in the cells with additional ground-water withdrawals; the maximum increase in drawdown in the Prairie du Chien-Jordan aquifer was about 15 ft. The increase in simulated drawdowns caused by the additional ground-water withdrawals was less than 10 ft in the confined-drift and St. Peter aquifers outside the immediate vicinity of the Minneapolis Water Works (fig. 49). Maximum drawdowns in the confined-drift and St. Peter aquifers near the Minneapolis Water Works site (in cells SP3 and SP4) are much greater (about doubled) than those to the north near Anoka County parkland (in cells SP1 and SP2) because the transmissivity of the confined-drift aquifer and downward leakage from the unconfined-drift aquifer are greater to the north. The water supplying the additional ground-water withdrawals (21.6 ft^3/s) was derived from (1) direct leakage of water from the Mississippi River to the unconfined-drift aquifer (35.7 percent) and the capture of ground water that would otherwise discharge to the river (21.3 percent), (2) water released from storage in the aquifers (23.6 percent), (3) increased boundary inflow (17.6 percent), and (4) a reduction in water returned to storage and in boundary outflow (1.8 percent). The percentage of water derived from direct leakage of water from the river to the unconfined-drift aquifer is much greater for this simulation as compared to the previous hypothetical simulations with additional ground-water withdrawals from the Prairie du Chien-Jordan aquifer (about 35 percent compared to about 10 percent) and the percentage derived from increased boundary inflow much less (about 18 percent compared to about 35 percent).

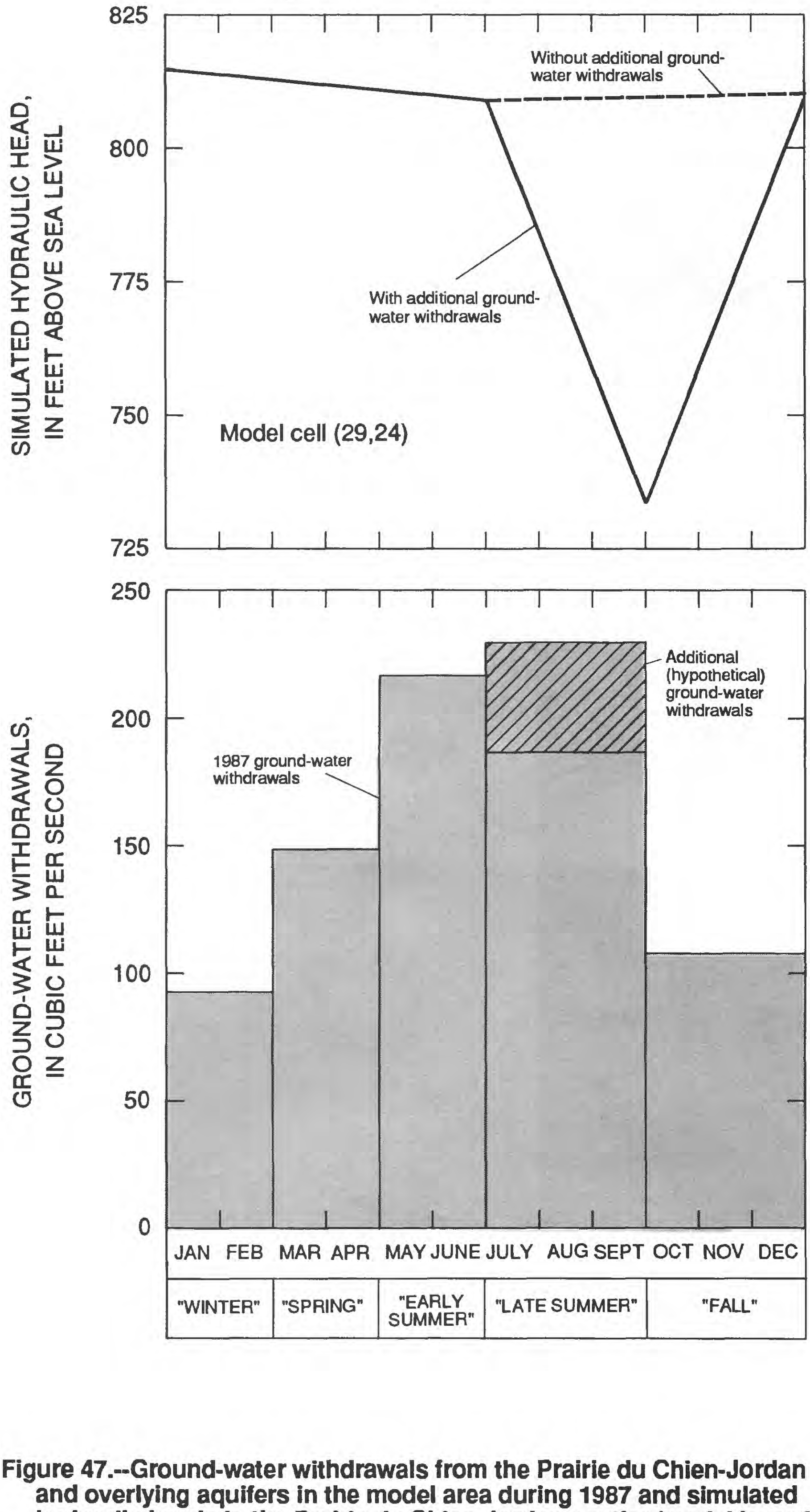
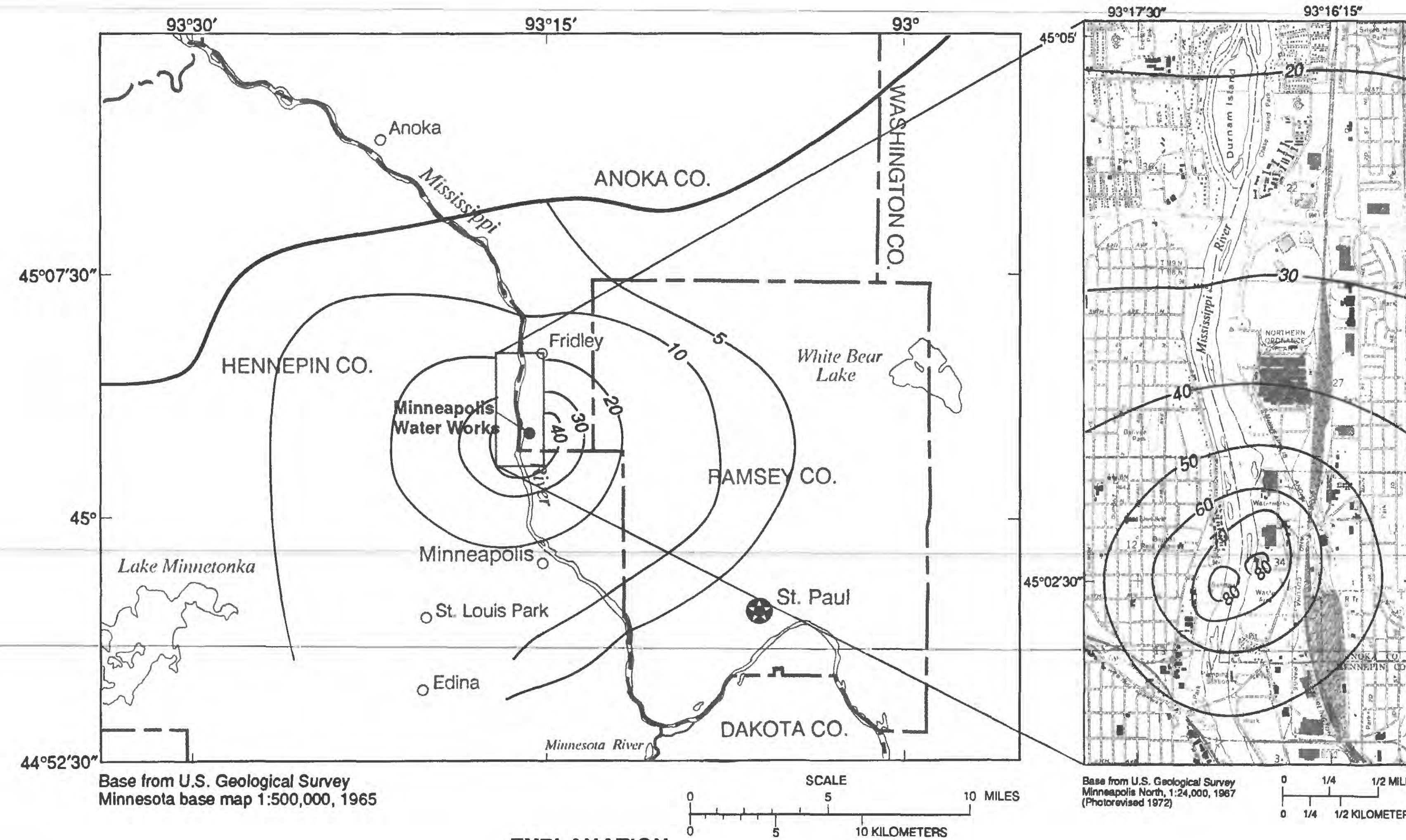


Figure 47.--Ground-water withdrawals from the Prairie du Chien-Jordan and overlying aquifers in the model area during 1987 and simulated hydraulic heads in the Prairie du Chien-Jordan aquifer (model layer 3) at model cell (29,24) near the Minneapolis Water Works, 1987.

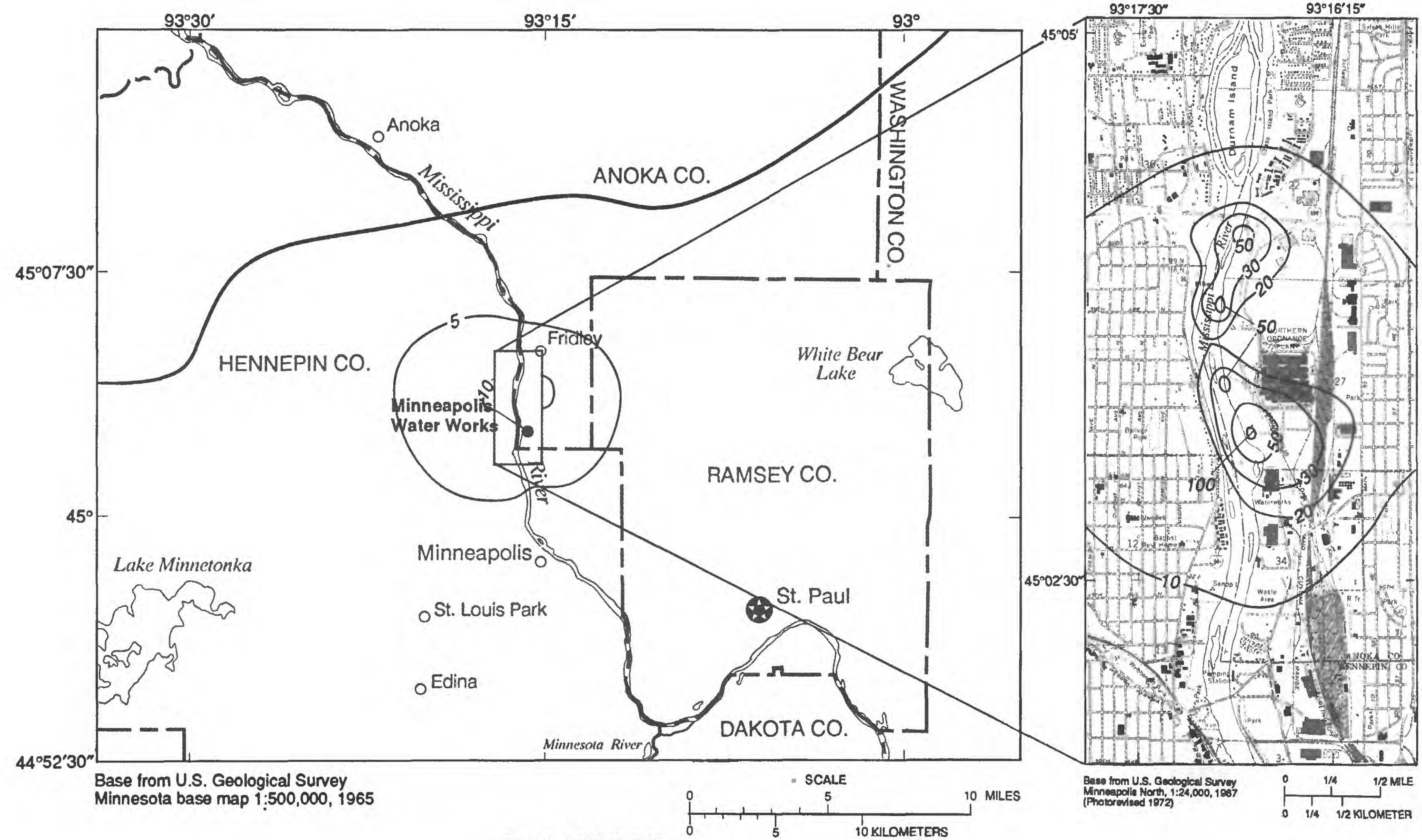


EXPLANATION

——— Generalized aquifer boundary

—10— Line of equal simulated drawdown in the Prairie du Chien-Jordan aquifer--Interval variable in feet.

Figure 48.--Simulated drawdowns in the Prairie du Chien-Jordan aquifer at the end of the "late summer" stress period for hypothetical 1-year transient simulation of four model cells (HP2, HP3, HP5, and HP6) with additional ground-water withdrawals totaling 42.55 cubic feet per second from the Prairie du Chien-Jordan aquifer.



EXPLANATION

——— Generalized aquifer boundary

—10— Line of equal simulated drawdown in the confined-drift and St. Peter aquifers-- Interval variable in feet.

Figure 49.--Simulated drawdowns in the confined-drift and St. Peter aquifers at the end of the "late summer" stress period for hypothetical 1-year transient simulation of four model cells (SP1, SP2, SP3, and SP4) with additional ground-water withdrawals totaling 21.6 cubic feet per second from the confined-drift and St. Peter aquifers.

A fifth hypothetical transient simulation was done by adding 10.64 ft^3/s in ground-water withdrawals from the Prairie du Chien-Jordan aquifer to each of eight model cells (cells SP1 through SP8, fig. 44), for a total additional withdrawal of 85.1 ft^3/s (55 Mgal/d), during the "late summer" stress period. The added ground-water withdrawals were simulated from the Minneapolis Water Works site and from Anoka County parkland north of the Minneapolis Water Works. The maximum simulated increase in drawdown in the Prairie du Chien-Jordan aquifer at the end of the "late summer" stress period was about 130 ft (in the cells with additional ground-water withdrawals); the maximum increase in drawdown in the confined-drift and St. Peter aquifers was about 105 ft. Outside the immediate vicinity of the Minneapolis Water Works, increases in simulated drawdowns in the Prairie du Chien-Jordan aquifer are substantially larger (fig. 50) compared to the increases in simulated drawdowns from the simulations with four cells with additional ground-water withdrawals because the total additional withdrawals are doubled. Increases in simulated drawdowns in the confined-drift and St. Peter aquifers were similar to those in the Prairie du Chien-Jordan aquifer. Figure 51 shows the simulated increase in drawdowns in the confined-drift and St. Peter aquifers and the Prairie du Chien-Jordan aquifer near the Minneapolis Water Works at the end of the "late summer" stress period.

The water supplying the additional ground-water withdrawals (85.1 ft^3/s) was derived from (1) direct leakage of water from the Mississippi River to the unconfined-drift aquifer (about 15 percent), (2) capture of ground water that would otherwise discharge to the river (about 19.5 percent), (3) water released from storage in the aquifers (about 29.5 percent) and a reduction in the amount of water returned to storage (about 0.2 percent), and (4) increased boundary inflow (about 34 percent) and a reduction in boundary outflow (about 1.8 percent). The total percentage of water derived from changes in leakage between the Mississippi River and the unconfined-drift aquifer is about the same as for the simulation with four cells (HP1, HP2, HP3, and HP4) with additional ground-water withdrawals from the Prairie du Chien-Jordan aquifer (about 34 percent). The percentage of direct leakage of water from the Mississippi River to the unconfined-drift aquifer increased from 9.5 to 15 percent, however, while the percentage of ground-water captured that would otherwise discharge to the river decreased from 24.5 to 19.5 percent. The higher percentage of water derived from direct leakage of water from the river is due to the greater vertical hydraulic conductivity of the upper drift confining unit underlying the area north of the Minneapolis Water Works (near additional withdrawals in cells SP1, SP2, and SP3). Downward leakage of water through the upper drift confining unit increased by about 230 percent (by a factor of 3.3) and through the lower confining unit by about 37 percent as compared to that observed for the calibrated 1987 transient simulation. Upward leakage of water through both confining units near the river decreased by about 20 percent.

A sixth hypothetical transient simulation was done by adding 10.64 ft^3/s in ground-water withdrawals from the Prairie du Chien-Jordan aquifer to each of eight model cells (cells SP1 through SP8, fig. 44), for a total additional withdrawal of 85.1 ft^3/s, during the "early summer" and "late summer" stress periods. The maximum drawdown at the end of the "late summer" stress period was about 130 ft in the Prairie du Chien-Jordan aquifer and about 105 ft in the confined-drift and St. Peter aquifers. Figure 52 shows the hydraulic head in each cell with additional simulated ground-water withdrawals. Simulated hydraulic heads in the cells near the center of the area (cell SP3, SP4, and SP5, fig. 44) fall below the top of the Prairie du Chien-Jordan aquifer by the end of June, during the "early summer" stress period. Hydraulic heads fall 85 to 120 ft by the end of May and continue to fall at a much slower rate during subsequent months, and rise to within about 5 ft of the starting hydraulic head in September. The simulated hydraulic heads in the cells are not accurate when the heads have fallen below the top of the Prairie du Chien-Jordan aquifer because the aquifer is simulated as being confined in the numerical model. This limitation was imposed by the author because historically the Prairie du Chien-Jordan aquifer has been under confined conditions in the study area. The computer program by McDonald and Harbaugh (1988), however, was written to simulate a change from confined to unconfined conditions. When hydraulic heads fall below the top of the aquifer, the rate of decline decreases because of delayed yield from gravity drainage, which is an additional source of water. Recovery of hydraulic heads, once ground-water withdrawals cease, is also slower because the desaturated pores must be refilled with water.

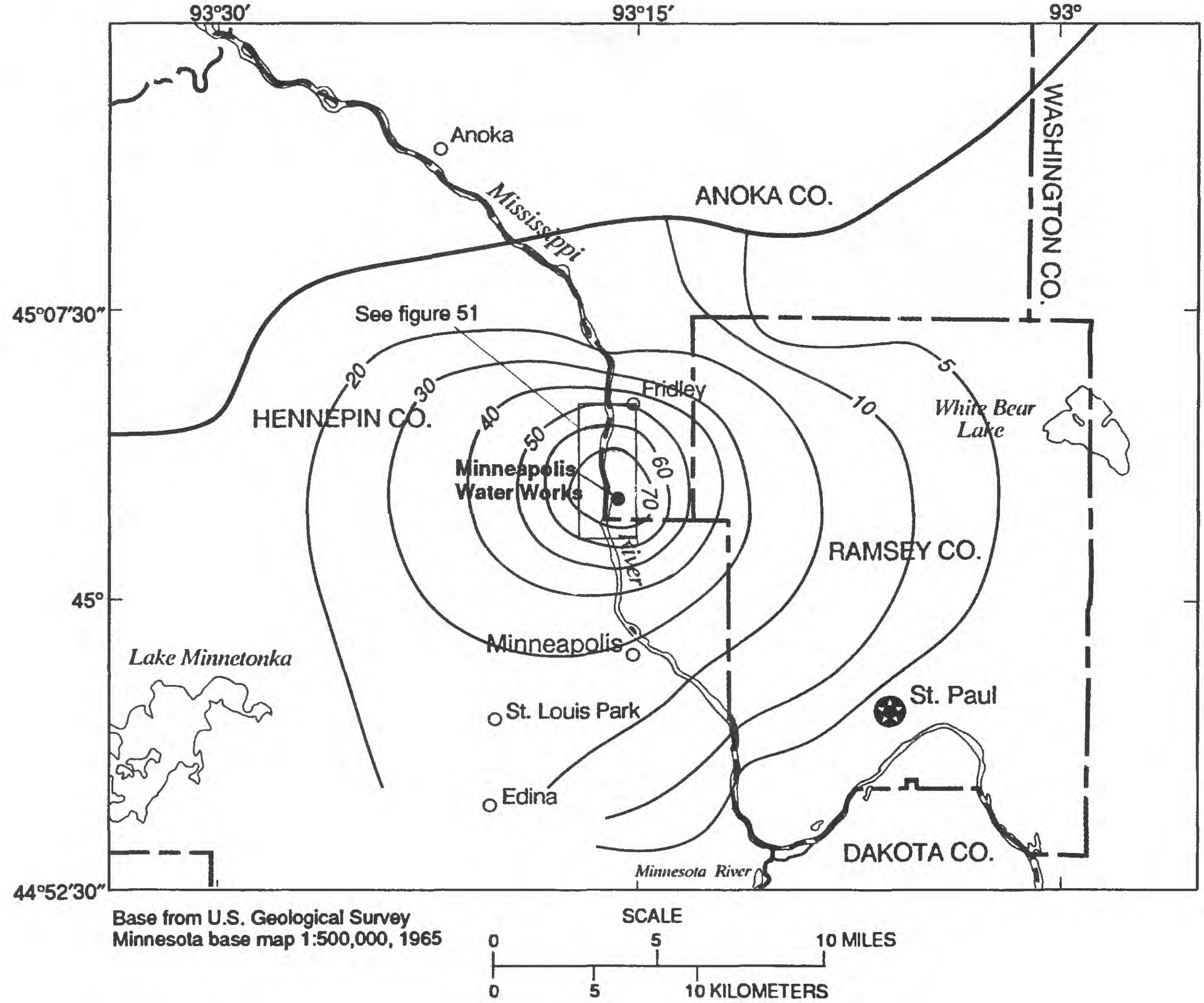
An additional hypothetical transient simulation was made. In this simulation ground-water withdrawals from the Prairie du Chien-Jordan aquifer were increased 10.64 ft^3/s from cells HP1, HP2, HP3, and HP4 (fig. 44). The total additional withdrawal was 42.55 ft^3/s. The simulation period was 5 years. The seasonal pumpage and recharge rates from the 1-year transient hypothetical simulations were cycled five times in the 5-year transient simulation. The assumption was made that there was no increase in withdrawal rates from high-capacity wells in the modeled area other than the additional withdrawals for the Minneapolis Water Works site. Seasonal maximum ground-water evapotranspiration rates were the same as those used for the calibrated transient simulation for 1987 and were also cycled five times. Hydraulic heads in the aquifers at the beginning of the calibrated transient simulation for 1987 were used as the initial hydraulic heads in the 5-year hypothetical transient simulation.

The maximum simulated drawdown in the Prairie du Chien-Jordan aquifer at the end of the "late summer" stress period for the fifth year of the 5-year simulation was about 85 ft (in the cells with additional withdrawals). The maximum simulated drawdown in the confined-drift and St. Peter aquifers was about 65 ft. The drawdowns represent the total drawdown due to ground-water withdrawals for 1987 plus the additional hypothetical ground-water withdrawals. The 5-year transient hypothetical simulation indicates that drawdowns in the confined-drift and St. Peter aquifers and Prairie du Chien-Jordan aquifer at the end of the "late summer" stress period are approximately the same after 5 years of additional ground-water withdrawals as after 1 year. The additional ground-water withdrawals do not exceed potential increases in recharge to or potential decreases in discharge from the aquifers and the aquifer system approaches a new steady-state condition. Simulated drawdowns in the Prairie du Chien-Jordan aquifer at the end of the "late summer" stress period for the fifth year of the simulation are shown in figure 53. Simulated drawdowns outside of the immediate vicinity of the Minneapolis Water Works (fig. 53) generally are similar to seasonal changes in hydraulic heads measured in the Prairie du Chien-Jordan aquifer (fig. 19); near the Minneapolis Water Works and to the north and northeast, the additional ground-water withdrawals cause lower hydraulic heads at the end of the "late summer" stress period and, equivalently, greater seasonal declines in hydraulic heads. Simulated drawdowns in the confined-drift and St. Peter aquifers at the end of the "late summer" stress period for the fifth year of the simulation are shown in figure 54. The simulated drawdowns are similar to those for the Prairie du Chien-Jordan aquifer, except in the immediate vicinity of the cells with additional ground-water withdrawals and in the southwestern part of the model area, where drawdowns in the confined-drift and St. Peter aquifers are less than those in the Prairie du Chien-Jordan aquifer. The simulated drawdowns in the confined-drift and St. Peter aquifers and Prairie du Chien-Jordan aquifer near the Minneapolis Water Works at the end of the "fall" stress period were about 5 ft (compared to 2.5 to 3.5 ft for the 1-year hypothetical transient simulation).

Steady-state hypothetical simulations

The steady-state model for 1970-79, calibrated by the principle of superposition, was used to simulate the effect of hypothetical ground-water withdrawals on hydraulic heads in the aquifers and flow in the Mississippi River under steady-state conditions. Ground-water-withdrawal rates used in the hypothetical steady-state simulations represent changes (increases) in ground-water withdrawals rather than total withdrawals; therefore, the ground-water withdrawals simulated in the steady-state hypothetical simulations consist of only the contemplated increase in ground-water withdrawals near the Minneapolis Water Works (ground-water withdrawals from all other wells in the modeled area are assumed to remain constant and therefore, by the principle of superposition, equal zero). Similarly, natural hydrologic boundaries and initial conditions are represented in terms of changes rather than in terms of observed values.

The same assumptions were made for the steady-state hypothetical simulations that were made for the transient hypothetical simulations with regard to recharge to the unconfined-drift aquifer and leakage to the confined-drift and St. Peter aquifers and hydraulic heads in the aquifers at the specified-head model boundaries. The assumption was made that natural recharge and leakage to the aquifer system does not change as a result of the increased ground-water withdrawals, therefore, recharge and leakage for the steady-state hypothetical simulations (by the principle of superposition) were zero. Hydraulic heads at the specified-head model boundaries were assumed to remain unchanged and were therefore represented as zero-potential boundaries. The assumption of no change in recharge to the aquifer system is conservative because, as indicated by the steady-state simulation for 1970-79, recharge-discharge relations would change in response to the increased ground-water withdrawals and would adjust to a new equilibrium. The assumption of constant heads at the specified-head model boundaries is nonconservative because these boundaries may be intercepted by the regional cone of depression caused by increased ground-water withdrawals.



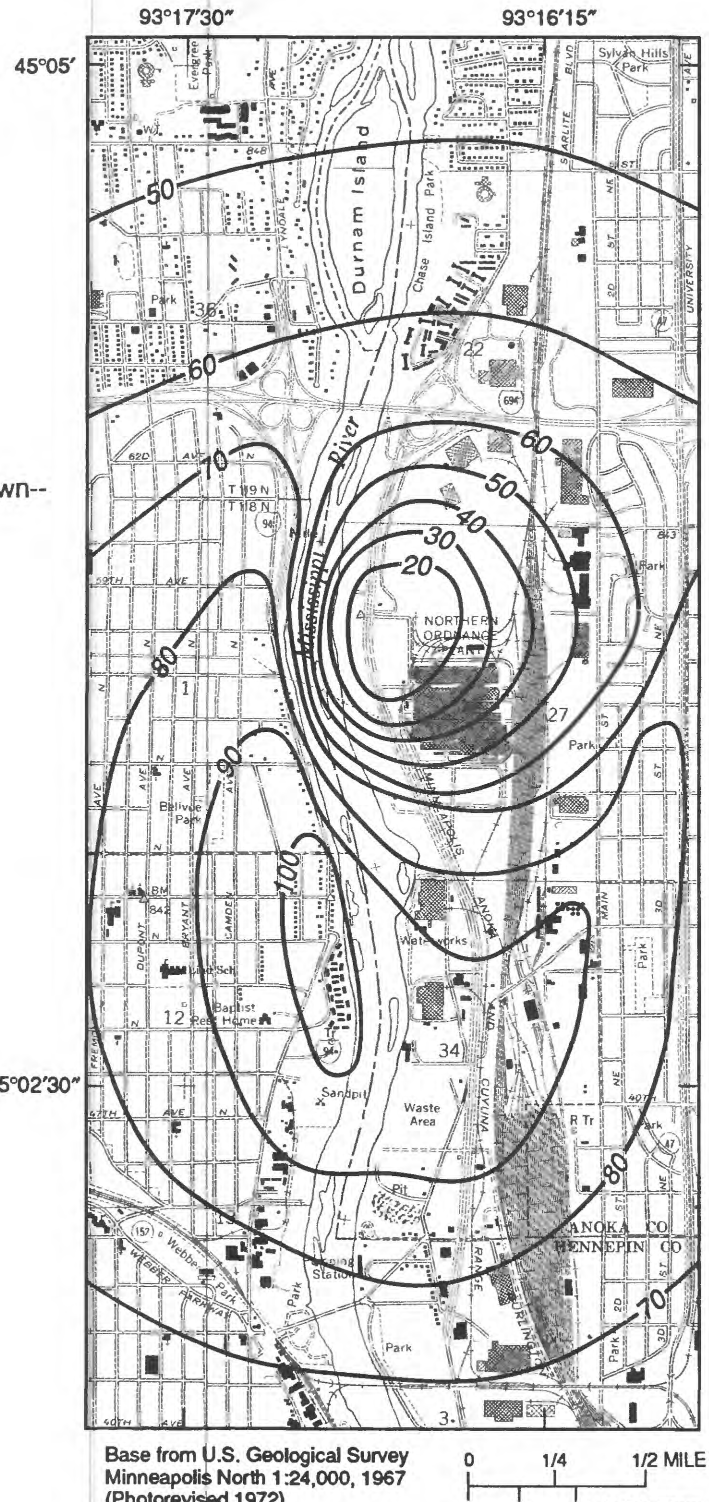
EXPLANATION

———	Generalized aquifer boundary
—20—	Line of equal simulated drawdown in the Prairie du Chien-Jordan aquifer-- Interval variable, in feet.

Figure 50.--Simulated drawdowns in the Prairie du Chien-Jordan aquifer at the end of the "late summer" stress period for hypothetical 1-year transient simulation of eight model cells (SP1 through SP8) with additional ground-water withdrawals totaling 85.1 cubic feet per second from the Prairie du Chien-Jordan aquifer.

EXPLANATION

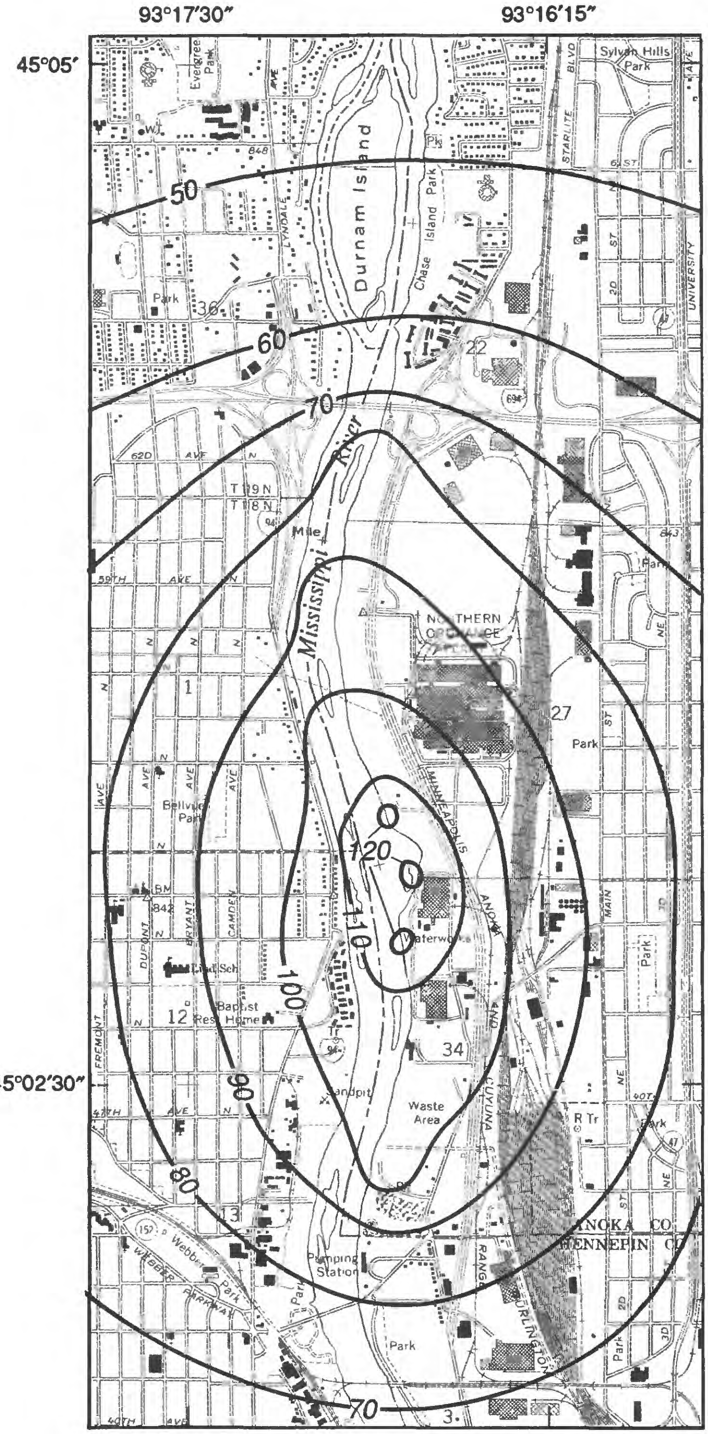
—*30*— Line of equal simulated drawdown--Interval 10 feet.



Base from U.S. Geological Survey Minneapolis North 1:24,000, 1967 (Photorevised 1972)

CONFINED-DRIFT AND ST. PETER AQUIFERS

Figure 51.--Simulated drawdowns in the confined-drift and St. Peter aquifers and the end of the "late summer" stress period for hypothetical 1-year ground-water withdrawals totaling 85.1 cubic feet



Base from U.S. Geological Survey
Minneapolis North 1:24,000, 1967
(Photorevised 1972)

0 1/4 1/2 MILE

0 1/4 1/2 KILOMETER

PRAIRIE DU CHIEN-JORDAN AQUIFER

in the Prairie du Chien-Jordan aquifer near the Minneapolis Water Works at transient simulation of eight model cells (SP1 through SP8) with additional per second from the Prairie du Chien-Jordan aquifer.

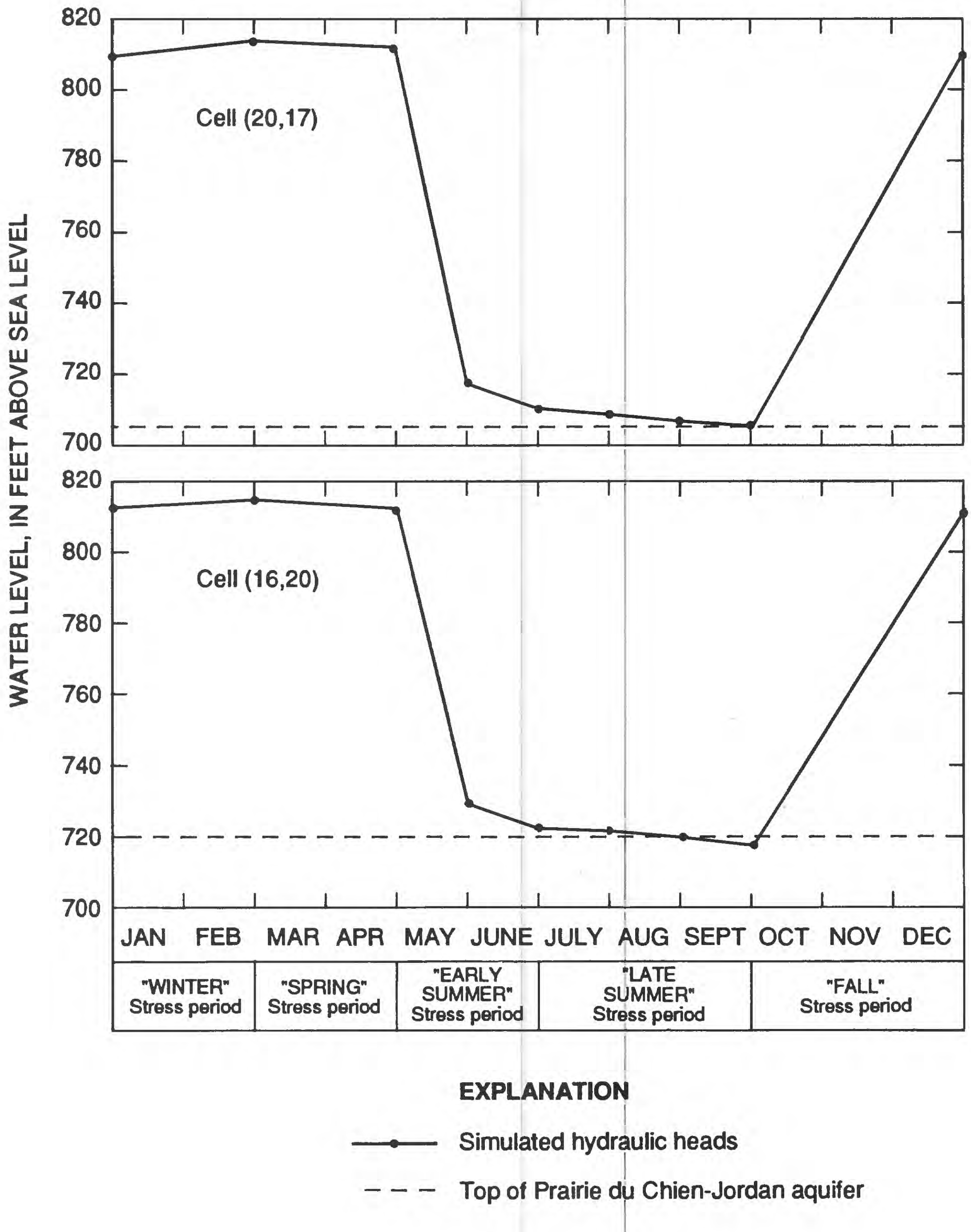
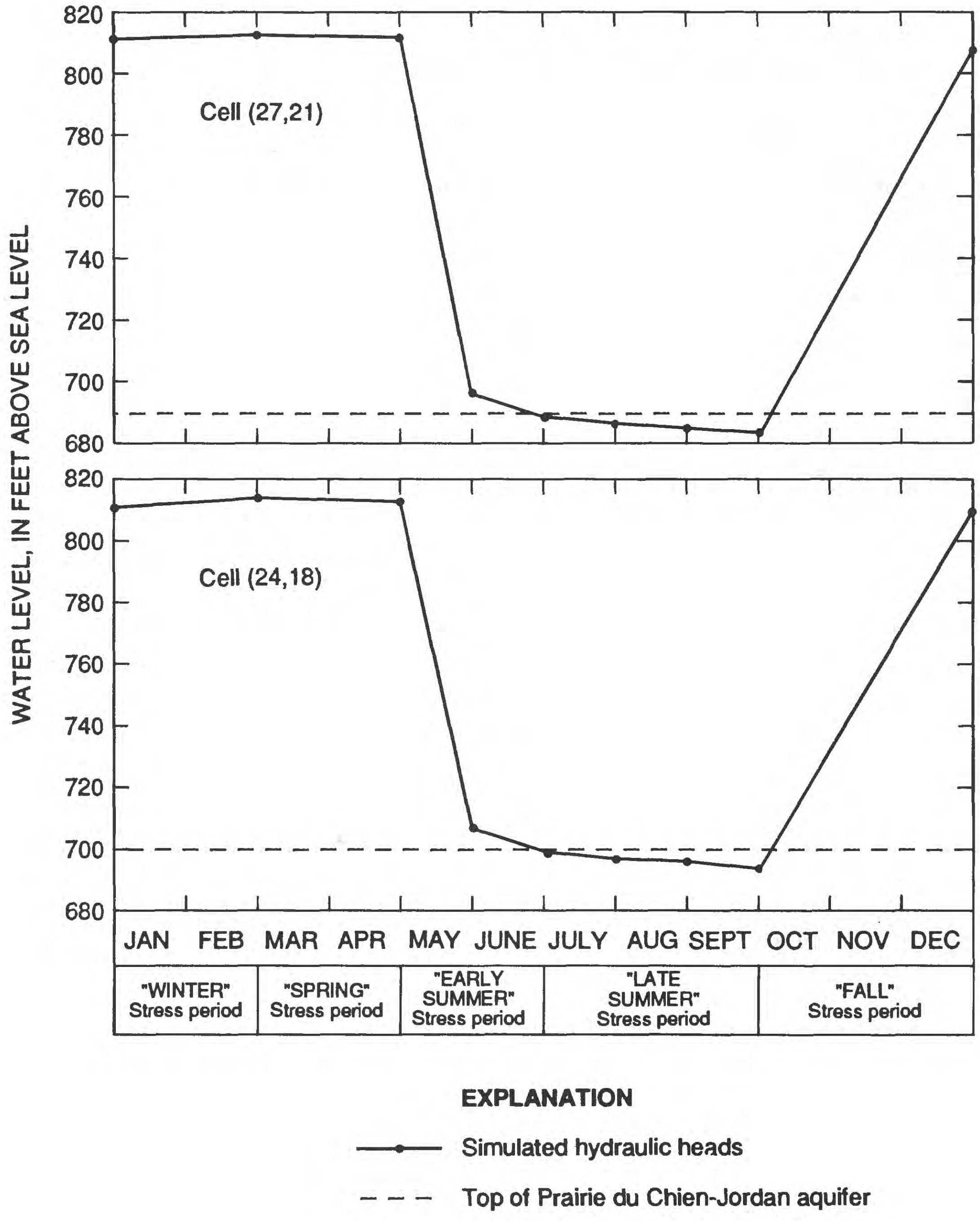


Figure 52.--Simulated hydraulic heads in the Prairie du Chien-Jordan aquifer model cells (SP1 through SP8) with additional ground-water withdrawals during the "early summer" and



for specified model cells for hypothetical 1-year transient simulation of eight totaling 85.1 cubic feet per second from the Prairie du Chien-Jordan aquifer "late summer" stress period.

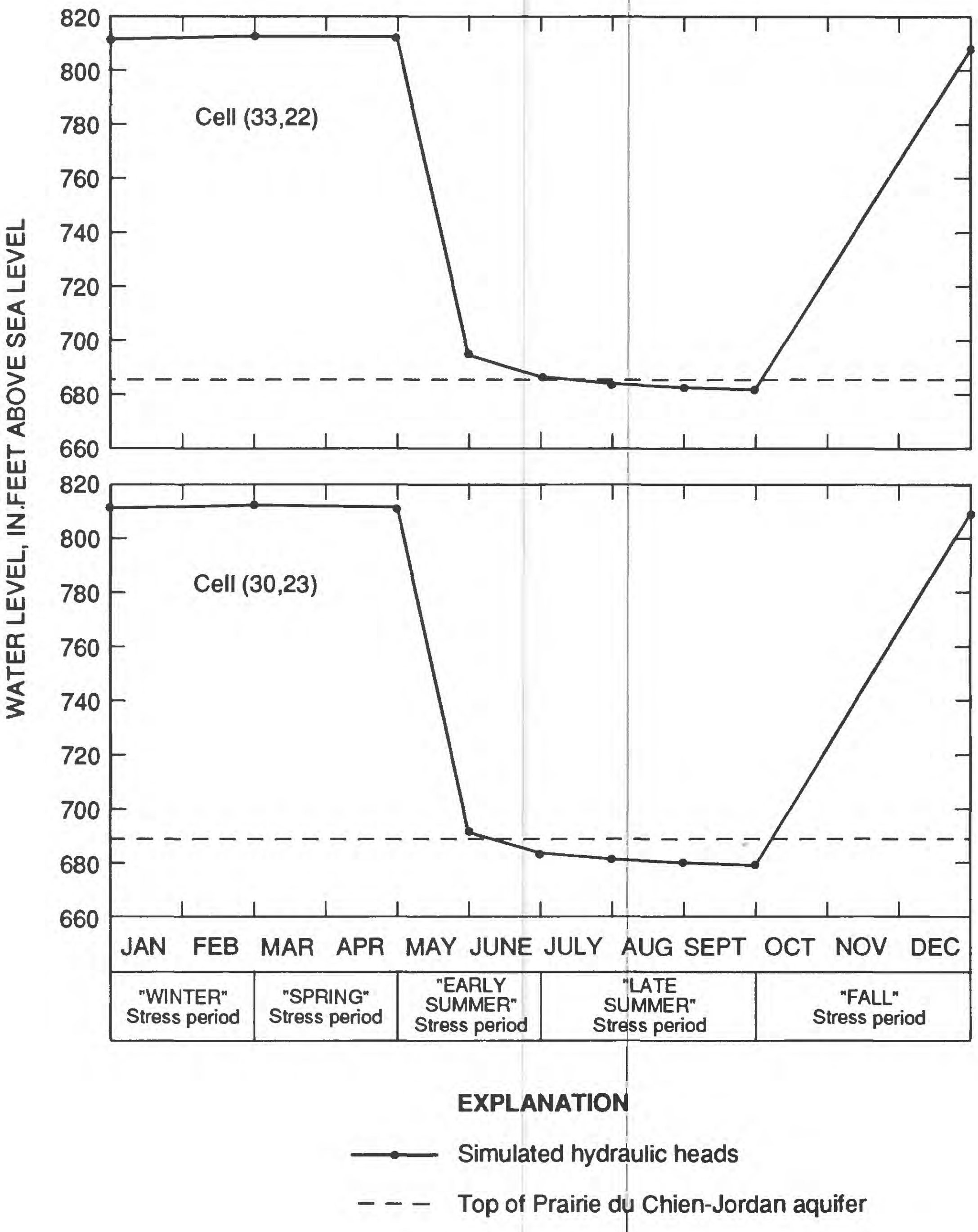
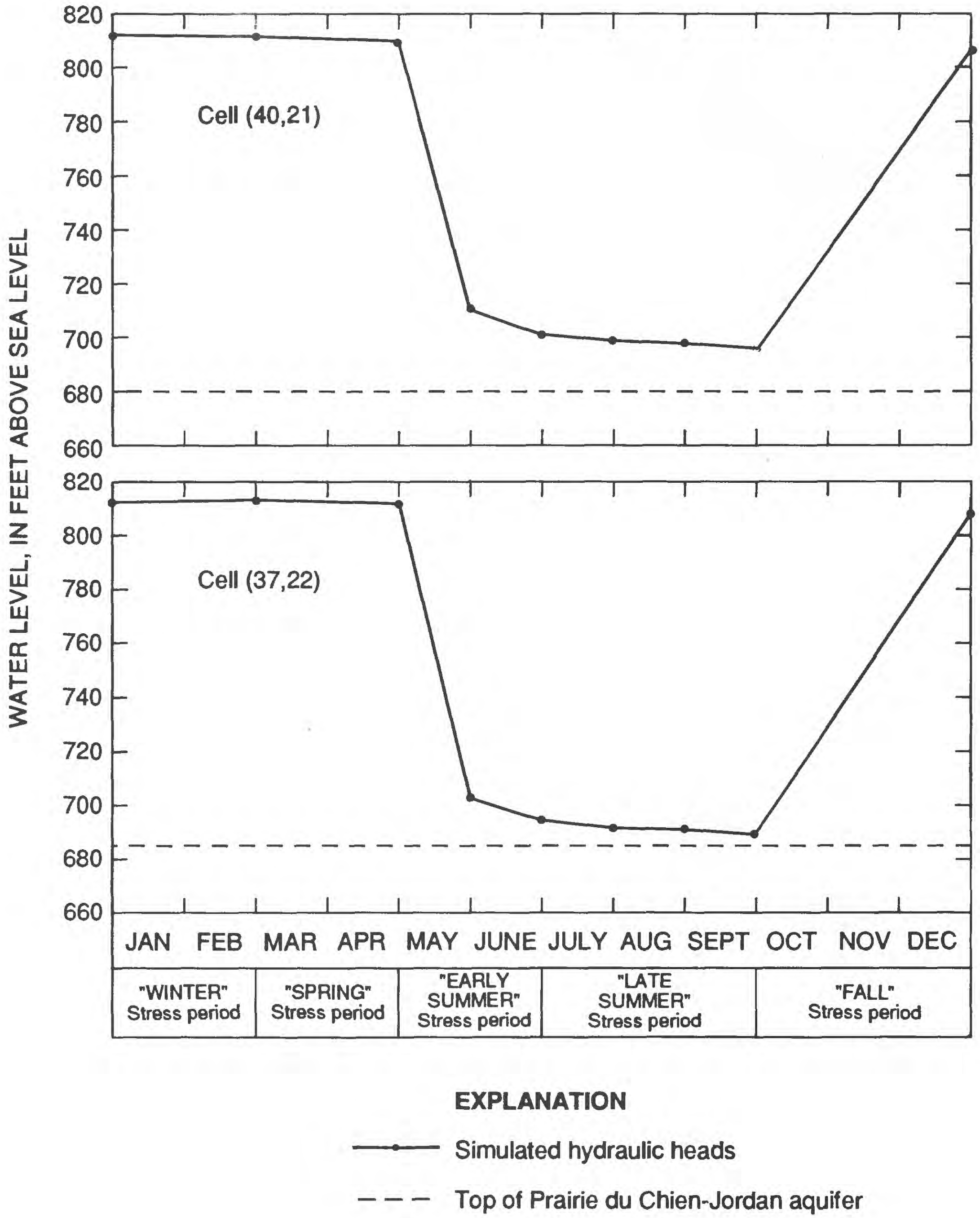


Figure 52.--Simulated hydraulic heads in the Prairie du Chien-Jordan aquifer model cells (SP1 through SP8) with additional ground-water withdrawals during the "early summer" and "late



for specified model cells for hypothetical 1-year transient simulation of eight totaling 85.1 cubic feet per second from the Prairie du Chien-Jordan aquifer summer" stress period--continued.

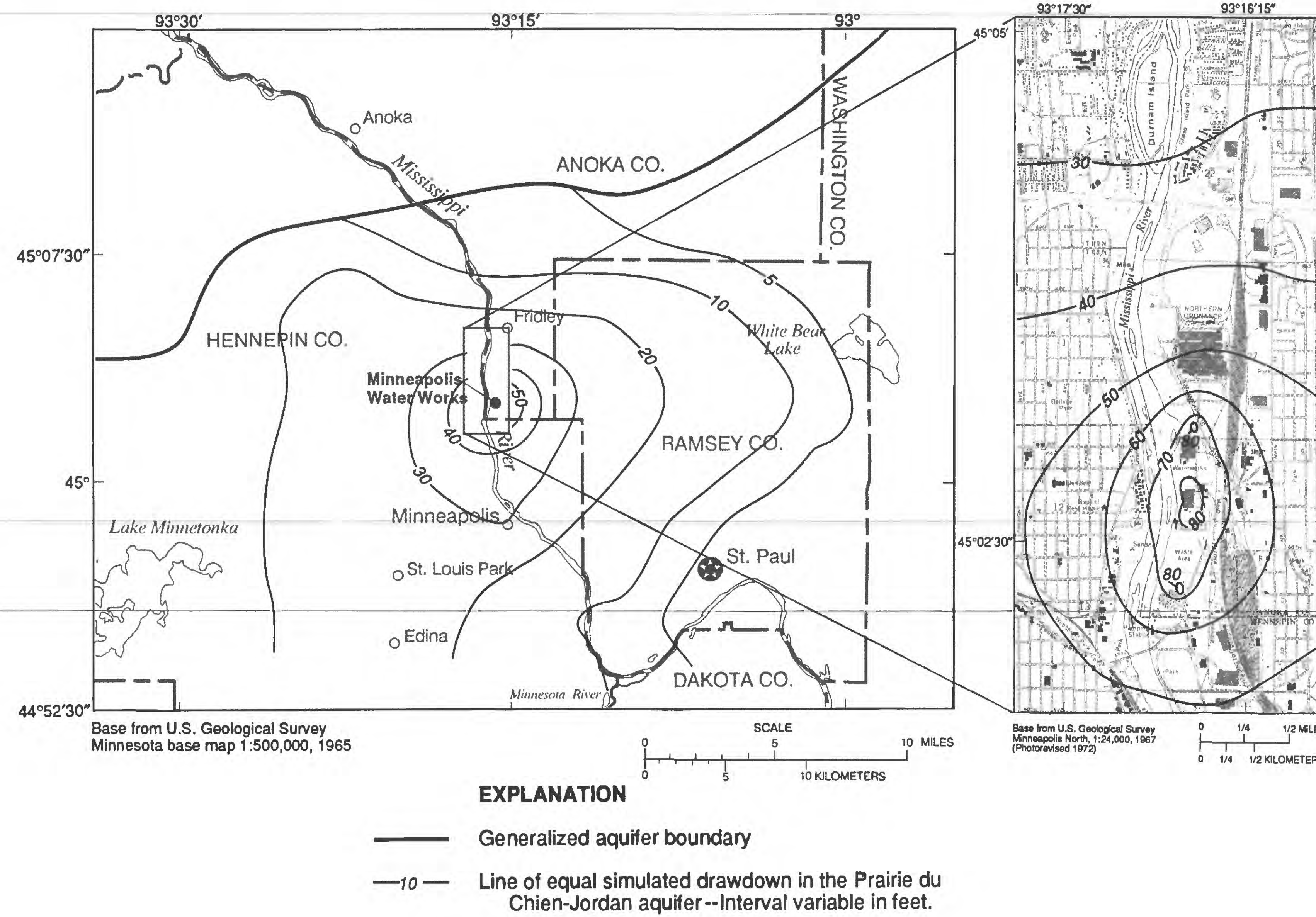
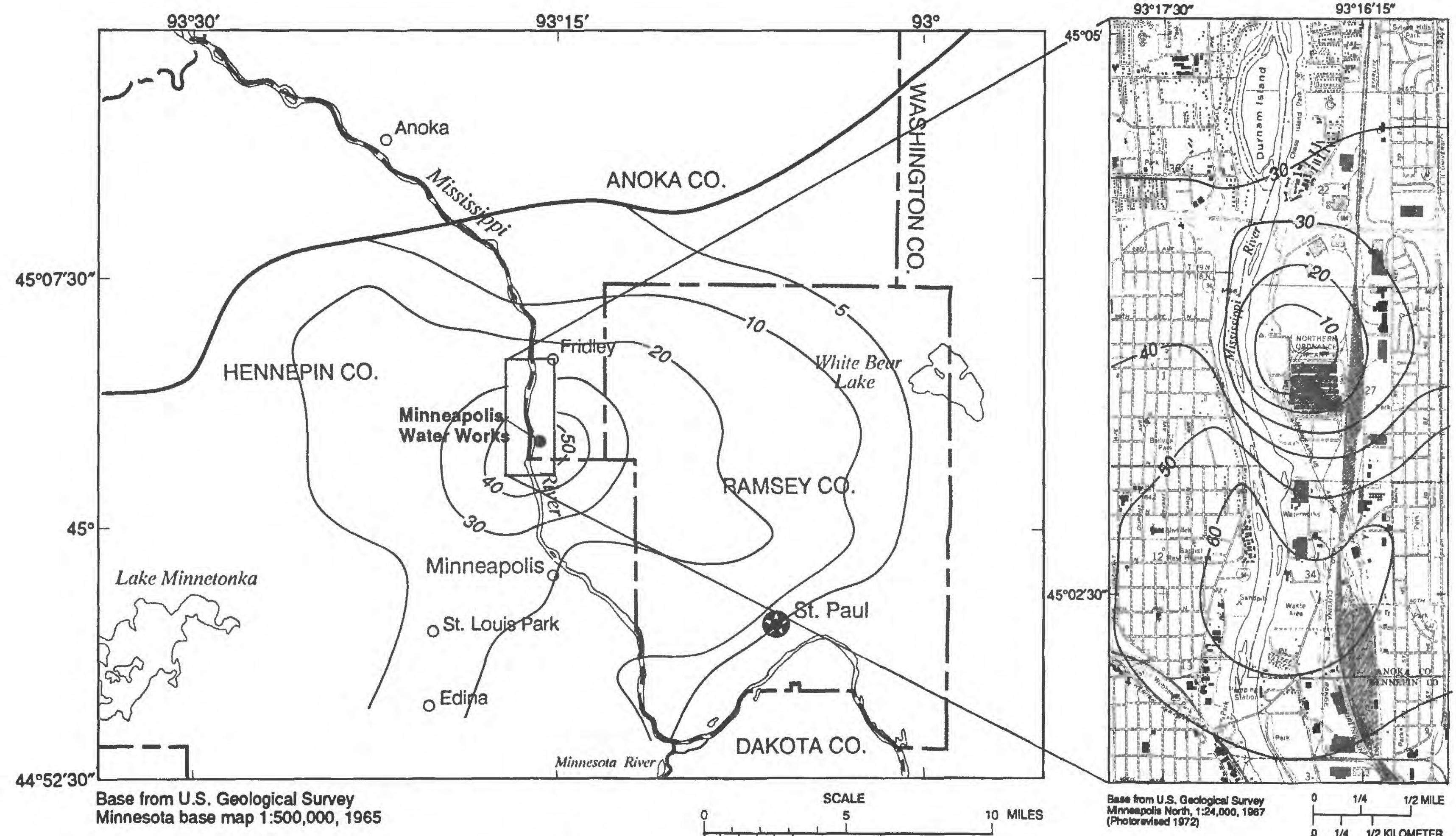


Figure 53.--Simulated drawdowns in the Prairie du Chien-Jordan aquifer at the end of the "late summer" stress period for hypothetical 5-year transient simulation of four model cells (HP1, HP2, HP3, and HP4) with additional ground-water withdrawals totaling 42.55 cubic feet per second from the Prairie du Chien-Jordan aquifer.



EXPLANATION

——— (heavy line)	Generalized aquifer boundary
—10—	Line of equal simulated drawdown in the confined-drift and St. Peter aquifers-- Interval variable in feet.

Figure 54.--Simulated drawdowns in the confined-drift and St. Peter aquifers at the end of the "late summer" stress period for hypothetical 5-year transient simulation of four model cells (HP1, HP2, HP3, and HP4) with additional ground-water withdrawals totaling 42.55 cubic feet per second from the Prairie du Chien-Jordan aquifer.

Simulations were done by varying the rate and distribution of hypothetical ground-water withdrawals near the Minneapolis Water Works. Simulations were done with additional ground-water withdrawals in two or four cells at total additional withdrawal rates (sum of individual rates for each cell) of 21.45, 21.6, or 42.55 ft^3/s. The locations of the cells from which the simulated additional withdrawals are made are shown in figure 44. The steady-state hypothetical simulations project the long-term or sustained drawdowns due to the hypothetical ground-water withdrawals, in contrast to the seasonal and relatively short-term (1- or 5-year) drawdowns simulated by the transient hypothetical simulations.

A simulation with additional ground-water withdrawals from four cells (cells HP1, HP2, HP3, and HP4, fig. 44), each at a rate of 10.64 ft^3/s, resulted in maximum simulated drawdowns in the Prairie du Chien-Jordan aquifer of greater than 200 ft. Actual drawdowns of similar magnitude in the Prairie du Chien-Jordan aquifer near the Minneapolis Water Works would result in a decline of hydraulic heads below the top of the aquifer (about 130 ft below land surface) and a change from confined to unconfined conditions. A change from confined to unconfined conditions would result in changes in the transmissivity of the aquifer and the response of the aquifer to pumping. The transmissivity of an unconfined aquifer decreases as the saturated thickness of the aquifer decreases; therefore, the actual drawdowns in response to the simulated ground-water withdrawals would be more than those predicted by the model. The calibrated steady-state model for 1970-79 is not suitable for accurate simulation of aquifer response to ground-water withdrawals that produce drawdowns of this magnitude. The steady-state model for 1970-79 was calibrated for hydrologic conditions under which the Prairie du Chien-Jordan aquifer remains confined.

The accuracy of hypothetical simulation results becomes more uncertain if the range of hydrologic conditions in the simulation exceeds the range used in calibration. In the case of the steady-state hypothetical simulations discussed in this report, an important factor affecting the uncertainty of the results is the magnitude of the drawdowns due to the hypothetical ground-water withdrawal rates. The steady-state model for 1970-79 was calibrated for hydrologic conditions resulting in drawdowns up to about 50 ft.

A second hypothetical steady-state simulation with additional ground-water withdrawals of 10.72 ft^3/s in each of two cells (HP1 and HP5, fig. 44) for a total additional withdrawal of 21.45 ft^3/s (13.9 Mgal/d) from the Prairie du Chien-Jordan aquifer resulted in a maximum simulated drawdown in the aquifer of about 80 ft. One cell (HP1) was east of the Mississippi River, and the other cell (HP5) west of the river. The simulated drawdowns are less than 20 ft outside the immediate vicinity of the Minneapolis Water Works and are less than 5 ft for much of the model area (fig. 55). Drawdowns to the south and west of the Minneapolis Water Works are greater than are drawdowns to the north and east. Simulated drawdowns for the confined-drift and St. Peter aquifers are similar to those for the Prairie du Chien-Jordan aquifer. Near the Minneapolis Water Works, drawdowns are less to the north of cells HP1 and HP5 than to the south because of the increased transmissivity of the confined-drift aquifer and increased downward leakage from the unconfined-drift aquifer to the north. Two cones of depression, one on each side of the river, correspond to the two cells from which additional ground-water withdrawals are made. Simulated drawdowns in the confined-drift and St. Peter aquifers near the Minneapolis Water Works are less than drawdowns in the Prairie du Chien-Jordan aquifer, but the pattern of relative drawdowns is the same. The simulated leakage of water from the Mississippi River to the aquifer system, or reduction in the discharge of water from the aquifer system to the river was 17.42 ft^3, or about 81.3 percent of the additional ground-water withdrawals. Ground-water inflow from areas beyond the model boundaries contributed about 18.7 percent of the additional water withdrawn, with about 59 percent entering through the Prairie du Chien-Jordan aquifer. About 95 percent of the water withdrawn was derived from the downward leakage of water to the Prairie du Chien-Jordan aquifer from the overlying aquifer. The remaining 5 percent was derived from boundary inflow to the Prairie du Chien-Jordan aquifer. The increase of ground-water withdrawals derived from changes in leakage of water between the Mississippi River and the aquifer system compared to the steady-state simulation for 1970-79 (81 percent compared to 63 percent) is caused by the proximity of the additional withdrawals to the river and relatively large distance from the specified-head boundaries.

A third hypothetical steady-state simulation with additional ground-water withdrawals of 5.4 ft^3/s in each of four cells (HP1, HP2, HP3, and HP4, fig. 44) for a total additional withdrawal of 21.6 ft^3/s from the Prairie du Chien-Jordan aquifer resulted in a maximum simulated drawdown in the aquifer of about 70 ft (fig. 56). The simulated drawdowns are similar to those for the simulation with two cells except that the distinct cone of depression on the west side of the river is absent (compare figs. 55 and 56). Simulated drawdowns for the confined-drift and St. Peter aquifers are similar to those for the Prairie du Chien-Jordan aquifer. The simulated leakage of water from the Mississippi River to the aquifer system, or reduction in the discharge of water from the aquifer system to the river, was about 80.6 percent of the additional ground-water withdrawals. This leakage was a small decrease compared to the simulation with two cells (81.3 percent). Ground-water inflow from areas beyond the model boundaries contributed about 19.4 percent of the additional water withdrawn.

A fourth hypothetical steady-state simulation was done by using a constant-flux boundary in place of a specified-head boundary to investigate the effects of a more conservative assumption about hydraulic heads in the aquifers. The simulation was done with additional ground-water withdrawals from the Prairie du Chien-Jordan aquifer of 5.4 ft^3/s in each of four cells (HP1, HP2, HP3, and HP4, fig. 44), as for the previous hypothetical steady-state simulation. The constant-flux boundaries were represented as no-flow boundaries in the superposition simulation; thus, no change occurred in ground-water flow to or from the aquifer system at the model boundaries. Hydraulic heads in the confined-drift and St. Peter aquifers and Prairie du Chien-Jordan aquifer near the Minneapolis Water Works were about 0.5 to 1.5 ft lower for the simulation with constant-flux boundaries than for the simulation with specified-head boundaries. The type of boundary condition used was found to have only a small affect on hydraulic heads near the Minneapolis Water Works. Either type of boundary condition is reasonable for the hypothetical steady-state simulations.

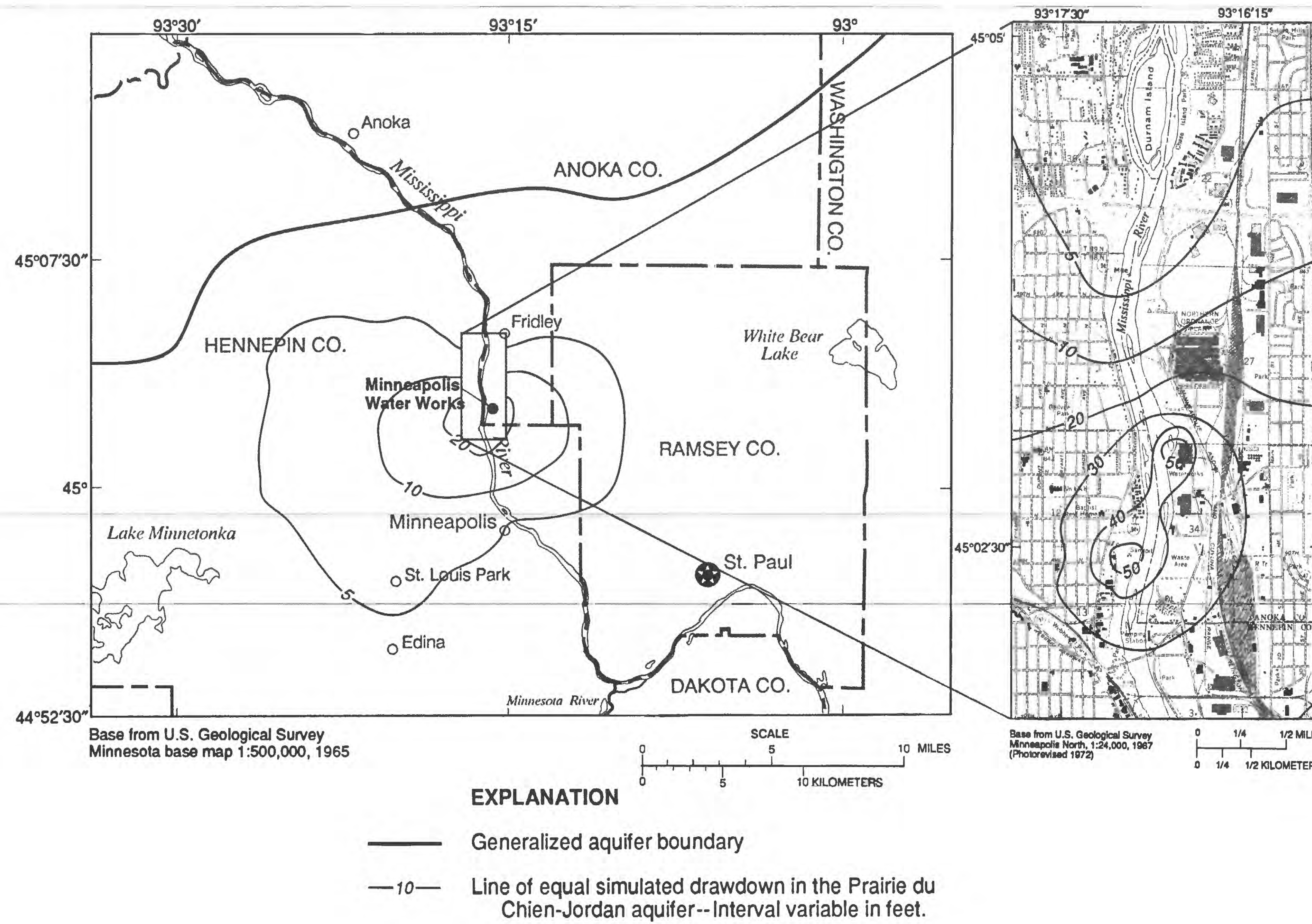
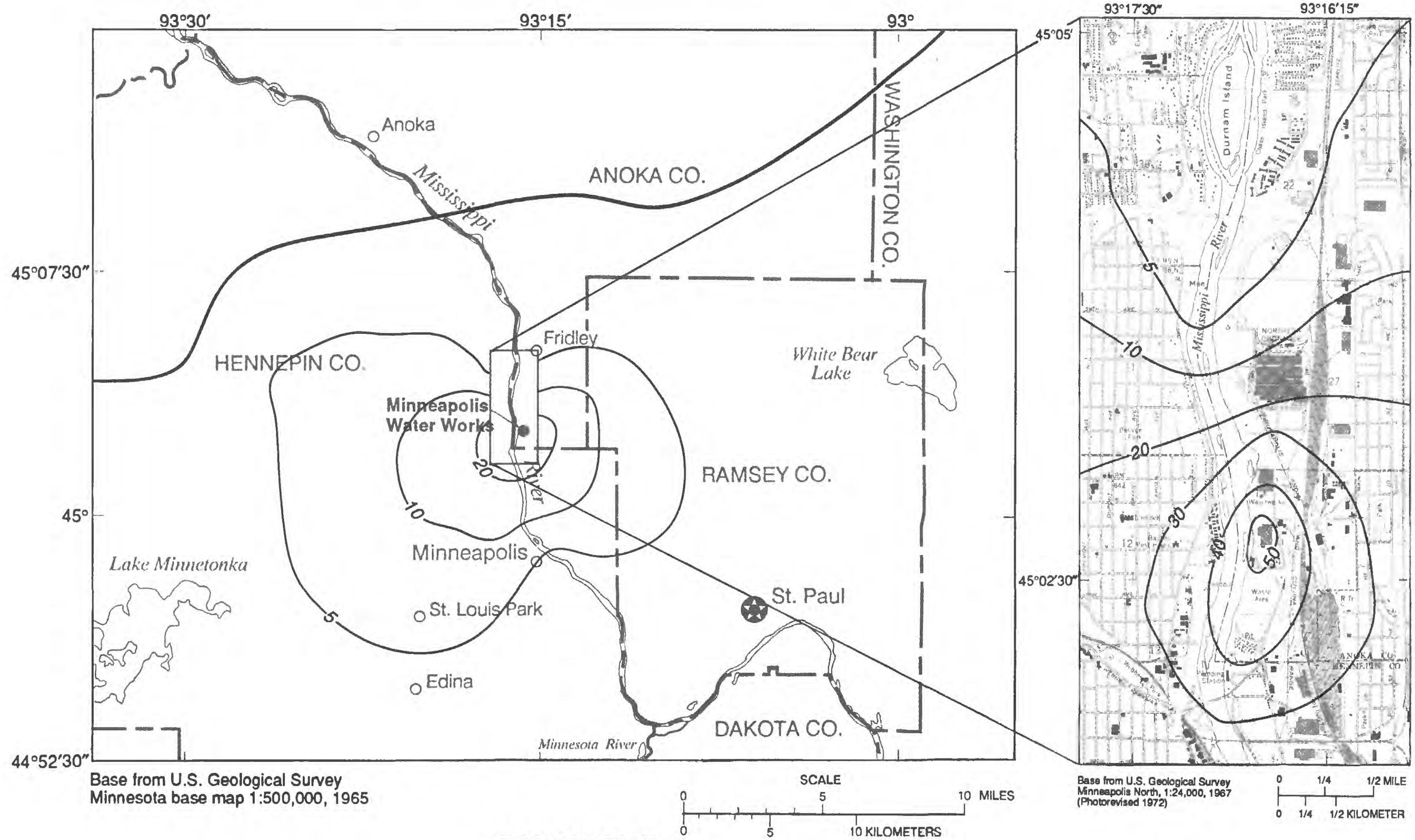


Figure 55.--Simulated drawdowns in the Prairie du Chien-Jordan aquifer for hypothetical steady-state simulation of two model cells (HP1 and HP5) with additional ground-water withdrawals totaling 21.45 cubic feet per second from the Prairie du Chien-Jordan aquifer.



EXPLANATION

—— Generalized aquifer boundary

—20— Line of equal simulated drawdown in the Prairie du Chien-Jordan aquifer--Interval variable in feet.

Figure 56.--Simulated drawdowns in the Prairie du Chien-Jordan aquifer for hypothetical steady-state simulation of four model cells (HP1, HP2, HP3, and HP4) with additional ground-water withdrawals totaling 21.6 cubic feet per second from the Prairie du Chien-Jordan aquifer.

A fifth hypothetical steady-state simulation with additional ground-water withdrawals of 5.4 ft^3/s in each of four cells (HP1, HP2, HP3, and HP4, (fig. 44) for total additional withdrawals of 21.6 ft^3/s from the confined-drift and St. Peter aquifers resulted in maximum simulated drawdowns of about 110 ft in the confined-drift and St. Peter aquifers and about 55 ft in the Prairie du Chien-Jordan aquifer. The simulated drawdowns outside the immediate vicinity of the Minneapolis Water Works are approximately the same for the confined-drift and St. Peter aquifers and the Prairie du Chien-Jordan aquifer. The simulated drawdowns outside the immediate vicinity of the Minneapolis Water Works are similar to those for the simulation of four cells with additional ground-water withdrawals from the Prairie du Chien-Jordan aquifer. The simulated drawdowns for the confined-drift and St. Peter aquifers near the Minneapolis Water Works are similar to those for the Prairie du Chien-Jordan aquifer in the simulation of four cells with additional ground-water withdrawals from the Prairie du Chien-Jordan aquifer (compare figs. 57 and 56). Although pumping from the confined-drift and St. Peter aquifers results in greater drawdowns in the pumped aquifer near the cells with additional ground-water withdrawals than does pumping at the same rate from the Prairie du Chien-Jordan aquifer; the drawdowns rapidly become about equal with increasing distance from the cells with the additional ground-water withdrawals. In this case, the 30-ft contour lines for the confined-drift and St. Peter aquifers and the Prairie du Chien-Jordan aquifer are about 0.5 to 0.75 mi from the cells with additional ground-water withdrawals regardless of which aquifer is being pumped. The simulated leakage of water from the Mississippi River to the aquifer system, or reduction in the discharge of water from the aquifer system to the river, was about 80.8 percent of the additional ground-water withdrawals, a small increase compared to the previous simulation with water being withdrawn from the Prairie du Chien-Jordan aquifer (80.6 percent). Ground-water inflow from areas beyond the model boundaries contributed about 19.2 percent of the additional water withdrawn. The additional water withdrawn from the confined-drift and St. Peter aquifers was derived from (1) downward leakage of water from the unconfined-drift aquifer, about 81.5 percent; (2) boundary inflow to the confined-drift and St. Peter aquifers, about 13.5 percent; and (3) upward leakage of water from the underlying Prairie du Chien-Jordan aquifer, about 5.0 percent.

Comparison of hypothetical simulations

Table 24 summarizes the results of the transient and steady-state hypothetical simulations. A denser spacing of cells with additional ground-water withdrawals than represented by the simulations given generally resulted in dewatering of the confined-drift aquifer and (or) the decline of hydraulic heads below the top of the Prairie du Chien-Jordan aquifer. The water supplying the additional ground-water withdrawals from the Prairie du Chien-Jordan aquifer in the transient simulations was derived mainly from ground-water inflow from areas beyond the model boundaries, water released from storage in the aquifers, the capture of ground water that would otherwise discharge to the river, and, to a much lesser amount, direct leakage of water from the Mississippi River to the unconfined-drift aquifer. The transient simulation with additional ground-water withdrawals from the confined-drift and St. Peter aquifers indicated a much greater contribution from direct leakage of water from the river to the unconfined-drift aquifer and a lesser contribution from ground-water inflow at the model boundaries. The probable reason for this is the good hydraulic connection between the unconfined-drift and confined-drift aquifers because of the absence and (or) high vertical hydraulic conductivity of the upper drift confining unit north of the Minneapolis Water Works where cells SP1-4 are located. The steady-state hypothetical simulations project the long-term or sustained drawdowns due to the hypothetical ground-water withdrawals and assume no change in storage in the aquifers. The water supplying the additional ground-water withdrawals in the steady-state simulations was derived mostly from direct leakage of water from the river to the unconfined-drift aquifer and or the capture of ground water that would otherwise discharge to the river (about 80 percent) and to a much lesser amount, increased ground-water inflow at the model boundaries (about 20 percent). New recharge-discharge relations were established, the sources of water indicated above supplied the portion of water supplied by the release of water from storage in the transient simulations, and the aquifer system approached a new equilibrium.

The results of the transient simulations are considered to reliably simulate the hypothetical conditions presented because the duration of the simulation period and variations in recharge and ground-water withdrawals are not greatly different than those for the model-calibration period (transient simulation for 1987). Changes in recharge to the aquifer system or changes in hydraulic heads and (or) hydraulic gradients at the model boundaries, would affect drawdowns near the Minneapolis Water Works resulting from additional ground-water withdrawals. The simulations indicated that almost 35 percent of the water supplying the additional ground-water withdrawals is derived from increased ground-water inflow at the model boundaries. The results of the steady-state simulations are considered to simulate the hypothetical conditions presented because the type of boundary condition used (specified-head or specified-flux) had only a small affect on hydraulic heads near the Minneapolis Water Works and the simulated drawdowns were not greatly different from those for the model-calibration period (steady-state simulation for 1970-79) in most (three out of four) of the hypothetical simulations. Changes in recharge to the aquifer system or changes in hydraulic gradients at the model boundaries, would affect drawdowns near the Minneapolis Water Works resulting from additional ground-water withdrawals.

IMPLICATIONS OF SIMULATED GROUND-WATER WITHDRAWALS ON CONTAMINANT MOVEMENT

The ground-water withdrawals in the hypothetical transient simulations result in substantially increased drawdowns in the confined-drift and St. Peter aquifers and Prairie du Chien-Jordan aquifer near the cells with additional withdrawals. These results indicate that contaminated water from areas of known contamination would move toward depressions in the potentiometric surfaces of the aquifers if additional ground water is withdrawn.

RMT, Inc. (1987) reports horizontal hydraulic gradients ranging from 0.0005 to 0.014 for the shallow and deep parts of the drift aquifer near the naval weapons systems manufacturing facility site for pumping conditions during 1983-86 and estimates that contaminants in the shallow drift aquifer would take about 0.5 years to travel from the western boundary of the site to the Mississippi River (about 0.25 mi). Horizontal hydraulic gradients in the Prairie du Chien aquifer were reported to be 0.0008, and the estimated time for contaminants in the Prairie du Chien aquifer to travel the same distance was about 15 years. The direction of ground-water flow from the site in both the drift and bedrock aquifers is to the west and southwest toward the Mississippi River.

The 1-year transient hypothetical simulation with additional ground-water withdrawals of 10.64 ft^3/s from the Prairie du Chien-Jordan aquifer in each of four cells (HP1, HP2, HP3, and HP4, fig. 44) during the "late summer" stress period was chosen as a representative scenario to investigate the effects of increased ground-water withdrawals on contaminant movement. The simulated potentiometric surfaces for the confined-drift and St. Peter aquifers and the Prairie du Chien-Jordan aquifer are shown in figures 58 and 59. The direction of ground-water flow in the confined-drift and St. Peter and Prairie du Chien-Jordan aquifers from the naval weapons systems manufacturing facility site (site of known contamination) under the simulated pumping conditions would be predominantly toward the cells with additional ground-water withdrawals at horizontal hydraulic gradients of as much as about 0.05. Some of the ground water that would normally discharge to the Mississippi River would be diverted toward the areas of additional ground-water withdrawals.

Near the Minneapolis Water Works and naval weapons systems manufacturing facility sites the unconfined-drift, confined-drift, and Prairie du Chien-Jordan aquifers are hydraulically connected by discontinuities in the confining units that elsewhere would impede ground-water flow and the movement of contaminants between the aquifers. The upper drift confining unit is discontinuous in the area underlying the Minneapolis Water Works and naval weapons systems manufacturing facility sites; thus, contaminants could potentially migrate downward from the unconfined-drift aquifer to the confined-drift aquifer. The analysis of the results of this simulation (additional ground-water withdrawals of 10.64 ft^3/s from the Prairie du Chien-Jordan aquifer in each of four cells, HP1-4) presented previously indicated that downward leakage of water through the upper drift confining unit increased by about 99 percent (nearly doubled) and through the lower confining unit increased by about 18 percent because of the additional ground-water withdrawals compared to that for the calibrated 1987 transient simulation. The additional ground-water withdrawals increase the downward hydraulic gradient in the aquifers underlying sites of known ground-water contamination. The basal St. Peter confining unit is absent in the bedrock valley underlying the Minneapolis Water Works and in the southern part of the naval weapons systems manufacturing facility site; thus, contaminants could potentially migrate downward from the confined-drift aquifer to the Prairie du Chien-Jordan aquifer. At some locations, the sand and gravel of the confined-drift aquifer directly overlies the Prairie du Chien-Jordan aquifer, although elsewhere the two aquifers are separated by less permeable beds of sandy silt or clay.

Table 24 --*Results of hypothetical transient and steady-state simulations*

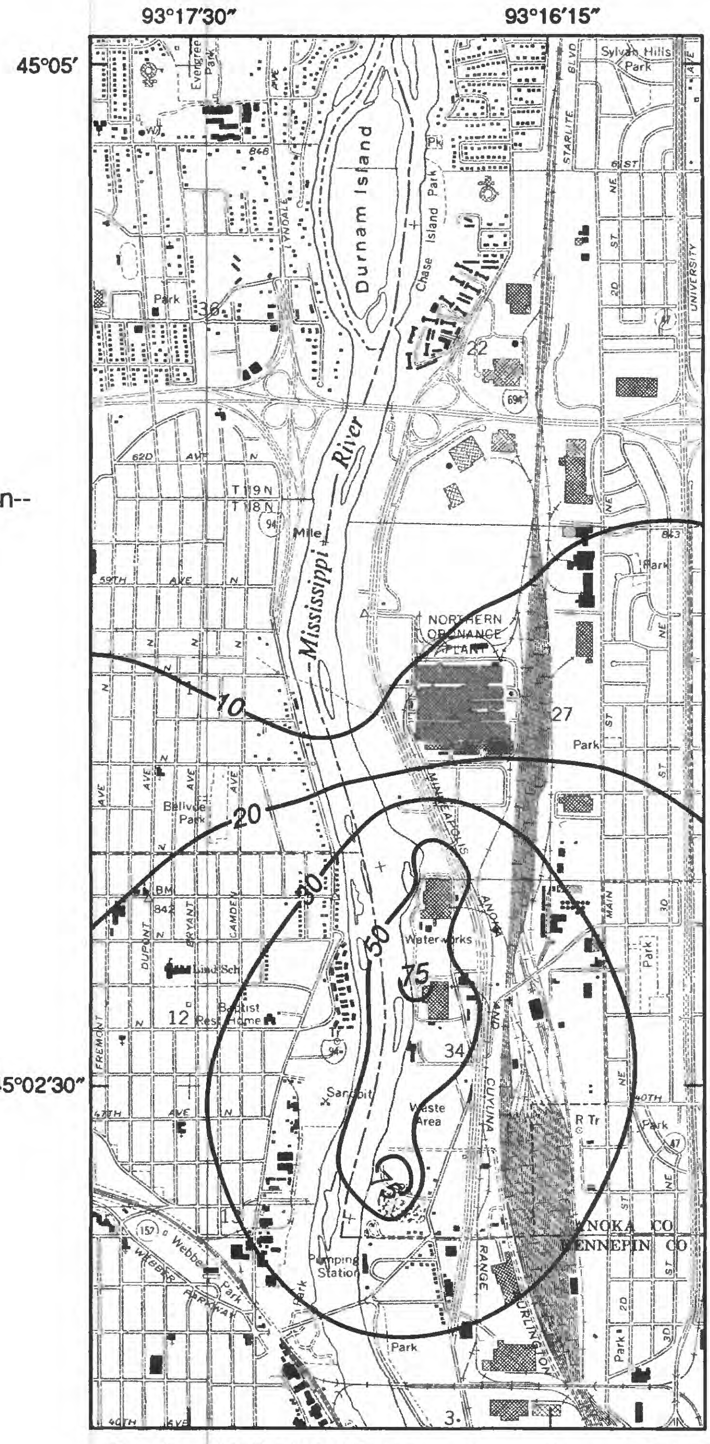
[HP1-HP6 and SP1-8 are model cells corresponding to the location of hypothetical ground-water withdrawals. Location of cells shown on fig. 44. LR is direct leakage of water from the Mississippi River to the unconfined-drift aquifer, CGW is the capture of ground water that would otherwise discharge to the river, RS is water released from storage in the aquifers, and BI is ground-water inflow from areas beyond the model boundaries.]

Total pumpage from all cells (ft^3/s)	Number of cells	Model layer pumped	Maximum drawdown, model layer 2 (feet)	Maximum drawdown, model layer 3 (feet)	Percentages contributed by sources of water supplying the additional ground-water withdrawals: LR	CGW	LR + CGW	RS	BI
Transient simulations									
42.55 HP1-4	4	3	60	80	9.5	24.5	34.0	29.0	34.5
42.55 HP2, HP3, HP5, HP6	4	3	85	90	9.2	24.7	33.9	29.0	34.8
21.6 SP1-4	4	2	118	15	35.7	21.3	57.0	23.6	17.6
85.1 SP1-8	8	3	105	130	15.0	19.5	34.5	29.5	34.0
Steady-state simulations									
42.55 HP1-4	4	3	--	>[1]200	--	--	--	--	--
21.45 HP1, HP5	2	3	60	80	--	--	81.3	--	18.7
21.6 HP1-4	4	3	55	70	--	--	80.6	--	19.4
21.6 HP1-4	4	2	110	55	--	--	80.8	--	19.2

[1] Simulated drawdown results in hydraulic head declining below the top of the Prairie du Chien-Jordan aquifer.

EXPLANATION

—*30*— Line of equal simulated drawdown--Interval variable, in feet.

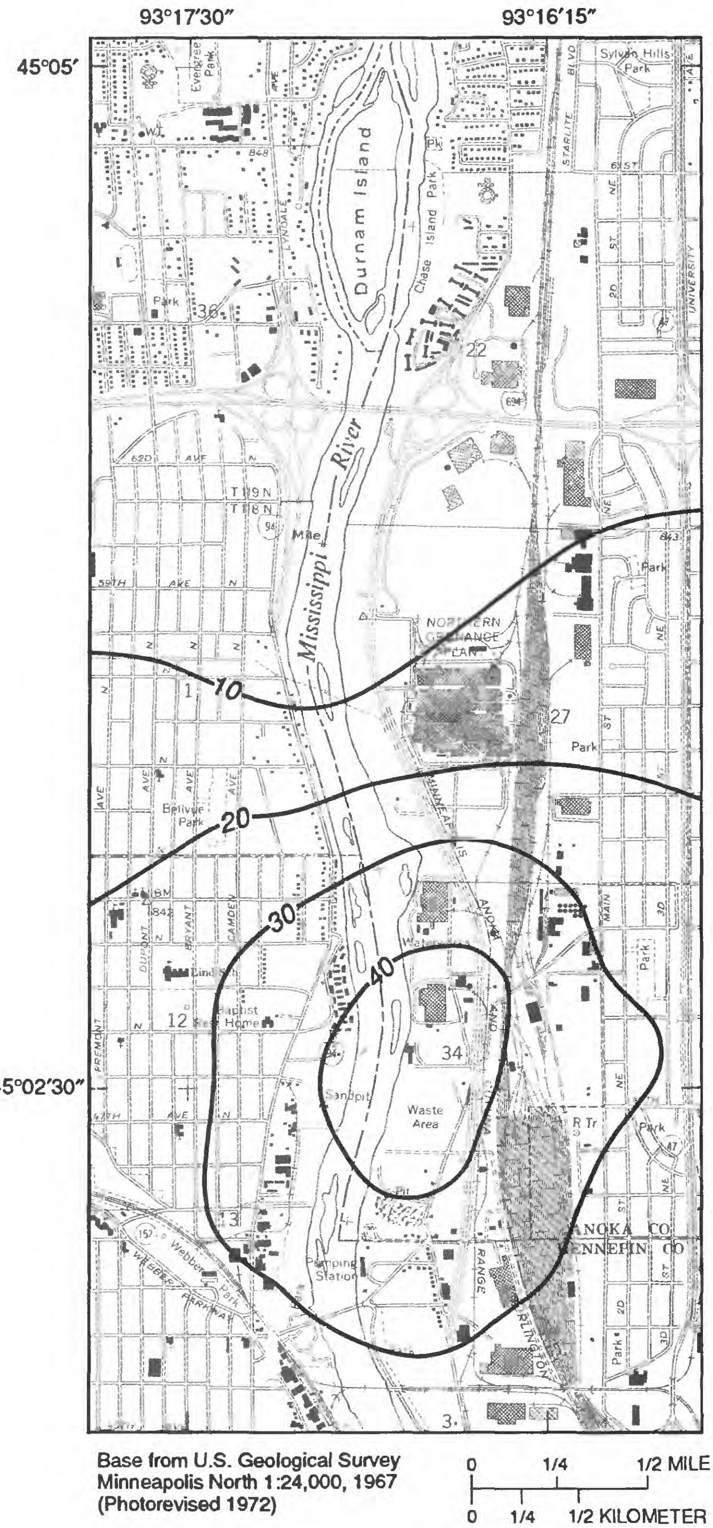


Base from U.S. Geological Survey
Minneapolis North 1:24,000, 1967
(Photorevised 1972)

0 1/4 1/2 MILE
0 1/4 1/2 KILOMETER

CONFINED-DRIFT AND ST. PETER AQUIFERS

Figure 57.--Simulated drawdowns in the confined-drift and St. Peter aquifers and hypothetical steady-state simulation of four model cells (HP1, HP2, HP3, per second from the confined-

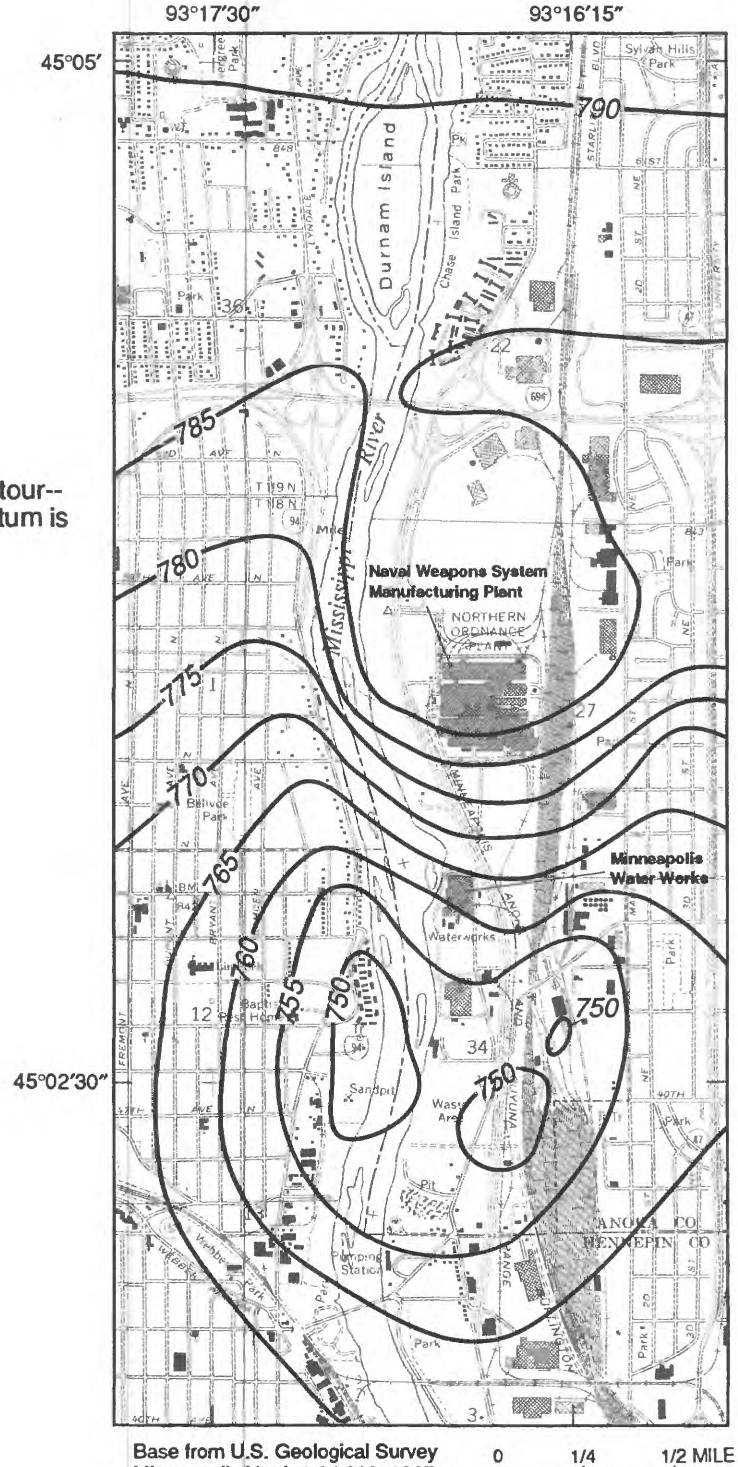


PRAIRIE DU CHIEN-JORDAN AQUIFER

In the Prairie du Chien-Jordan aquifer near the Minneapolis Water Works for and HP4) with additional ground-water withdrawals totaling 21.6 cubic feet drift and St. Peter aquifers.

EXPLANATION

—725— Simulated potentiometeric contour--Contour interval 5 feet. Datum is sea level.

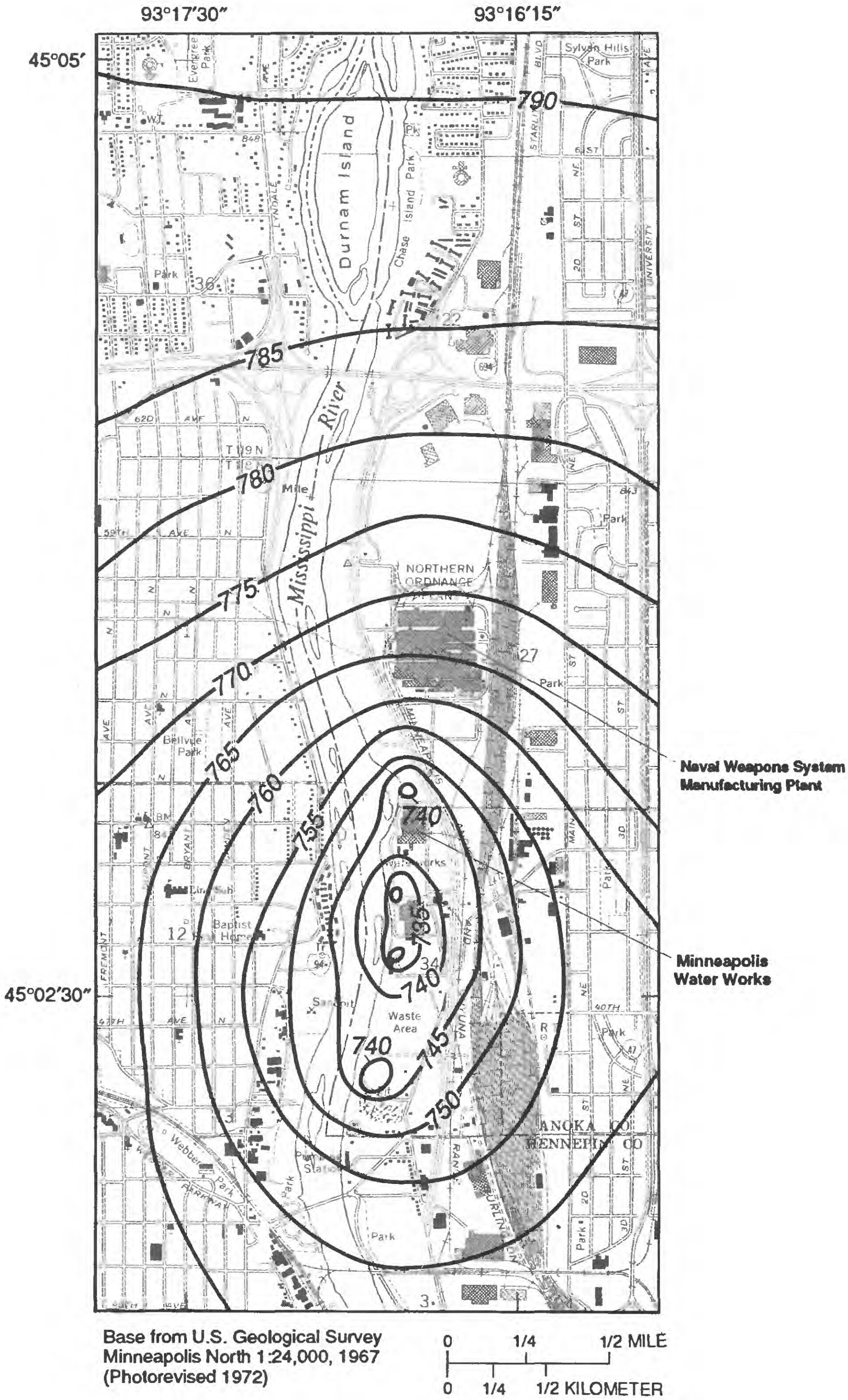


Base from U.S. Geological Survey Minneapolis North 1:24,000, 1967 (Photorevised 1972)

0 1/4 1/2 MILE
0 1/4 1/2 KILOMETER

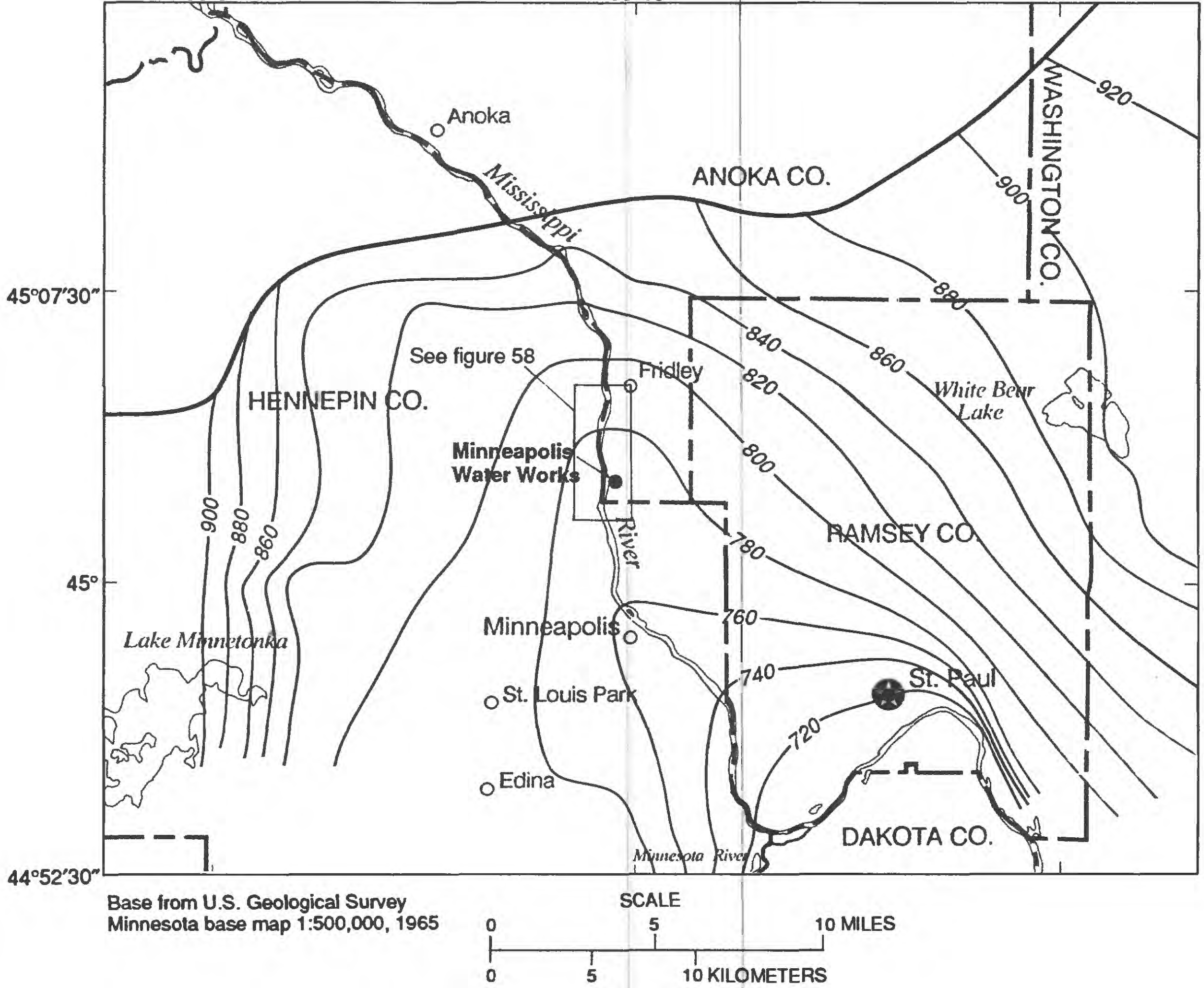
CONFINED-DRIFT AND ST. PETER AQUIFERS

Figure 58.--Simulated hydraulic heads in the confined-drift and St. Peter aquifers at the end of the "late summer" stress period for hypothetical 1-year transient ground-water withdrawals totaling 42.55 cubic



PRAIRIE DU CHIEN-JORDAN AQUIFER

and in the Prairie du Chien-Jordan aquifer near the Minneapolis Water Works simulation of four model cells (HP1, HP2, HP3, and HP4) with additional feet per second from the Prairie du Chien-Jordan aquifer.



EXPLANATION

—— Generalized aquifer boundary

—*800*— Simulated potentiometeric contour--Interval 20 feet. Datum is sea level.

Figure 59.--Simulated hydraulic heads in the Prairie du Chien-Jordan aquifer at the end of the "late summer" stress period for hypothetical 1-year transient simulation of four model cells (HP1, HP2, HP3, and HP4) with additional ground-water withdrawals totaling 42.55 cubic feet per second from the Prairie du Chien-Jordan aquifer.

SUMMARY AND CONCLUSIONS

A three-dimensional, numerical ground-water-flow model was developed to gain a better understanding of the ground-water-flow system and its response to withdrawals near the Minneapolis Water Works in Fridley, Minnesota. The model was developed to help (1) estimate the capacity of the aquifer system to yield water to wells, (2) determine the hydraulic connection between the Prairie du Chien-Jordan aquifer, overlying aquifers, and the Mississippi River, and (3) estimate the effects of ground-water withdrawals on water levels in wells and the extent to which these withdrawals induce flow from areas of known ground-water contamination.

Two bedrock aquifers (St. Peter and Prairie du Chien-Jordan), two glacial aquifers (unconfined- and confined-drift), and four confining units (upper drift, basal-drift, basal St. Peter, and Decorah-Platteville-Glenwood) are simulated in the ground-water-flow model. The distribution of sand and gravel deposits and the much less permeable clay and silt confining units within the drift is highly variable and complex and is generally not well known. A surficial layer of sand and gravel as much as 60-ft thick underlies the Mississippi River valley and the Anoka Sand Plain. A discontinuous layer of silty to sandy clay (upper drift confining unit) underlies the unconfined-drift aquifer and hydraulically separates it from the underlying confined-drift aquifer. The glacial drift is underlain by the St. Peter aquifer, or the Prairie du Chien-Jordan aquifer in bedrock valleys and in the northern part of the study area. In the southern part of the study area, the glacial drift is underlain by the Decorah-Platteville-Glenwood confining unit.

The basal St. Peter confining unit consists of siltstone and shale at the base of the St. Peter Sandstone and, where present, hydraulically separates the St. Peter aquifer from the underlying Prairie du Chien-Jordan aquifer. The surface of the St. Peter Sandstone was highly dissected by erosion, and the basal St. Peter confining unit is thin and discontinuous in the northern part of the St. Peter's extent.

The Prairie du Chien-Jordan aquifer is the major source of water for wells in the study area and accounts for about 80 percent of the total ground water pumped in the seven-county Twin Cities Metropolitan Area. Withdrawals from the Prairie du Chien-Jordan aquifer have resulted in long term (1885-1980) declines in hydraulic heads in the aquifer ranging from 0 to 48 ft. The Prairie du Chien-Jordan aquifer is underlain by the St. Lawrence-Franconia confining unit, which is considered to be a relatively impermeable layer regionally.

The bedrock surface in the study area is dissected by deep valleys filled with glacial drift and alluvial material. The Minneapolis Water Works is underlain by a buried bedrock valley that provides hydraulic continuity between the bedrock aquifers, the overlying glacial drift, and the Mississippi River. The bedrock valley and discontinuities in the upper drift confining unit also provide a pathway for the potential downward migration of contaminants from the surficial glacial deposits to the Prairie du Chien-Jordan aquifer.

The Mississippi River is the major stream draining the study area and is the regional discharge area for the aquifers. The gain in flow of the Mississippi River in the study area attributable to ground-water discharge, was estimated to be about 110 ft^3/s on the basis of average January (low-flow) conditions.

Initially, a two-layer ground-water-flow model was developed to test the sensitivity of selected hydrologic properties and boundary conditions of the Prairie du Chien-Jordan aquifer, basal St. Peter confining unit, and the confined-drift and St. Peter aquifers. The model was calibrated for steady-state conditions for a period before substantial ground-water development (1885-1930). Hydraulic head was found to be most sensitive to changes in the hydrologic properties controlling the discharge of water from the confined-drift and St. Peter aquifers to the Mississippi River. Simulated leakage to the confined-drift and St. Peter aquifers was 2.0 in/yr.

After calibration of the two-layer model, a three-layer model was constructed to represent, in descending order, the unconfined-drift aquifer, the upper drift and Decorah-Plateville-Glenwood confining units (upper confining unit), the confined-drift and St. Peter aquifers, the basal-drift and basal St. Peter confining unit (lower confining unit), and the Prairie du Chien-Jordan aquifer. The three-layer model was calibrated for two steady-state conditions: (1) conditions before substantial ground-water development (1885-1930), and (2) conditions during a period of significant pumping stress (1970-79). Transient calibration was accomplished by simulating (1) an aquifer test conducted at the Minneapolis Water Works site, and (2) a period during which seasonal changes in hydraulic head were significant and sufficient ground-water-level data was available (1987).

Sensitivity analyses for the steady-state simulation that represented conditions prior to substantial ground-water development indicated hydraulic heads were most sensitive to changes in the vertical hydraulic conductivity of the upper confining unit, which controls the amount of discharge from the confined-drift and St. Peter aquifers and the Prairie du Chien-Jordan aquifer to the unconfined-drift aquifer and subsequently to the Mississippi River. Simulated recharge to the unconfined-drift aquifer was 6.5 in/yr. Leakage to the confined-drift and St. Peter aquifers from overlying deposits varies, depending on the vertical hydraulic conductivity of the overlying deposits, the saturated thickness of the deposits, and the hydraulic head difference between the water table and the potentiometric surface of the confined-drift and St. Peter aquifers. Simulated leakage to the confined-drift and St. Peter aquifers outside the boundaries of the unconfined-drift aquifer varied spatially from 1.0 to 2.3 in/yr.

The principle of superposition was used in the steady-state simulation for a period of significant pumping stress (1970-79). When using superposition to solve ground-water-flow problems, the appropriate quantities are changes in hydraulic head and flow rather than absolute values of head and flow. Sensitivity analysis for the steady-state simulation for the period of significant pumping stress (1970-79) indicated that hydraulic heads were most sensitive to changes in the vertical hydraulic conductivity of the upper confining unit and decreases in the vertical hydraulic conductivity of the lower confining unit. The simulated recharge and leakage rates, representing the change in recharge caused by the simulated withdrawals by wells, were zero for the unconfined-drift aquifer and ranged from 0 to 3.0 in/yr for the confined-drift and St. Peter aquifers.

The principle of superposition was also used in the transient aquifer-test simulation. For the calibrated best-fit simulation, the vertical hydraulic conductivity of the Mississippi riverbed material was increased from 1.0 to 2.25 ft/d. Hydraulic heads were relatively insensitive to variations in specific yield for the unconfined-drift aquifer and storage coefficients for the confined-drift and St. Peter aquifers and Prairie du Chien-Jordan aquifer.

The transient simulation for 1987 reproduced fluctuations in hydraulic heads caused by seasonally variable ground-water withdrawals and recharge and leakage rates during 1987. The simulation was calibrated by adjusting seasonal recharge and leakage rates until the simulated hydraulic heads acceptably matched water levels measured in wells. Simulated recharge to the unconfined-drift aquifer varied seasonally, ranging from 0 to 2.3 in. Simulated leakage to the confined-drift and St. Peter aquifers also varied seasonally (0.4 to 2.1 in. per season) as well as spatially (2.6 to 5.7 in/yr).

The calibrated transient simulation for 1987 was used to simulate the effects of hypothetical ground-water withdrawals near the Minneapolis Water Works on hydraulic heads in the aquifers and ground-water discharge to the Mississippi River. Transient hypothetical simulations were made for periods of 1 year and 5 years. Additional ground-water withdrawals of 21.6 ft^3/s to 85.1 ft^3/s were simulated from four or eight model cells during the "early summer" and "late summer" stress periods. Hypothetical 1-year transient simulations with total simulated withdrawals from the Prairie du Chien-Jordan aquifer of 42.55 ft^3/s from four model cells resulted in maximum simulated increases in drawdowns in the Prairie du Chien-Jordan aquifer ranging from 60 to 85 ft at the end of the "late summer" stress period. Simulated hydraulic heads in the confined-drift and St. Peter aquifers and the Prairie du Chien-Jordan aquifer rebounded and quickly approached equilibrium conditions following the cessation of the hypothetical ground-water withdrawals. Simulated hydraulic heads at the end of the "fall" stress period in the cell(s) with additional ground-water withdrawals were only about 2.5 ft lower than the simulated hydraulic heads at the end of the "fall" stress period for the calibrated transient simulation for 1987. A hypothetical 1-year transient simulation with total simulated withdrawals of 85.1 ft^3/s (from eight model cells) from the Prairie du Chien-Jordan aquifer resulted in maximum simulated increases in drawdowns of about 130 ft in the Prairie du Chien-Jordan aquifer and about 105 ft in the confined-drift and St. Peter aquifers.

A hypothetical transient simulation was made for a period of 5 years by recycling the 1987 seasonal withdrawal and recharge and leakage rates for each of the 5 years. Total simulated additional hypothetical withdrawals from the Prairie du Chien-Jordan aquifer during the "late summer" stress period were 42.55 ft^3/s. The 5-year hypothetical transient simulation resulted in little decline in hydraulic heads in the confined-drift and St. Peter aquifers and Prairie du Chien-Jordan aquifer from year to year at the end of corresponding stress periods. Hydraulic heads at the end of the "late summer" and "fall" stress periods during the fifth year were approximately the same as the corresponding heads during the first year of the simulation.

The calibrated steady-state model for 1970-79, which was based on the principle of superposition, was used to simulate the effects of hypothetical ground-water withdrawals near the Minneapolis Water Works under steady-state conditions. Simulations were made by varying the rate and distribution of hypothetical ground-water withdrawals. Total simulated withdrawals of 42.55 ft^3/s from four model cells pumping from the Prairie du Chien-Jordan aquifer resulted in simulated drawdowns exceeding 200 ft in the Prairie du Chien-Jordan aquifer in the pumped cell(s). Actual drawdowns of comparable magnitude near the Minneapolis Water Works would result in hydraulic heads declining below the top of the aquifer and a change from confined to unconfined conditions. Simulations with total withdrawals of 21.45 ft^3/s and 21.6 ft^3/s from the Prairie du Chien-Jordan aquifer resulted in drawdowns in the Prairie du Chien-Jordan aquifer in the pumped cell(s) ranging from about 70 to about 80 ft. A simulation with withdrawals of 21.6 ft^3/s from the confined-drift and St. Peter aquifers resulted in drawdowns of about 110 ft in the confined-drift and St. Peter aquifers in the pumped cells and about 55 ft in the Prairie du Chien-Jordan aquifer.

Contaminated water from areas of known contamination would move toward depressions in the potentiometric surfaces of the confined-drift and St. Peter aquifers and Prairie du Chien-Jordan aquifer if additional ground water were withdrawn. Additional ground-water withdrawals comparable to those simulated for this study would result in significantly increased drawdowns and the diversion of water from sites of known contamination near the Minneapolis Water Works toward the pumping centers.

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