SIMULATION OF GROUND-WATER FLOW IN THE ST. PETER AQUIFER IN AN AREA CONTAMINATED BY COAL-TAR DERIVATIVES, ST. LOUIS PARK, MINNESOTA

By D. L. Lorenz and J. R. Stark

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CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS

Page

TABLES

CONVERSION FACTORS

Multiply	By	To obtain
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
acre	0.4047	hectare
square mile (mi^2)	2.590	square kilometer
inch per year (in/yr)	25.4	millimeter per year
foot per second (ft/s)	0.3048	meter per second
foot per day (ft/day)	0.3048	meter per day
gallon per minute (gal/min)	0.06308	liter per second
million gallons per day (Mgal/d)	0.04381	cubic meter per second
square foot per day (ft^2/d)	0.09294	square meter per day

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

SIMULATION OF GROUND-WATER FLOW IN THE ST. PETER AQUIFER IN AN AREA CONTAMINATED BY COAL-TAR DERIVATIVES, ST. LOUIS PARK, MINNESOTA

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ABSTRACT

A model constructed to simulate ground-water flow in part of the Prairie du Chien-Jordan and St. Peter aquifers, St. Louis Park, Minnesota, was used to test hypotheses about the movement of ground water contaminated with coal-tar derivatives and to simulate alternatives for reducing the downgradient movement of contamination in the St. Peter aquifer. The model, constructed for a previous study, was applied to simulate the effects of current ground-water withdrawals on the potentiometric surface of the St. Peter aquifer. Multiaquifer wells served as conduits for vertical exchange of water from the St. Peter aquifer to the Prairie du Chien-Jordan aquifer. Model simulations predict that the multiaquifer wells have the potential to limit downgradient migration of contaminants in the St. Peter aquifer caused by cones of depression created around the multiaquifer wells. Differences in vertical leakage to the St. Peter aquifer may exist in areas of bedrock valleys. Model simulations indicate that these differences are not likely to affect significantly the general patterns of ground-water flow.

Model simulations also indicated that drawdown caused by pumping two wells, each pumping at 75 gallons per minute and located about 1 mile southeast of the source of contamination, would be effective in controlling movement and volume of contaminated ground water in the immediate area of the source of contamination. Some contamination may already have moved beyond the influence of these wells, however, because of a complex set of hydraulic conditions.

INTRODUCTION

Ground water in the St. Peter aquifer, St. Louis Park, Minnesota, was contaminated by activities at a coal-tar distillation and wood-preserving plant that operated from 1918 to 1972 (Hult and Schoenberg, 1984). Coal-tar derivatives--a mixture of many compounds--are the major contaminants. Polynuclear aromatic hydrocarbons (PAH) are a class of compounds found in coal-tar derivatives. These compounds are of particular concern to human health because some are carcinogenic (U.S. Environmental Protection Agency, 1980).

This project and report are a result of a cooperative agreement between the U.S. Environmental Protection Agency and the U.S. Geological Survey. This report is one of several reports by the U.S. Geological Survey that document ground-water contamination at St. Louis Park, Minnesota. Hult and Schoenberg (1984) present an overview of the problem. Hult (1984) and Stark and Hult (1985) discuss contamination of the Prairie du Chien-Jordan aquifer and document the construction and calibration of a three-dimensional ground-water-flow model used to evaluate pumping strategies to control ground-water movement in the Prairie du Chien-Jordan aquifer. This report evaluates various pumping strategies to control ground-water movement in the St. Peter aquifer. The study, documented in this report, utilizes a ground-water-flow model developed by Stark and Hult (1985). Changes to the previous model include updates of water-use values to 1985 and minor changes to model calibration.

Purpose and Scope

The primary purpose of this report is to describe the simulated effect of several proposed gradient-control wells on the flow of water in the St. Peter aquifer. A secondary purpose of this report is to document the application of an existing model used to improve understanding of ground-water flow in the St. Peter aquifer. The model was developed to simulate ground-water flow in the Prairie du Chien-Jordan aquifer, which underlies the St. Peter aquifer. The original model simulated movement of water in the Prairie du Chien-Jordan aquifer and included simulation of the flow in the St. Peter aquifer and basal St. Peter confining unit. The model incorporated municipal, commercial, and industrial withdrawals (from about 100 municipal, irrigation, or industrial supply wells) in the modeled area and simulated changing patterns of ground-water withdrawals and their influence on the movement of contaminants.

Location and Description of the Area and History of Contamination

The former coal-tar distillation and wood-preserving plant is in St. Louis Park, Minnesota, a western suburb of Minneapolis (fig. 1). In this report the term "plant site" refers to the approximately 80-acre tract of land on which the plant was located (fig. 1). The term "study area" refers to the modeled area bounded by Lake Minnetonka to the west, the Minnesota and Mississippi Rivers to the south and east, and a latitude of 45° 05′ N to the north.

Contaminants from the former coal-tar distillation and wood-preserving plant have affected the ground-water quality in several aquifers in the St. Louis Park area. Hult and Schoenberg (1984) reported that the contaminants percolated to the water table from ponds and wetlands that received storm runoff and process water from the plant. Bedrock aquifers underlying glacial drift were contaminated by downward leakage and by downward flow in wells open to more than one aquifer. The movement and concentrations of coal-tar derivatives in water in the St. Peter aquifer are not well documented, however, because few wells tap this aquifer.

A discharge rate of 150 gal/min (gallons per minute) from the St. Peter aquifer to the underlying Prairie du Chien-Jordan aquifer was measured in a well located near the plant site and open to both aquifers (Hult and Schoenberg, 1984) (fig. 2). Because water in this well had become contaminated by the 1950's, it was reconstructed in 1979 to prevent leakage of water from the St. Peter aquifer to the Prairie du Chien Jordan aquifer (Hult and Schoenberg, 1984). Ground-water flow toward this well may have affected the movement of contaminants in the St. Peter aquifer. Flow to this well and other nearby multiaquifer wells created cones of depression around the wells in the

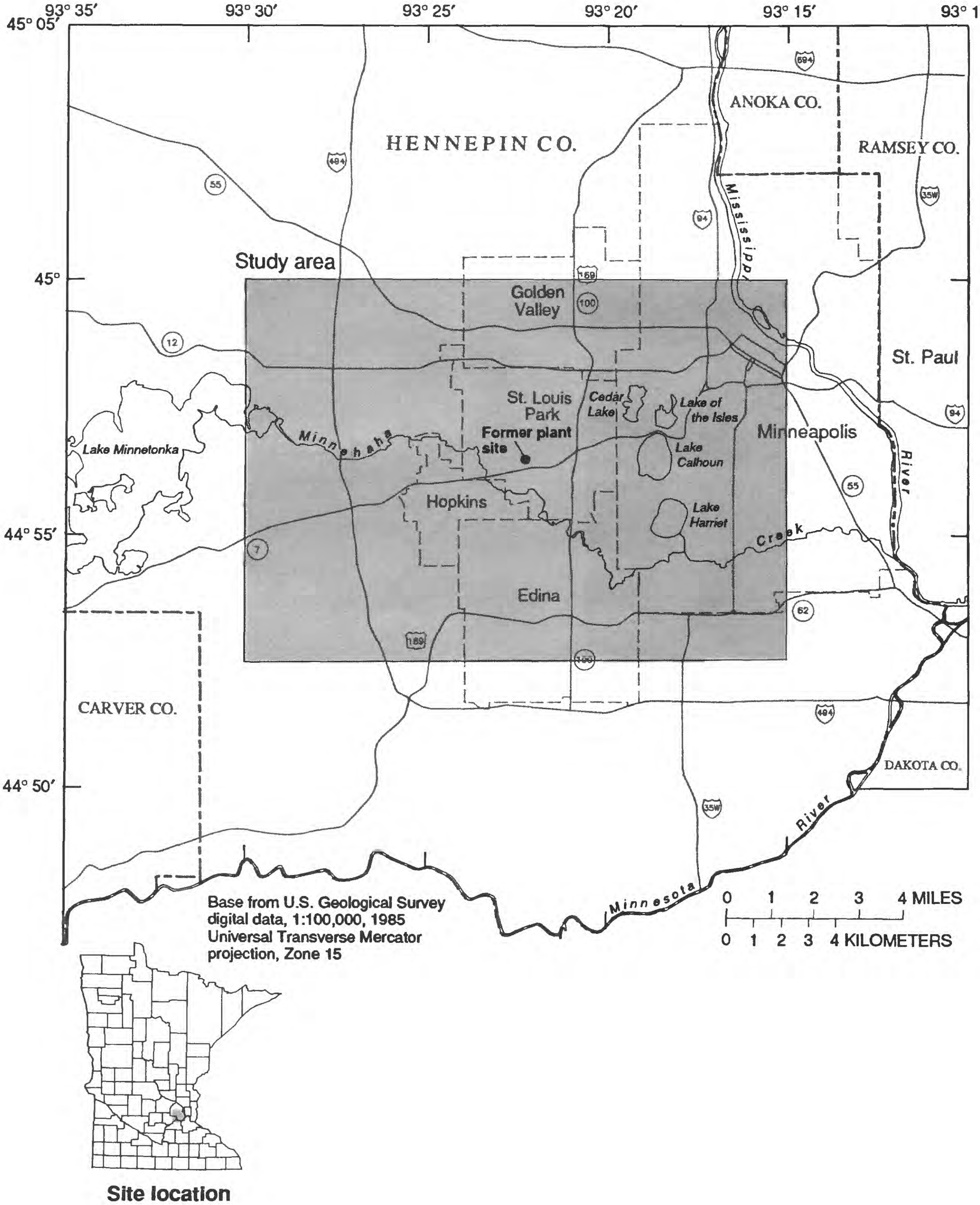


Figure 1.--Location of study area, St. Louis Park, and plant site in the Minneapolis-St. Paul Metropolitan Area.

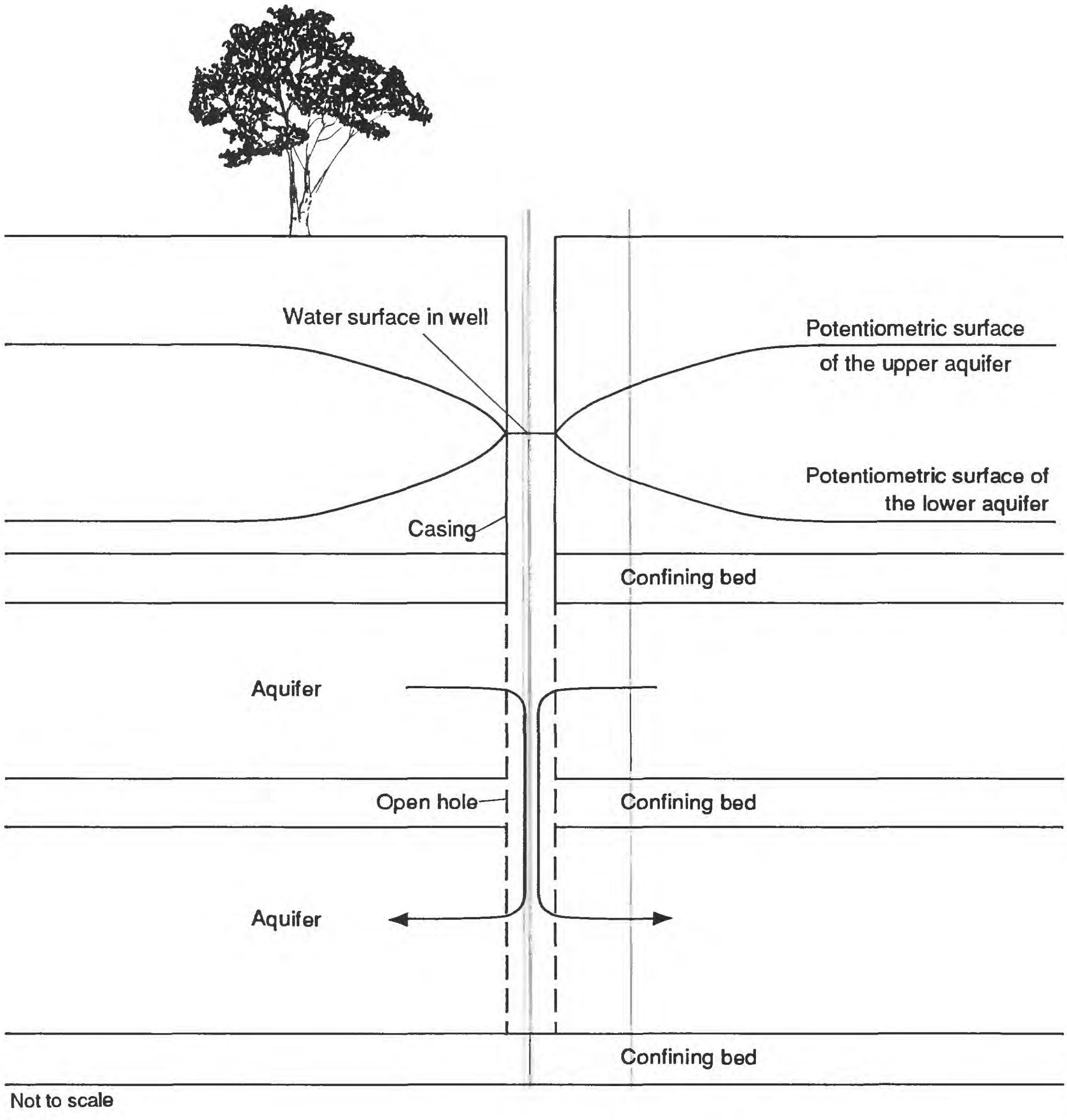


Figure 2.--Schematic hydrologic section showing a well connecting two confined aquifers, flow through the well bore, and the effects of this flow on the potentiometric surfaces of the two aquifers. (From Hult and Schoenberg, 1984, p. 37)

St. Peter aquifer and may have limited the lateral downgradient migration of contaminants. Inflow from the St. Peter aquifer at multiaquifer wells and pumping from production wells tapping the Prairie du Chien-Jordan aquifer could have increased lateral migration of contaminants in the Prairie du Chien-Jordan aquifer from the area of the plant site. Because of intensive effort by State and local officials, all known multiaquifer wells have been sealed, thereby reducing the hydraulic stresses that influence the movement of contaminants in the study area.

HYDROGEOLOGY AND GROUND-WATER FLOW IN THE ST. PETER AQUIFER

The St. Peter aquifer and the underlying basal St. Peter confining unit comprise the St. Peter Sandstone of Ordovician age. The aquifer is overlain by the Decorah-Platteville-Glenwood confining unit. This regional confining unit is dissected by erosion over much of the study area and consists of the Ordovician Decorah Shale, Platteville Limestone, and Glenwood Shale. Although these units generally are considered a regional confining unit, the Platteville Limestone yields water to wells in the study area and is considered an aquifer. The Decorah Shale has been reduced to rubble in the study area, and has not been identified as a continuous geologic unit. The remaining units are referred to as the Glenwood confining unit and the Platteville aquifer in this report. The glacial drift overlies those units and consists of a complex sequence of from 70 to 100 ft (feet) of sand aquifers and glacial-till confining units.

The St. Peter aquifer overlies the basal St. Peter confining unit, which consists of about 5 ft of siltstone and shale. This confining unit overlies the Prairie du Chien-Jordan aquifer, which consists of dolomite and sandstone of the Ordovician Prairie du Chien Group and the Cambrian Jordan Sandstone, respectively. The Prairie du Chien-Jordan aquifer overlies the St. Lawrence-Franconia confining unit in the Cambrian St. Lawrence and Franconia Formations, which separate the overlying hydrogeologic units from deeper aquifers. Figure 3 shows the hydrogeologic units in the study area.

Erosion has removed the Glenwood confining unit and the Platteville aquifer and, locally, the St. Peter aquifer and St. Peter confining unit from several areas. The St. Peter aquifer or the Prairie du Chien-Jordan aquifer subcrops directly below glacial drift in these areas.

The St. Peter aquifer is composed of well sorted, fine- to medium-grained quartzose sandstone. It is absent in many areas because of erosion (fig. 4). The bedrock valleys formed by erosion and subsequently filled with permeable glacial drift have the potential for increasing vertical movement of ground water between the glacial drift and the St. Peter aquifer, and also for facilitating vertical movement of contaminants between bedrock aquifers.

In Hennepin County, water in the St. Peter aquifer generally flows from west to east under the influence of a regional hydraulic gradient of about 10 ft/mi (feet per mile). This gradient increases, however, near the Mississippi and Minnesota Rivers. The aquifer is recharged by leakage from overlying units. Discharge from the aquifer, in Hennepin County, is to unconsolidated sediments in the valleys of the Minnesota and Mississippi Rivers, to

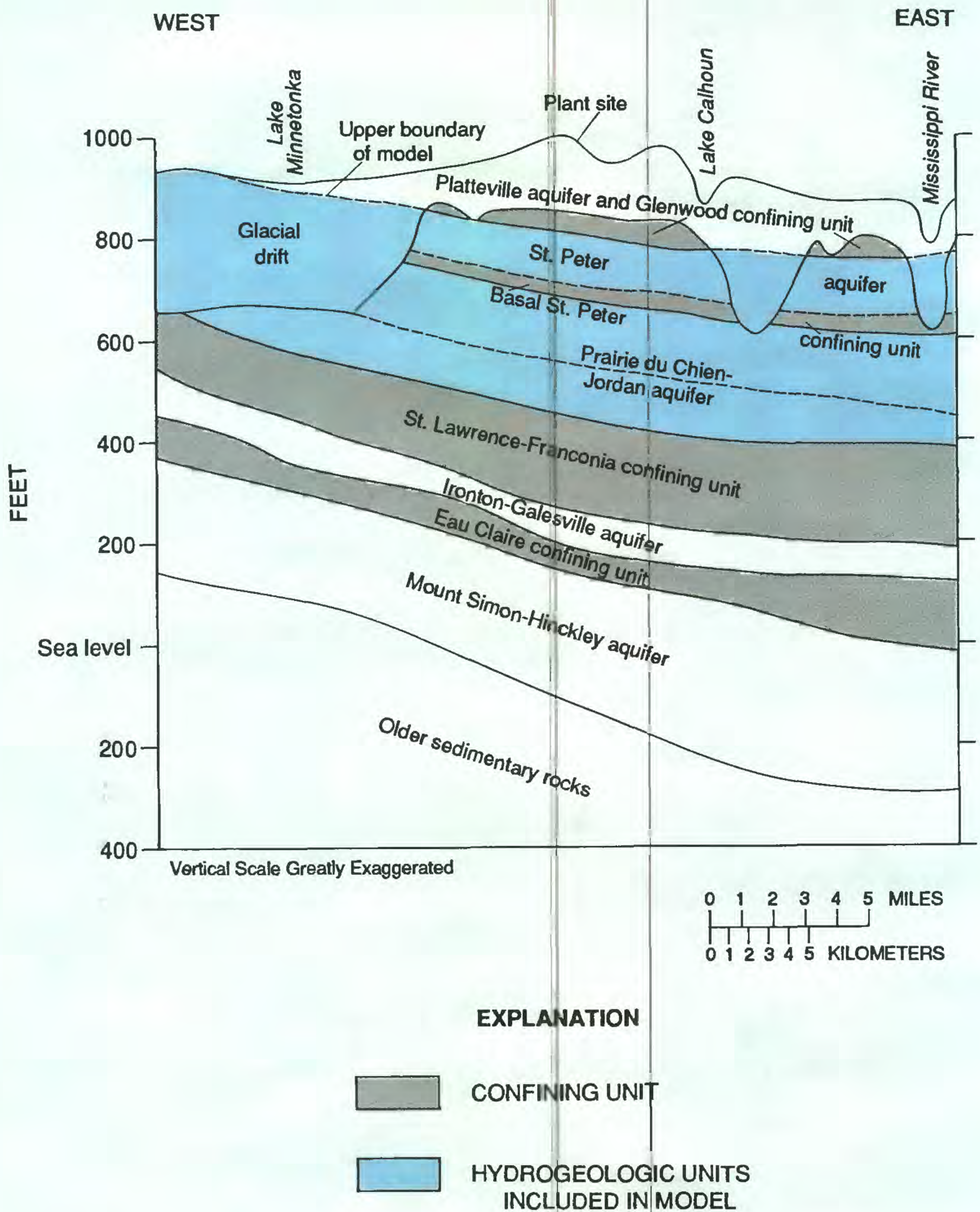
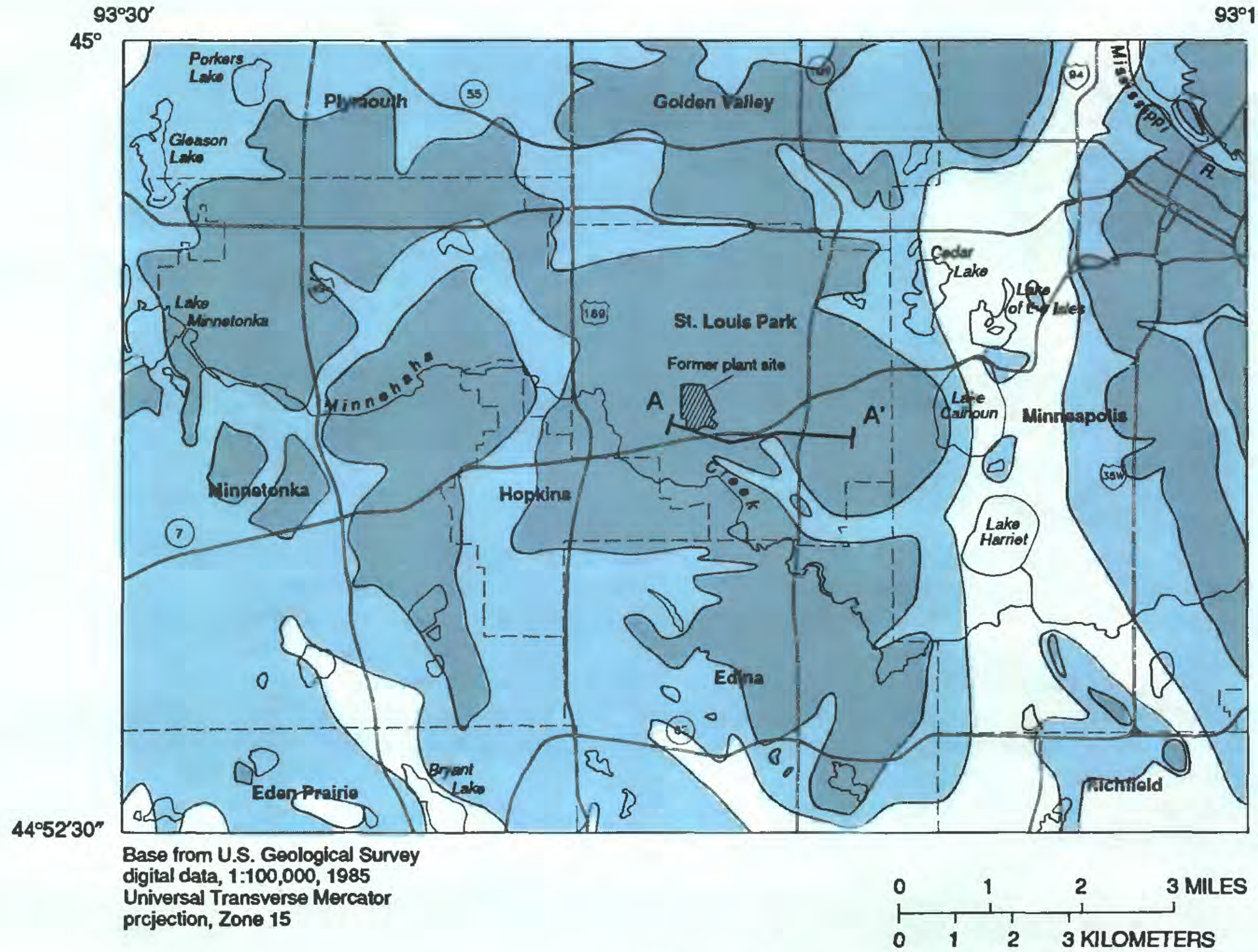


Figure 3.--Generalized section showing hydrogeologic units in the study area.
(From Stark and Hult, 1985, p.9)



EXPLANATION

DEEP BEDROCK VALLEY--Shows where thick glacial drift overlays the Prairie du Chien-Jordan aquifer

PLATTEVILLE AQUIFER AND GLENWOOD CONFINING UNIT

ST. PETER AQUIFER

APPROXIMATE GEOLOGIC CONTACT

A A'

LINE OF SECTION--Section shown in figures 5 and 6

Figure 4.--Areal extent of the St. Peter aquifer and generalized bedrock geology.

production wells completed in the aquifer, and to leakage to underlying units. Larson-Higdem and others (1975) estimated that leakage to the underlying Prairie du Chien-Jordan aquifer, in Hennepin County, is about 3.5 in/yr (inches per year) and that about 1 inch of additional leakage occurs as the result of increased summer pumping and resulting drawdown in the Prairie du Chien-Jordan aquifer.

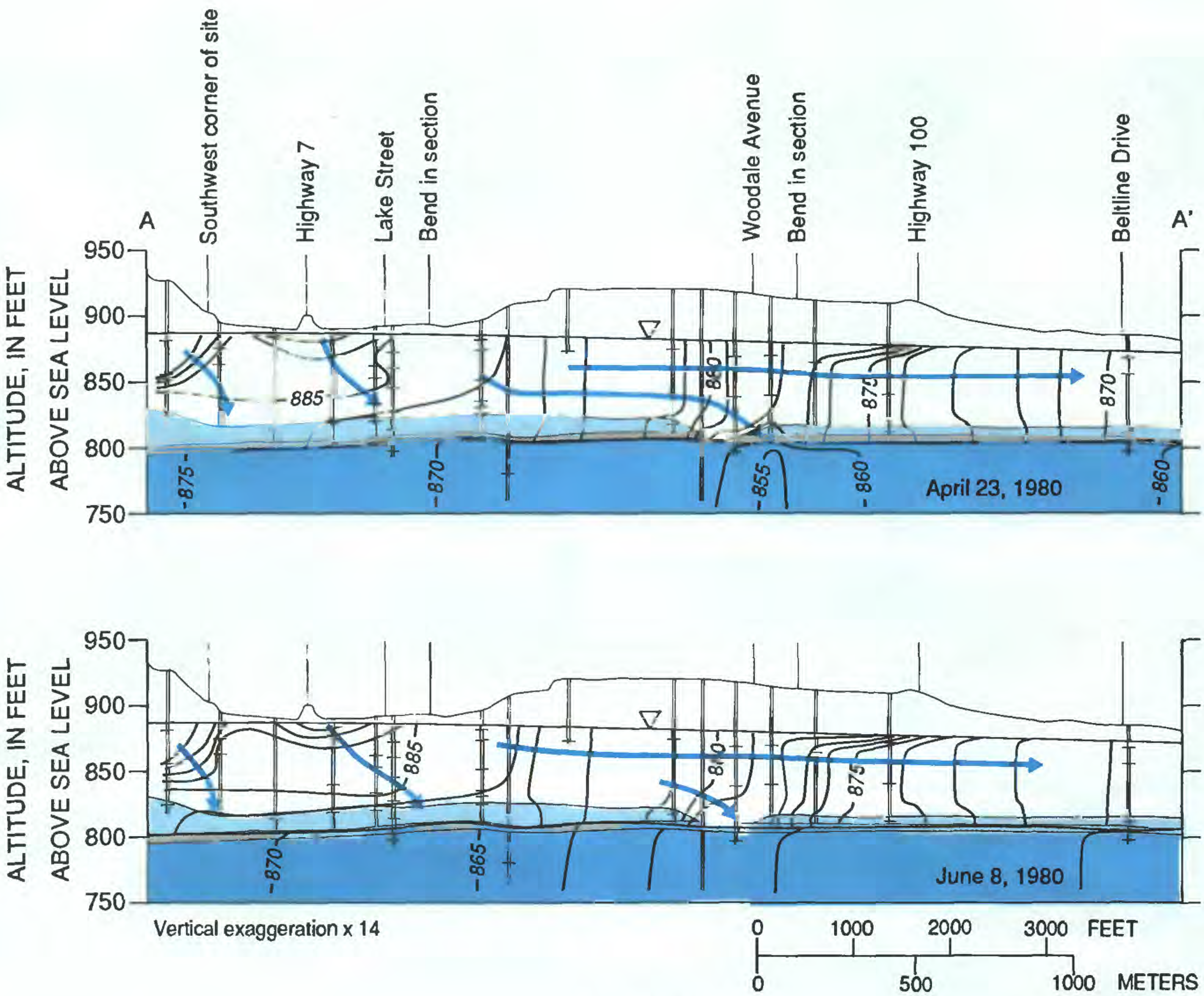
Withdrawals of ground water primarily from the Prairie du Chien-Jordan aquifer have produced both long-term (1885-1980) and short-term (seasonal) potentiometric-surface declines in that aquifer. Ground water is pumped from the study area for four major uses: (1) Municipal supply, (2) commercial supply (mostly air-conditioning), (3) self-supplied industrial, and (4) irrigation (mostly cemeteries and golf courses). Public-supply demand has increased dramatically since 1940 because of increased population and per-capita consumption. Commercial use also has increased as a result of an increase in water-cooled air-conditioning. Reduction in the use of ground water by industries since the late 1960's is mostly the result of conservation measures.

The Prairie du Chien-Jordan aquifer supplies about 80 percent of the ground water used in Hennepin County. Within the study area, the volume of water pumped from the aquifer has increased during the century and currently averages about 24 Mgal/d (million gallons per day). Early in the century, withdrawals were concentrated within the downtown Minneapolis area. This was followed by expansion of pumping centers in the suburban areas. Most recently, withdrawal from the aquifer has declined in Minneapolis but has continued to increase in the suburban areas (Horn, 1983). Ground-water withdrawal from the St. Peter aquifer accounts for only about 1 percent of ground water used in Hennepin County (Horn, 1983).

Ground-water withdrawal in the study area is highly seasonal. During the period 1977-79, summer withdrawals averaged about 1.7 times the average withdrawal for non-summer months. Commercial air-conditioning and public supply cause the greatest variability in seasonal withdrawals.

Withdrawals from the Prairie du Chien-Jordan aquifer have produced long-term and short-term potentiometric-surface declines. In Hennepin County, the greatest potentiometric-surface declines (as much as 50 ft) have occurred in the downtown Minneapolis area and in certain areas of St. Louis Park. In addition, potentiometric-surface declines have occurred as a result of increased pumpage in the summer months. These short-term seasonal declines are as much as 50 ft in the downtown Minneapolis area and as much as 40 ft in certain areas of St. Louis Park. Changes in the potentiometric surface of the St. Peter aquifer are less well documented, but probably are significantly less, both seasonally and historically, than in the Prairie du Chien-Jordan aquifer.

Ground-water flow in the St. Peter aquifer moves in a general west to east direction near the plant site (Hult, 1984) (fig. 5). Contaminant movement into the St. Peter aquifer has been influenced by flow in a multiaquifer well located on the plant site, by other nearby multiaquifer wells, by stresses from production wells and by downward ground-water flow in bedrock valleys. Hult (1984) and Ehrlich and others (1982) presented data that showed that the concentrations of several inorganic constituents, resulting from activities at



EXPLANATION

HYDROGEOLOGIC UNIT

- Undifferentiated glacial drift
- Platteville aquifer
- Glenwood confining unit
- St. Peter aquifer

LOCATION OF WELL OR PIEZOMETERS--Symbol shows middle of opening

APPROXIMATE ALTITUDE OF WATER TABLE

DIRECTION OF GROUND-WATER FLOW

—800— EQUIPOTENTIAL CONTOUR--Shows altitude of hydraulic head. Contour interval, in feet, is variable. Datum is sea level.

Figure 5.--Direction of ground-water flow, April 23, 1980 and June 8, 1980.
(Trace of section shown in Figure 4) (Hydrogeology from Hult, 1984, p. 19)

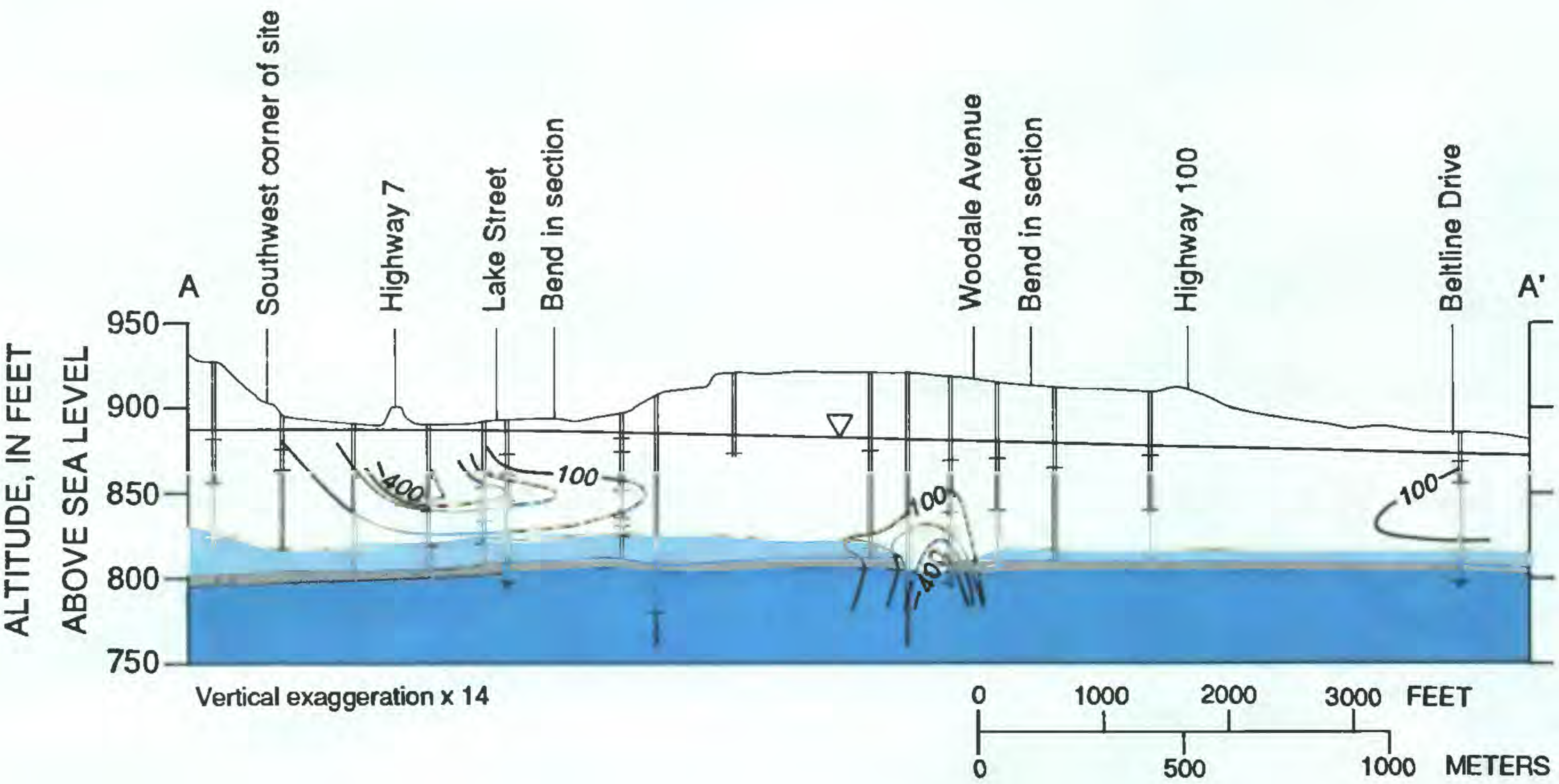
the plant site decreased downgradient in the glacial-drift aquifers. The data also showed that the concentrations of the constituents were elevated near a bedrock valley. The inorganic constituents in ground water in the glacial-drift and Platteville aquifer were selected as tracers in evaluating transport processes because concentrations of organic contaminants in the aquifer were very low. The hydrogeologic section in figure 6 shows the concentration of sodium along the line of section and probably is a good representation of the geometry of the organic-contaminant plume. The figure shows an increase in the concentration of sodium near the bedrock valley where ground water flows into the St. Peter aquifer from overlying aquifers. The distribution and concentration of other inorganic constituents--nitrogen species (ammonia, nitrite and nitrate), sulfur (sulfide and sulfate), dissolved oxygen, and manganese and iron--also indicate that the main body of the organic-contaminant plume is affected by downward movement of water into the St. Peter aquifer in the vicinity of bedrock valleys.

SIMULATION OF GROUND-WATER FLOW

A computer-model code by Trescott (1975), later modified by Trescott and Larson (1976) and Torak (1982), was used to develop the ground-water-flow model for the original study. The model code solves finite-difference approximations to the ground-water-flow equation in three dimensions. The numerical model calculates the flow of water through the aquifers and confining units at St. Louis Park as a function of aquifer characteristics, the amount of water in storage, and the rates of inflow and outflow.

A conceptual model and simplifying assumptions of the ground-water system were formulated to construct the original digital model. The conceptual model is a qualitative description of the known characteristics and behavior of the system. The major concepts and assumptions of the numerical model are given below.

1. The Prairie du Chien-Jordan aquifer, basal St. Peter confining unit, and St. Peter aquifer are recharged by leakage through overlying hydrogeologic units, and by lateral inflow.
2. At the scale of the numerical model the hydrogeologic units are considered to be homogeneous and horizontally isotropic, and the assumption of laminar flow through porous media with primary and secondary porosity and permeability is considered to be valid.
3. Aquifers discharge water to wells and to the Mississippi and Minnesota Rivers.
4. The upper model layer represents the St. Peter aquifer or the glacial-drift aquifer where the St. Peter aquifer is absent.
5. Water is pumped from each of the aquifers in the system.
6. The volume of water that moves vertically across the base of the Prairie du Chien-Jordan aquifer is small relative to lateral flow; the base can be treated as a no-flow boundary.
7. Some natural hydrologic boundaries lie outside the modeled area; ground water flows laterally across arbitrarily imposed model boundaries.



EXPLANATION

HYDROGEOLOGIC UNIT

- Undifferentiated glacial drift
- Platteville aquifer
- Glenwood confining unit
- St. Peter aquifer

LOCATION OF WELL OR PIEZOMETERS--Symbol shows middle of opening

APPROXIMATE ALTITUDE OF WATER TABLE

—100— LINE OF EQUAL SODIUM CONCENTRATION--Interval 100 milligrams per liter

Figure 6.--Concentration of sodium in water from glacial-drift and bedrock aquifers, May through July 1980.

(Trace of section shown in Figure 4) (Hydrogeology from Hult, 1984, p. 21)

Additional assumptions, conditions, and limitations for the use of the numerical model are given below.

1. General hydrologic conditions have not changed significantly since the original numerical model was developed (1982).
2. Only minor modifications are required to calibrate the numerical model more accurately to simulate flow in the St. Peter aquifer. The original numerical model simulated flow in the St. Peter aquifer to represent leakage to the Prairie du Chien part of the Prairie du Chien-Jordan aquifer.
3. Calibration of the current numerical model to simulate flow in the St. Peter aquifer is limited by a lack of hydraulic-head data with which to compare model-simulated values of hydraulic head.

The numerical model is designed to simulate ground-water flow under St. Louis Park. The area modeled is larger than St. Louis Park in order to include ground-water withdrawals and boundary conditions that affect hydraulic head near St. Louis Park.

Model Design

The approximately 380-mi^2 (square mile) area of the model was subdivided by the use of a rectangular finite-difference grid with variable spacing (fig. 7). The grid has 40 rows and 42 columns that have horizontal dimensions ranging from 400 to 14,000 ft. The smallest cells are near the former plant site. The finite-difference equations solved by the model are based on a block-centered method where each node is located at the center of each grid cell. Nodes are the locations at which the hydraulic heads are computed by the model. The values for transmissivity, storage, hydraulic head, pumpage, and recharge represent average conditions within the grid cells.

The hydrogeologic units represented in the model include, in ascending order, the Jordan part (layer 1) and Prairie du Chien part (layer 2) of the Prairie du Chien-Jordan aquifer, the basal St. Peter confining unit (layer 3), and the St. Peter aquifer (layer 4). Glacial deposits are not represented by a discrete layer; they represent areas in which bedrock units have been removed by erosion (bedrock valleys). In order to minimize the number of cells included in the model, the upper surface of the top layer generally coincides with the top of the St. Peter aquifer. The entire thickness of glacial drift, therefore, is not simulated in the model-layer configuration. The lower model layer, representing the Jordan part of the Prairie du Chien-Jordan aquifer, is considered to have an impermeable lower boundary because the underlying St. Lawrence-Franconia confining unit is considered to isolate it from other, underlying aquifers.

Geologic data from maps prepared by the Minnesota Geological Survey (1980) were used to assign hydrogeologic characteristics (lithology and thickness) to each cell. The assignment included selecting cells that represent glacial drift in bedrock valleys. Initial values for horizontal and vertical hydraulic conductivity for each layer were the same as those used in a regional ground-water-flow model developed by the U.S. Geological Survey for the seven-county Twin Cities Area (M.E. Schoenberg, U.S. Geological Survey, oral commun., 1990).

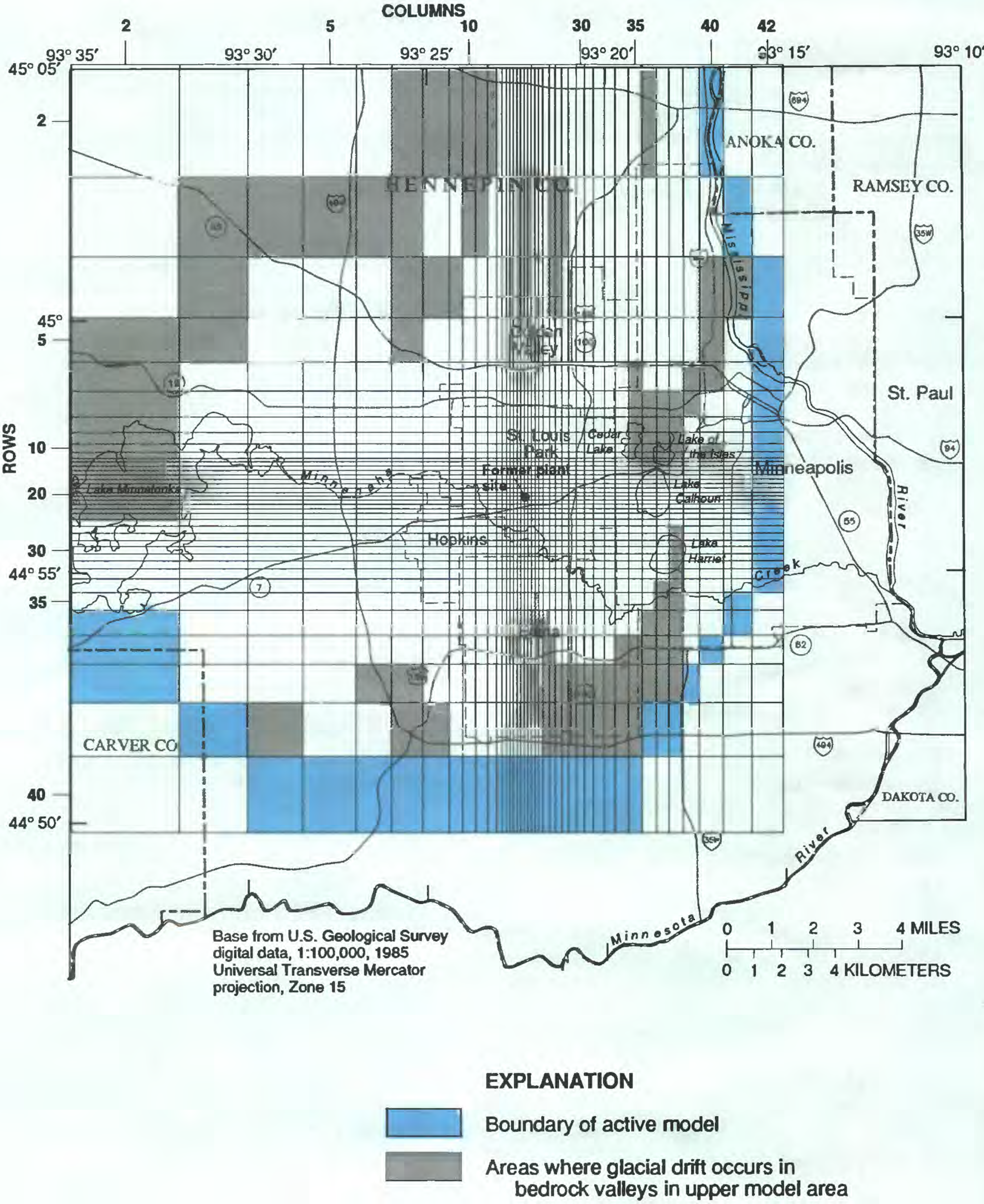


Figure 7.--Finite-difference grid.
(From Stark and Hult, 1985, p. 25)

The boundaries of the model grid simulate hydrologic boundaries of the St. Peter and Prairie du Chien-Jordan aquifers. In the north and west, the boundaries represent the approximate lateral extent of the Prairie du Chien-Jordan aquifer. The simulated hydraulic head at these boundary cells was held constant because historical data show that long-term and seasonal changes in water levels are insignificant in these areas. Flow conditions near the Minnesota and Mississippi Rivers are simulated at the southern and eastern boundaries of the model. These boundaries consisted of constant-head cells in which the potentiometric heads were defined on a seasonal basis to represent the hydraulic head measured in the aquifers at specific times. The model boundaries do not coincide exactly with the rivers because hydraulic-head data are not available for the aquifers under the rivers.

Mean yearly and seasonal ground-water-withdrawal data for about 100 high-capacity wells were compiled for use in model simulations. Average yearly data were used for steady-state simulations and average seasonal data were used for transient simulations. Each calendar year had three "pumping seasons": (1) "spring," January through April; (2) "summer," May through September; and (3) "fall," October through December. Seasonal water-use estimates were created by averaging monthly-estimated and monthly-reported water use within each pumping season. Summer was generally the season of greatest pumpage.

Calibration of Original Model

Calibration and evaluation of the original model were conducted for two steady-state (equilibrium) conditions and a transient condition. Under steady-state conditions, inflow to the system, such as leakage from overlying geologic units and lateral inflow, is balanced by natural outflow from the system and pumpage. Transient conditions include storage within the ground-water system and, therefore, are time dependent.

The steady-state simulations were for (1) conditions prior to significant ground-water development (approximately 1885-1930) and (2) average winter conditions in the ground-water system during 1970-77, a period of large annual ground-water withdrawal. Seasonal ground-water withdrawals from 1977-80, which changes in potentiometric surfaces with time were documented, were used for transient calibration. Performance of the model was evaluated by comparing model-computed and observed water levels. Model performance was improved be varying values of model properties (horizontal and vertical hydraulic conductivity, leakage to the top layer, and storage) until the mean differences between observed and model-computed water levels were minimized.

Steady-State Calibration

The initial phase of calibration of the original model involved simulating conditions in the Prairie du Chien and Jordan model layers for the period representing 1885-1930. Water-level data for this period were used to define boundary conditions and heads for the simulation and to evaluate model performance. The earliest water levels generally are from the downtown Minneapolis area. Data represent water levels measured in wells constructed as urbanization progressed to the west in Hennepin County. Although these data do not represent a single time, they do reflect hydraulic heads before significant ground-water development.

Few water-level data are available for the St. Peter aquifer from 1885 to 1930. Therefore, hydraulic heads assigned to constant-head cells at the boundaries of the Prairie du Chien and Jordan layers also were assigned to boundary cells in the St. Peter layer. The justification for this assignment is that (1) at 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 are presently similar to water levels in the Prairie du Chien-Jordan aquifer, and (2) available data indicate that the potentiometric surface of the St. Peter aquifer has not declined significantly from 1880 to 1980. Although a downward vertical hydraulic gradient across the basal St. Peter confining bed may have existed during the late 1800's, the vertical-head difference between the St. Peter and the Prairie du Chien-Jordan aquifers probably was small.

A sensitivity analysis of hydrologic properties was conducted for the 1885 steady-state calibration. During the sensitivity analysis, values were evaluated for (1) transmissivity and vertical hydraulic conductivity for each hydrogeologic unit in the model layers and (2) leakage to the top layer. Values of transmissivity and leakage were varied by a factor of 2, and vertical hydraulic conductivities were varied by a factor of 10. Leakage to the top layer (St. Peter aquifer-glacial drift) was found to be the most sensitive hydrologic property. Variation of this property resulted in about a 5- to 10-ft difference in hydraulic head in all layers. The model is not very sensitive to changes in the values of the other properties.

The 1885 simulation was calibrated by varying values of hydraulic properties (horizontal and vertical hydraulic conductivity and leakage to the top layer) until model-computed hydraulic head matched measured water levels (best-match simulation). The effect of variable leakage rates (rates which varied with the absence or presence of the overlying Glenwood Shale) to the upper model layer on hydraulic head was examined early in the calibration process. Because of the high transmissivity of all hydrogeologic units in the upper model layer, the effect of variable leakage was found to be not significant, and a uniform value was considered acceptable. Model-computed hydraulic heads for all layers where water-level data are available were generally within 10 feet of measured water levels. The model-computed water balance is shown in Stark and Hult (1985).

Model calibration was improved by simulating average winter steady-state conditions for 1970 through 1977. The period 1970 through 1977 was selected because water-level and water-use data were available, because it was a period of significant ground-water withdrawal, and because during this period no significant long-term changes in potentiometric surfaces occurred in the system.

Hydraulic heads assigned to constant-head cells at the boundaries of the Jordan and Prairie du Chien layers were 10 to 50 ft lower than heads assigned during 1885 simulations because the potentiometric surface of the Prairie du Chien-Jordan aquifer changed from 1885 to the 1970's. Heads assigned to constant-head cells at the boundaries of the St. Peter layer (layer 4), however, were identical to heads used during earlier simulations because water levels in the St. Peter aquifer had not changed significantly (generally less than 10 ft) from 1885 to the 1970's.

Average annual ground-water pumpage for 1970-77 was incorporated into the model simulations. The pumpage used was 8.3 billion gallons per year from 121 high-capacity wells. Most of these wells are open to the Jordan, to the Prairie du Chien parts of the Prairie du Chien-Jordan aquifer, or to both. Pumpage from wells that are open to only one of the two units was assigned to the corresponding model layer. Pumpage from wells open to both the Prairie du Chien and Jordan parts of the Prairie du Chien-Jordan aquifer were divided in proportion to the transmissivities assigned to the open interval in each unit.

Sensitivity analysis was also conducted for the 1970 through 1977 calibration period. Adjustments were made to the horizontal hydraulic conductivity assigned to the hydrogeologic unit in each layer and leakage to the top layer. All values, except leakage to the top layer, were increased and decreased by a factor of 2.0. Leakage was varied by about ± 20 percent because the range of possible values was known from previous studies (Larson-Higdem and others, 1975; Guswa and others, 1982). Leakage and the vertical hydraulic conductivity of the basal St. Peter confining unit (layer 3) were the properties to which the model was most sensitive.

Model calibration for average winter steady-state conditions, 1970-77, was accomplished by adjusting model hydrologic properties until the average deviation between measured water level and model-calculated hydraulic heads was minimized. Values of the adjusted properties used in the calibrated model are shown in table 1. The model-calculated potentiometric surface and water levels measured during January and February 1978 are shown for the Prairie du Chien layer in Stark and Hult (1985, fig. 17). The average difference between model-calculated and field-measured water levels was 4 ft in the Prairie du Chien or Jordan layers or both and 6 ft in the St. Peter layer.

The model-computed water budget for the simulation that most closely matches 1970-77 winter water levels (Stark and Hult, 1985) is significantly different from the model-calculated budget for the 1885 simulation period. Flow into the system and discharges from the system increased. Flow into the system is predominantly lateral inflow to the St. Peter aquifer (layer 4) and leakage to the top layer. The increased flow into the system was caused by increased pumpage, which lowered the hydraulic head in the aquifers and changed their vertical and horizontal gradient. Modeled lateral outflow increased because hydraulic heads were lowered in constant-head cells along the southern and eastern boundaries of the model. The hydraulic heads were lowered to reflect the effects of pumping stress outside the modeled area.

Transient Calibration

Transient simulations of the original model were conducted to further refine values of hydrologic properties and to test assumptions of aquifer storage. The period 1977-80 was selected for transient simulation because water-use and seasonal potentiometric-surface data were available and because changes in seasonal potentiometric surfaces, as great as 50 feet, had occurred.

Table 1.--*Values of model hydrologic properties*

(1970's steady-state simulation)

[K_z, vertical hydraulic conductivity; K_x, horizontal hydraulic conductivity; ft/d, feet per day; in/yr, inches per year; NA, not applicable]

Hydrogeologic unit	Horizontal hydraulic conductivity (ft/d)	Thickness (feet)	Anisotropy (K_z/K_x)	Leakage (in/yr)
Glacial drift (Layers 1-4)	[1]80-160	variable	1.0×10^{-5} to 4.5×10^{-5}	NA
St. Peter aquifer (Layer 4)	20	135	.14	5.5
Basal St. Peter confining unit (Layer 3)	20	30	4.5×10^{-5}	NA
Prairie du Chien-group part of Prairie du Chien-Jordan aquifer (Layer 2)	[1]36-56	125	1	NA
Jordan Sandstone part of Prairie Chien-Jordan aquifer (Layer 1)	[1]18-25	80	.1	NA

[1]Ranges in values reflect changes to model properties to account for areal variations in thickness of unit.

Each year in the period 1977-80 was divided into three pumping seasons. Each pumping season consisted of four time steps. The "seasons" were selected to simulate potentiometric-surface changes resulting from measured changes in pumpage in the model area, and to reflect seasonal variability in water withdrawals. Changes in pumpage outside the south and east boundaries of the modeled area, primarily in downtown Minneapolis, were simulated by changing values of constant head at the boundaries. The pumping seasons are "spring" (January-April), "summer" (May-September), and "fall" (October-December). Average seasonal water use was estimated for each season. Summer water use, which averaged about 33 Mgal/d, was about 1.7 times the average spring and fall rates of use. Because estimated ground-water withdrawals represent seasonal averages, and because continuous water-level data are not available for the aquifers, the model could not be calibrated for intervals shorter than a pumping season.

The initial hydraulic heads for the first seasonal simulation (spring 1977) were the heads calculated in the 1970-77 steady-state simulation. The hydraulic heads calculated in each seasonal simulation were used as the starting hydraulic heads in the simulation of the next season. Boundary hydraulic heads assigned to constant-head cells in the Jordan and Prairie du Chien layers were modified before each seasonal simulation to reflect measured changes in head at the southern and eastern boundaries of the model.

Values of hydrologic properties from the 1970-77 steady-state simulation were used as initial values for transient simulations. Initial values of aquifer storage coefficients were from Norvitch and others (1974) (table 2).

Sensitivity testing showed that transient simulations were not greatly affected by variations in values of storage because equilibrium conditions were approached quickly during each pumping season. Only 1 percent or less of model inflow comes from storage on the basis of model-calculated water-balance statistics for a typical season (Stark and Hult, 1985).

Model-calculated values of hydraulic head from transient simulations generally are within 10 ft of measured water levels. Transient-model water-balance statistics for January 1979 (spring pumping season) are similar to water-balance statistics for the 1970-77 steady-state model. The similarities indicate that the system approaches steady-state conditions each winter and that the steady-state model can be used to approximate fall through spring conditions in the aquifer. These data also indicate that average yearly withdrawal data are good approximations of withdrawal rates for the fall and spring pumping seasons. Differences between water-balance statistics for the June 1979 (summer pumping season) simulation and for the January 1979 (spring pumping season) simulation reflect the effects of increased summer withdrawals in the modeled area and changes in hydraulic head at the boundaries because of increased withdrawals outside the modeled area.

Table 2.--*Initial values of aquifer-storage coefficients for transient model calibration*

[Norvitch and others (1974)]

Hydrogeologic unit	Storage coefficient
Glacial drift (Layers 1-3)	1×10^{-4}
Basal St. Peter aquifer (Layer 4)	1×10^{-4}
St. Peter confining unit (Layer 3)	1×10^{-5}
Prairie du Chien group part of Prairie du Chien-Jordan aquifer (Layer 2)	4×10^{-4}
Jordan Sandstone part of Prairie du Chien-Jordan aquifer (Layer 1)	7×10^{-5}

Calibration for St. Peter Aquifer

Additional calibration and testing of the model was conducted for this study to evaluate and test the performance of the model for the model layer representing the St. Peter aquifer. The model was calibrated for steady-state conditions in the St. Peter aquifer from March through May 1980. Measured water levels in 12 wells were used for calibration (fig. 8). Table 3 lists wells, measured water levels, and simulated hydraulic heads. The simulated hydraulic heads were generally within 11 ft of measured water levels. Calculated hydraulic heads and observed water levels agree fairly well at wells D, and F located near the plant site. The simulated hydraulic head at the cell included in well C differed significantly from the measured water level. Completion details for this well are not available; the measured water level probably represents the hydraulic head in another aquifer or a combination of hydraulic heads in more than one aquifer.

The value of constant-head cells in layer 4 at the model's boundaries were changed to simulate the effect of data reliability at the boundaries. The changes had little effect on simulated heads and, therefore, the values from the original model were used for this calibration.

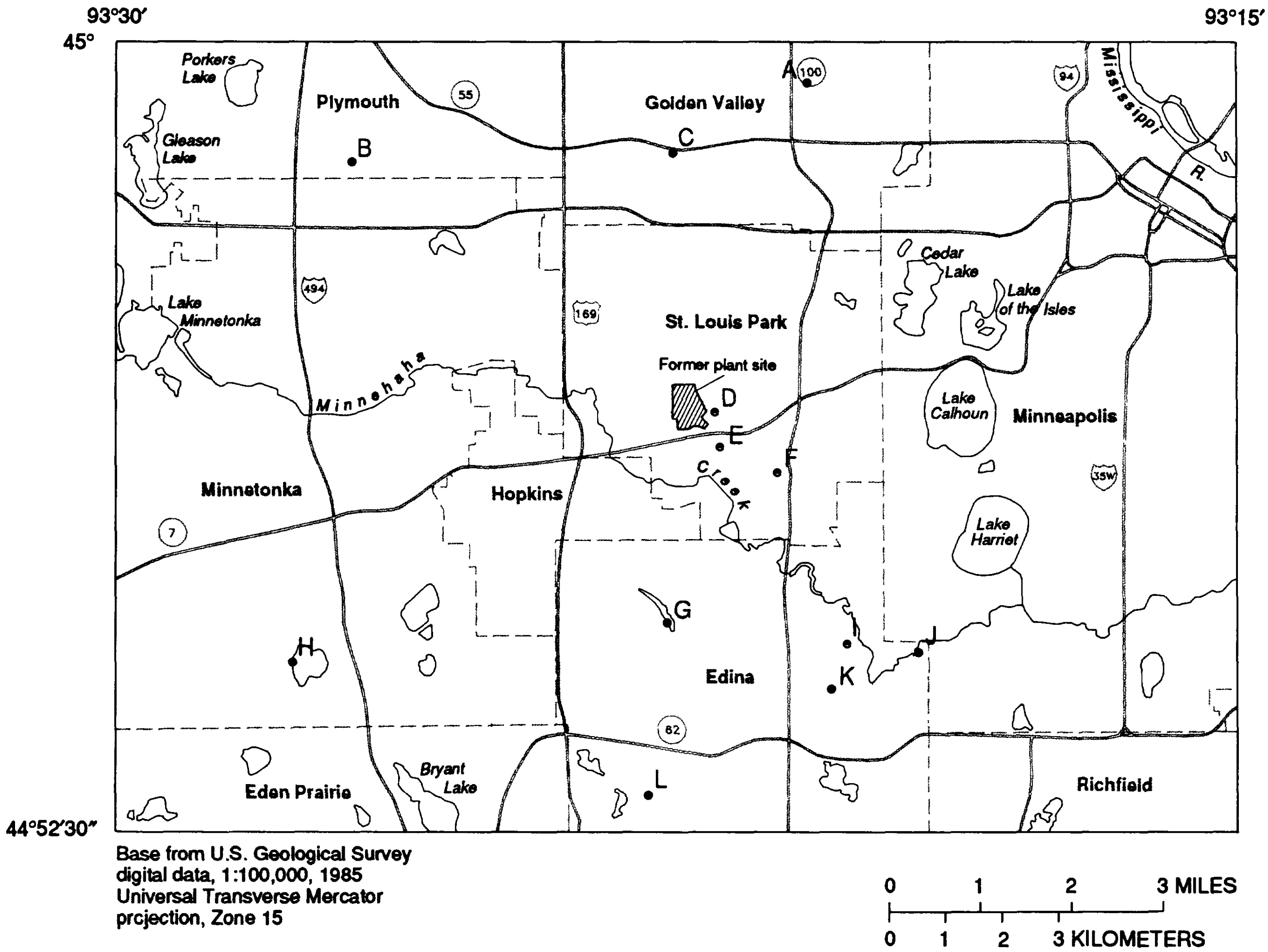
Model-Simulation Results

Transient simulations

Transient simulations were conducted to evaluate the effects of storage caused by seasonal changes in pumping and seasonal changes at flow-system boundaries in the St. Peter model layer. The transient simulations were made for spring and summer pumping seasons for 1985. Average seasonal ground-water withdrawals were simulated for each season. Because simulated ground-water withdrawals represent seasonal averages, transient behavior of the system cannot be evaluated for time intervals shorter than a pumping season.

Simulated potentiometric surfaces for 1980 were used as initial conditions for the transient simulation. The year 1980 was selected because it was the most recent period simulated with the original model and because observed values of hydraulic heads in spring 1985 agreed well with the simulated hydraulic heads from spring 1980. There are no data to evaluate the seasonal change in head from the spring to the summer of 1985.

Figures 9 and 10 show simulated potentiometric surfaces in the St. Peter aquifer at the end of the 1985 spring and summer pumping periods. A comparison of the general trend in figures 9 and 10 indicates that ground-water flow in the vicinity of the plant-site is in a east-southeasterly direction for both periods and that the general shape of the potentiometric surfaces are similar. The effect of increased pumping in far eastern (downtown Minneapolis) and south-eastern (Edina) parts of the study area during summer is indicated by lowered hydraulic heads (fig. 10).



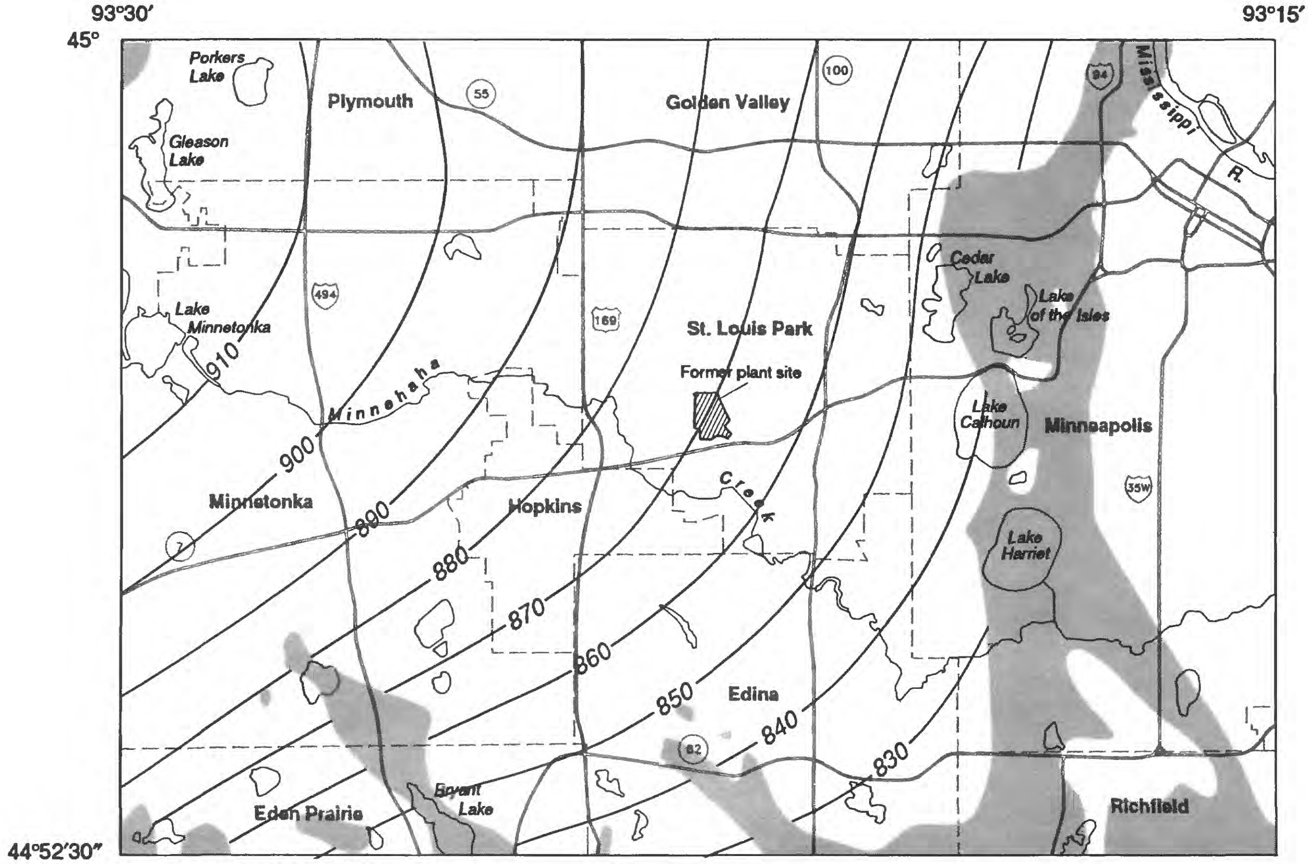
EXPLANATION

•A LOCATION OF WELL--Letter is well identifier in table 3

Figure 8.--Locations of wells used to calibrate the model for the St. Peter aquifer, March through May 1980.

Table 3.--*Measured water levels in the St. Peter aquifer and simulated hydraulic heads in the St. Peter aquifer model layer, March through May (spring pumping season) 1980*

Well Location			Head, in feet above sea level		
Map letter (fig. 8)	Row	Column	Measured water level	Simulated head	Head difference
A	5	28	858	869	+11
B	6	6	909	905	-4
C	6	18	857	879	+22
D	22	22	867	867	0
E	24	23	868	865	-3
F	26	26	861	860	-1
G	35	16	858	856	-2
H	36	5	868	878	+10
I	36	32	845	837	-8
J	36	34	830	833	+3
K	37	30	842	835	-7
L	38	13	836	838	+2



Base from U.S. Geological Survey
digital data, 1:100,000, 1985
Universal Transverse Mercator
prcjection, Zone 15

0 1 2 3 MILES

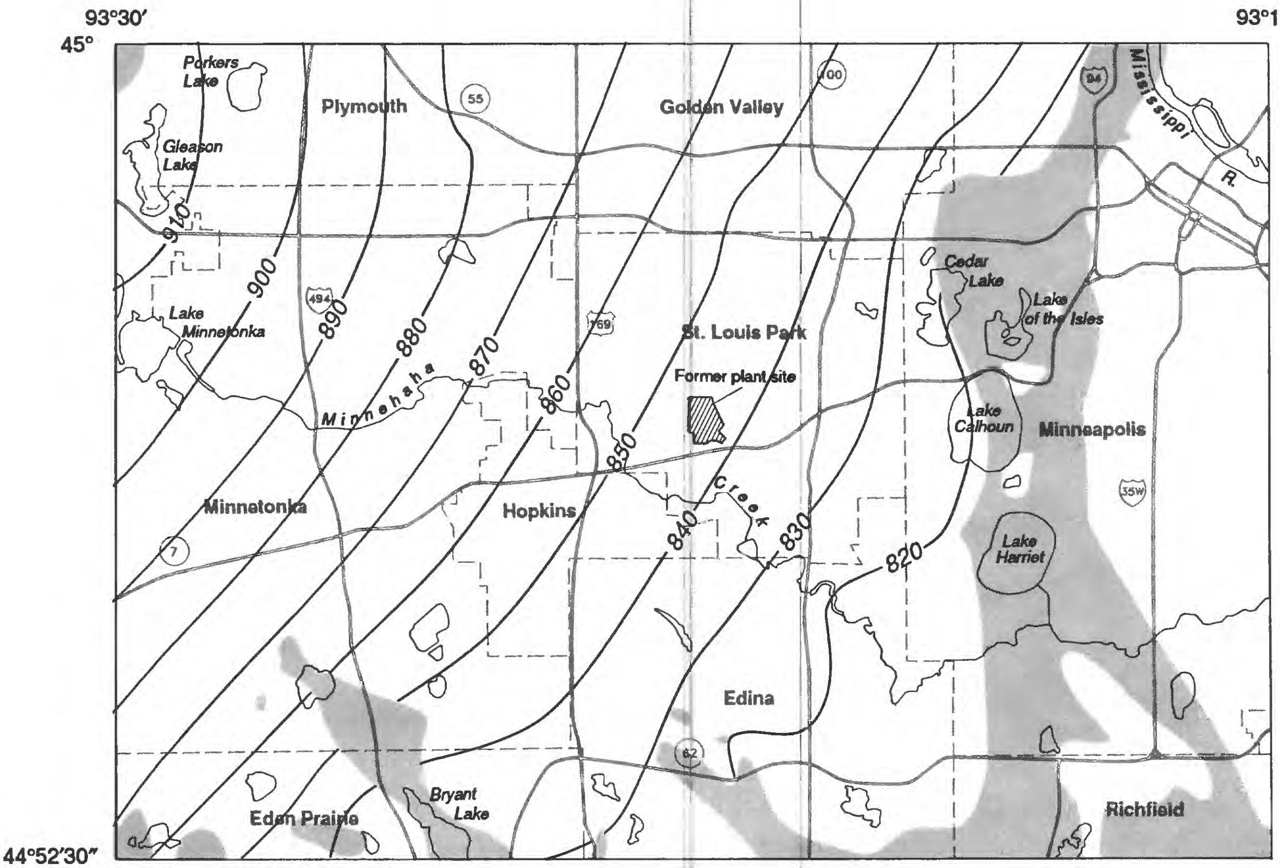
0 1 2 3 KILOMETERS

EXPLANATION

AREA WHERE ST. PETER AQUIFER IS MISSING

—*850*— SIMULATED POTENTIOMETRIC CONTOUR--
Shows altitude of potentiometric surface. Contour interval 10 feet. Datum is sea level

Figure 9.--Simulated potentiometric surface of the St. Peter aquifer, spring 1985.



Base from U.S. Geological Survey digital data, 1:100,000, 1985
Universal Transverse Mercator prcjection, Zone 15

0 1 2 3 MILES
0 1 2 3 KILOMETERS

EXPLANATION

AREA WHERE ST. PETER AQUIFER IS MISSING

—*850*— SIMULATED POTENTIOMETRIC CONTOUR-- Shows altitude of potentiometric surface. Contour interval 10 feet. Datum is sea level

Figure 10.--Simulated potentiometric surface of the St. Peter aquifer, summer 1985.

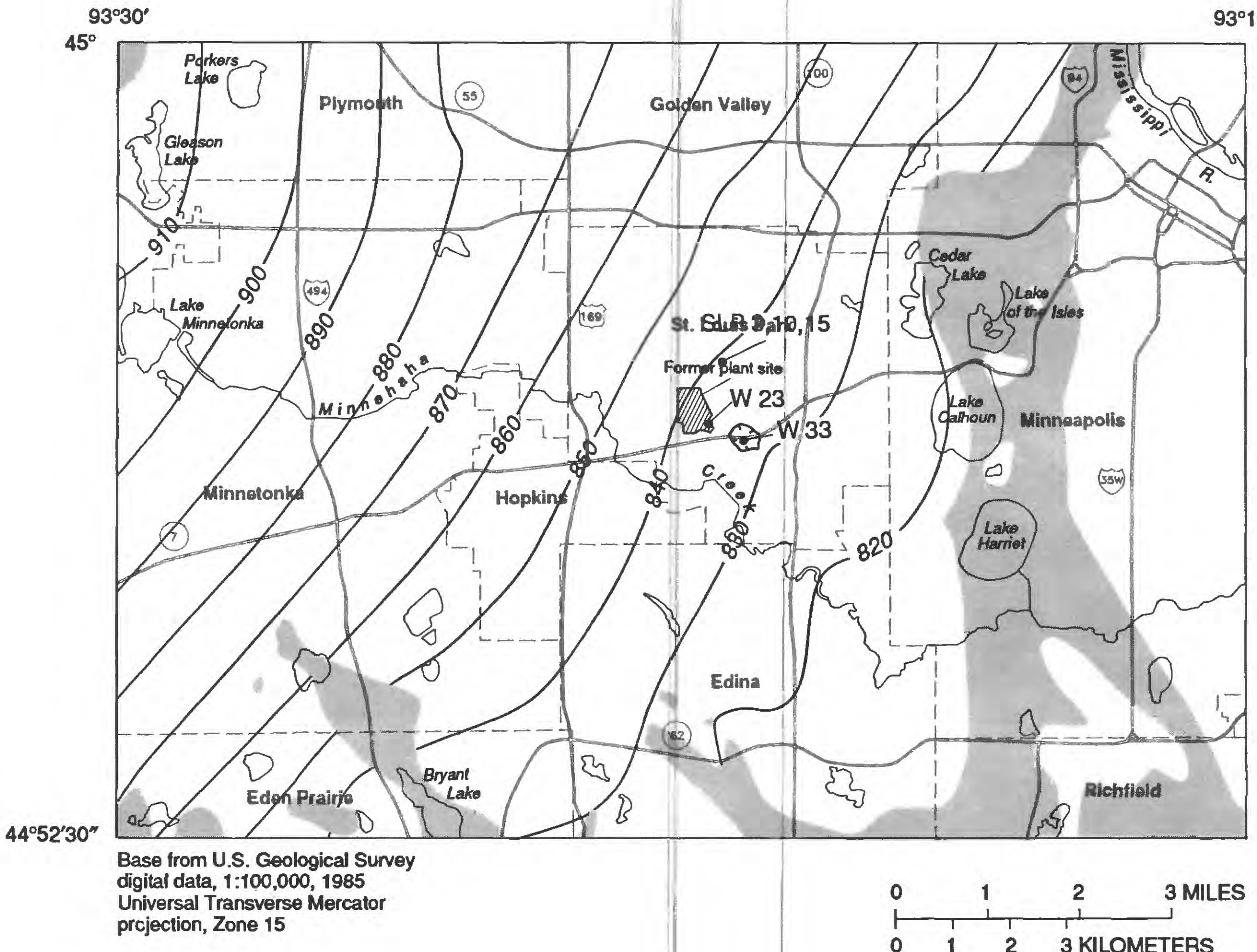
The transient simulations indicated that the effects of storage on the system were minimal at the end of the spring and summer pumping periods. The rate of change in values of hydraulic head were minimal at the end of each pumping period, indicating that the equilibrium conditions had been reached. Therefore, steady-state simulations were used to analyze the alternative pumping strategies for controlling ground-water flow.

Multiaquifer Wells

Hult and Schoenberg (1984) discuss the hydraulic impact of a multiaquifer well (W23) located at the plant site (fig. 11). Flow from the St. Peter aquifer into the Prairie du Chien-Jordan aquifer was measured at 150 gal/min in this well. This created a cone of depression in the St. Peter and a cone of impression in the Prairie du Chien-Jordan until 1979 when the flow was stopped. In addition to the hydraulic impact of well W23, another multiaquifer well (W33) was pumped during the same time period. This well is completed in the St. Peter aquifer and is 2,000 ft southeast of the plant site. A model simulation assessed the effect of these two multiaquifer wells and other nearby production wells on ground-water flow in the vicinity of the plant site. An estimate of the potentiometric surface in the St. Peter aquifer before the multiaquifer well was sealed in 1979 is shown in figure 11. The surface was estimated by simulating the hydraulic effect of the wells on the summer of 1985 potentiometric surface in the St. Peter aquifer. The combined hydraulic effect of these wells had the potential to limit the downgradient migration of the contaminants in the St. Peter aquifer. Accurate pumpage data for well W33, however, are not available, and were estimated to be about 135 gal/min on the basis of historical usage. Wells SLP3, SLP10, and SLP15, located just north of the plant site, were pumped at a total rate of 90 gal/min from the St. Peter aquifer.

Recharge and Bedrock Valleys

Stark and Hult (1984) found that the simulated potentiometric surface of the St. Peter aquifer (layer 4) was sensitive to the amount of vertical leakage to that layer. A uniformly distributed value of leakage to layer 4 of 5.5 in/yr was used for the original model. The presence of bedrock valleys, where the Platteville aquifer and Glenwood confining unit have been eroded and the St. Peter aquifer is in direct hydrologic connection with the glacial drift aquifer, probably increases local ground-water leakage to the St. Peter aquifer. Figure 4 shows the location of bedrock valleys near the plant site. The St. Peter aquifer is hydraulically connected with the glacial-drift aquifer in these bedrock valleys. Vertical flow to the St. Peter aquifer in these valleys was estimated from Darcy's law for one-dimensional flow. Several sets of geologic conditions representing possible conditions in the valley were considered. Vertical flow to the St. Peter aquifer was calculated from a range of vertical hydraulic conductivity values. The range represented a variety of hydrologic conditions from the presence of a full thickness of Glenwood Shale to permeable glacial drift directly overlying St. Peter. Table 4 shows the vertical and horizontal hydraulic conductivities and the thickness of the hydrologic units overlying the St. Peter aquifer.



EXPLANATION

AREA WHERE ST. PETER AQUIFER IS MISSING

—850— SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude of potentiometric surface. Contour interval 10 feet. Datum is sea level

• LOCATION OF WELL

Figure 11.--Simulated potentiometric surface of the St. Peter aquifer before 1979.

Table 4.--*Vertical and horizontal hydraulic conductivity values and thickness of the aquifers and confining units overlying the St. Peter aquifer*

Hydrologic unit	Vertical hydraulic conductivity (feet per second)	Horizontal hydraulic conductivity (feet per second)	Thickness (feet)
Glacial drift	[c] 3.1×10^{-8} [a] 1.6×10^{-4}	[a] 3.1×10^{-7} [c] 1.6×10^{-3}	[a] 55-70
Glacial till	[b] 3.0×10^{-9}	[c] 3.3×10^{-8}	[c] 0-5
Platteville aquifer	[c] 1.1×10^{-4}	[a] 1.1×10^{-3}	[b] 0-35
Glenwood confining unit	[a] 3.3×10^{-10}	[c] 3.3×10^{-9}	[b] 0-7
St. Peter aquifer	[e] 3.1×10^{-5}	[d] 3.1×10^{-4}	[b] 100

Sources of hydraulic conductivities and thicknesses.

[a] From U.S. Geological Survey District files

[b] From Hult (1984)

[c] Assumed value

[d] From Moog (1962)

[e] From Stark and Hult (1985)

Several stratigraphic sequences were analyzed to determine rates of leakage into the St. Peter aquifer. The results are listed below using summer-season hydraulic-head conditions.

1. Greatest leakage (12.0 in/yr) occurs in bedrock valleys where drift with a vertical hydraulic conductivity of 1.6×10^{-3} ft/s (feet per second) was simulated overlying a thin (5-ft thick) layer of till.

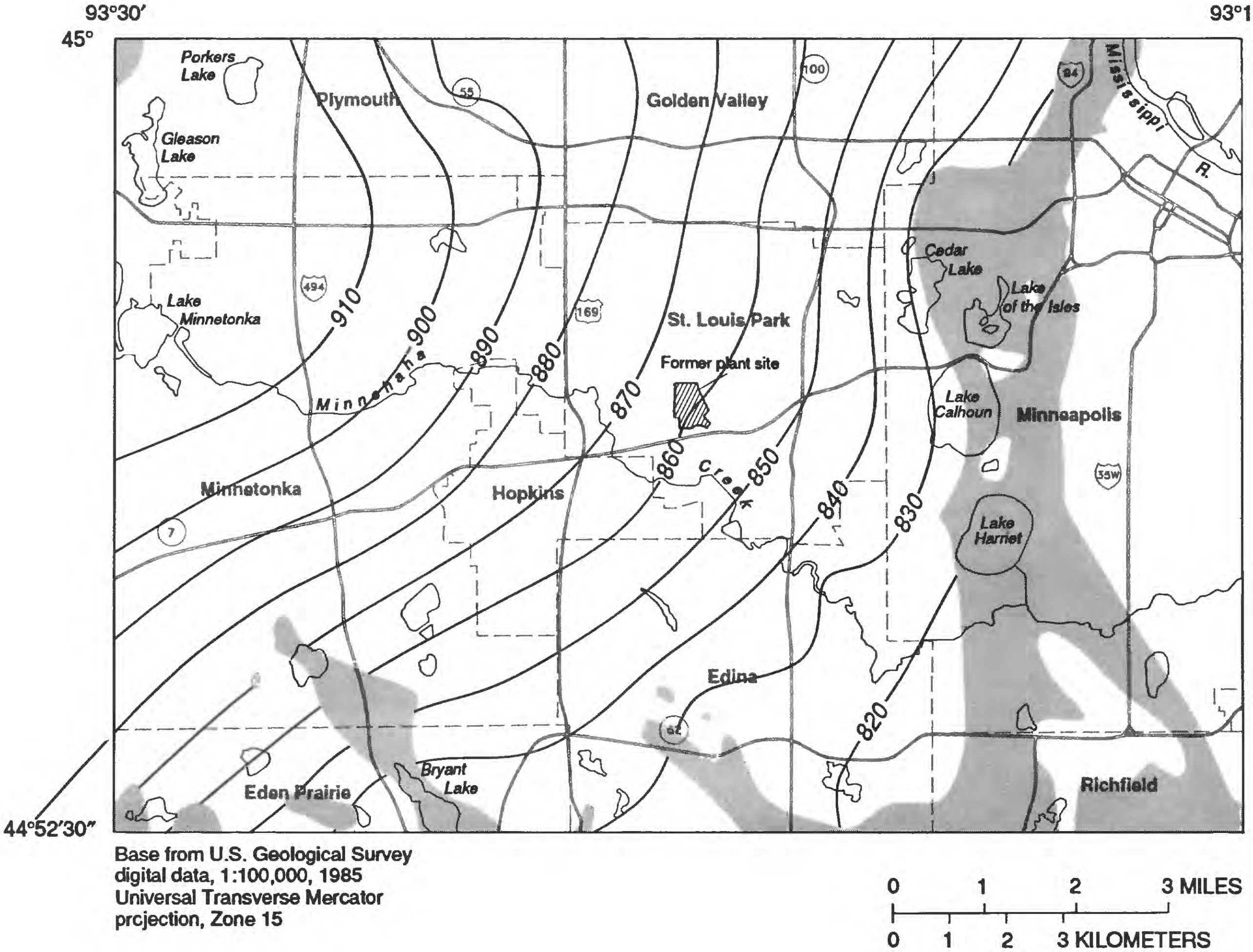
2. Fine-grained drift is more typical of conditions observed from wells drilled in the valley (M. F. Hult, U.S. Geological Survey, oral commun., 1987). This was simulated with 5 ft of till overlying 15 ft of low-conductivity drift (K_v=3.1×10^{-8} ft/s). This sequence resulted in a leakage rate of 9.1 in/yr.

3. The lowest rate of leakage simulated was a 7-ft-thick layer of Glenwood Shale and overlying drift of low hydraulic conductivity. This yielded a 0.9-in/yr leakage rate.

4. A more typical low value was assumed by simulating a 3-ft-thick layer of Glenwood Shale. This resulted in a leakage rate of 2.0 in/yr.

Figure 10 shows the simulated potentiometric surface for the summer of 1985 in the St. Peter aquifer when leakage to the St. Peter aquifer was specified as 5.5 in/yr. Figure 12 shows the simulated potentiometric surface when leakage was increased to 9.1 in/yr over areas of drift-filled bedrock valleys and held at 5.5 in/yr in areas where the St. Peter aquifer is overlain by the Platteville aquifer and Glenwood confining unit. Figure 13 shows the simulated potentiometric surface when a leakage rate of 9.1 in/yr was used over areas of bedrock valleys and a leakage rate of 2.0 in/yr was used in areas where the St. Peter aquifer is overlain by the Platteville aquifer and Glenwood confining unit. The altitude of the simulated potentiometric surface shown in figure 12 is higher than measured head (table 3) and higher than the calibrated potentiometric surface shown in figure 10. The potentiometric surface shown in figure 13 is lower in the northwest and slightly higher in the southeast than the potentiometric surface shown in figure 10 and the measured heads

Comparisons of figures 10, 12, and 13 indicate that a vertical leakage of 9.1 in/yr simulated for bedrock valleys is probably too high, even when used in conjunction with a leakage rate of 2.0 in/yr in confined areas. Several factors related to the location and structure of the bedrock valleys could complicate the model results. The exact location of the valleys is not precisely known. Field data are not sufficient to define, with precision, the stratigraphic sequence in the bedrock valleys. The valleys probably are filled with till and fine sand (M.F. Hult, U.S. Geological Survey, oral commun., 1987). Because of the high transmissivity of all hydrogeologic units in the upper model layer, and the uncertainty about the location and material filling bedrock valleys, a uniform value of leakage from the glacial-drift aquifer to the St. Peter aquifer was simulated with a uniform value of 5.5 in/yr in all subsequent simulations.

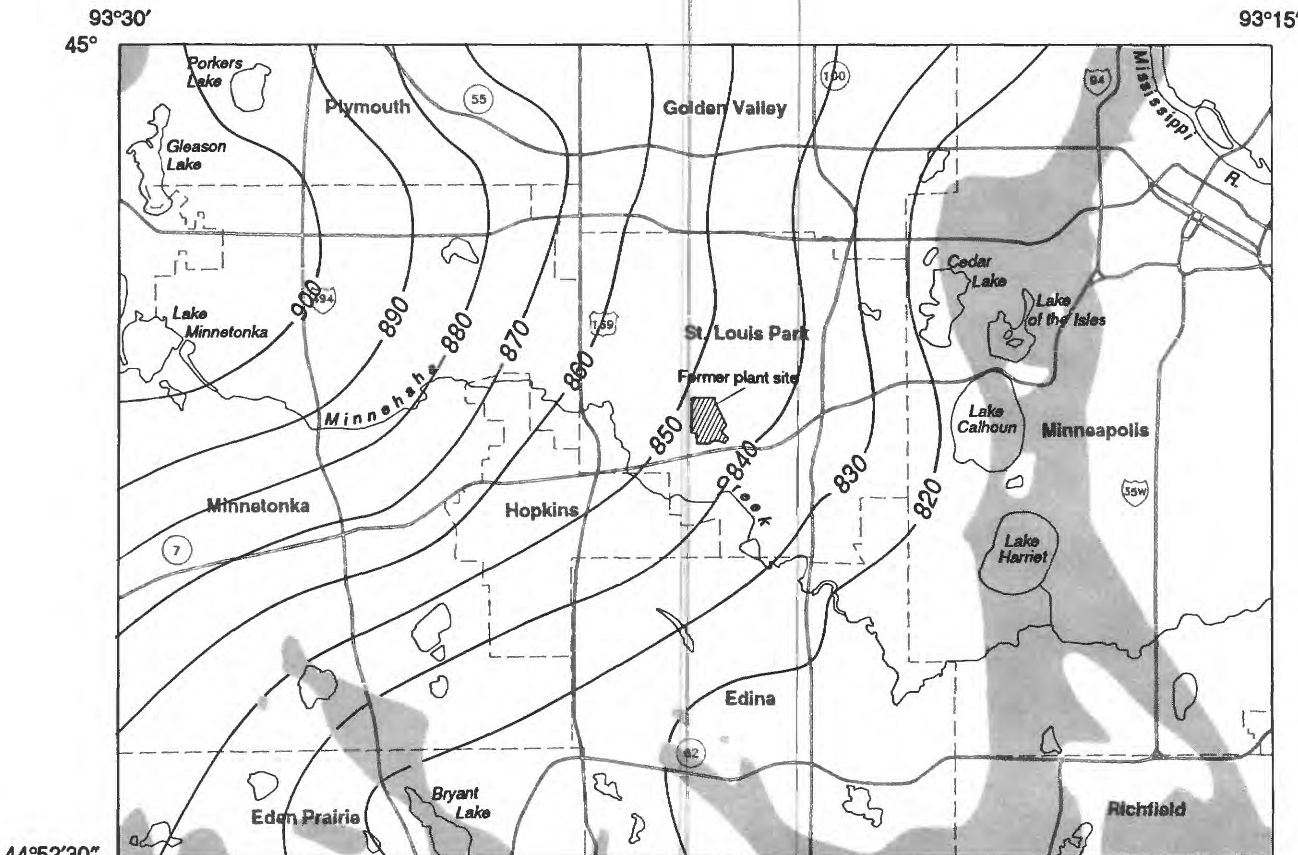


EXPLANATION

AREA WHERE ST. PETER AQUIFER IS MISSING

—850— SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude of potentiometric surface. Contour interval 10 feet. Datum is sea level

Figure 12.--Simulated potentiometric surface of the St. Peter aquifer that resulted from a leakage rate of 9.1 inches per year over areas of bedrock valleys and 5.5 inches per year where the St. Peter aquifer is overlain by the Glenwood confining unit.



Base from U.S. Geological Survey digital data, 1:100,000, 1985 Universal Transverse Mercator projection, Zone 15

0 1 2 3 MILES
0 1 2 3 KILOMETERS

EXPLANATION

AREA WHERE ST. PETER AQUIFER IS MISSING

—*850*— SIMULATED POTENTIOMETRIC CONTOUR-- Shows altitude of potentiometric surface. Contour interval 10 feet. Datum is sea level

Figure 13.--Simulated potentiometric surface of the St. Peter aquifer that resulted from a leakage rate of 9.1 inches per year over areas of bedrock valleys and 2.0 inches per year where the St. Peter aquifer is overlain by the Glenwood confining unit.

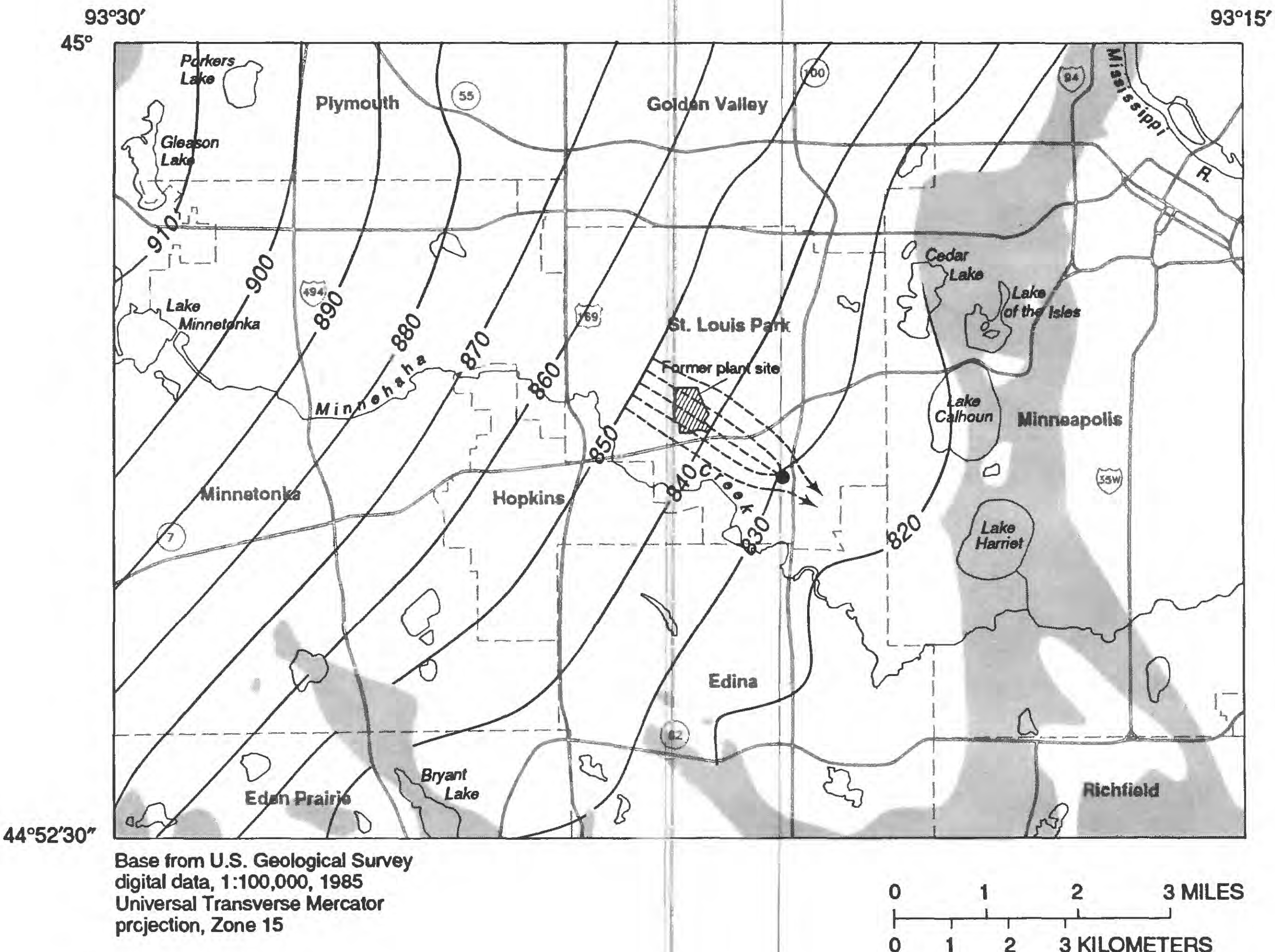
Pumping Alternatives for Controlling Ground-Water Flow

The intent of proposed gradient control in the St. Peter aquifer is to confine or reduce the volume of contaminated ground water by locating one or more wells downgradient from the source and pumping at a rate to include the area under the plant site within the zone of contribution to the wells (Justin Blum, Minnesota Pollution Control Agency, oral commun., 1988). Simulations of options to accomplish this goal were limited to simulations involving withdrawal of water from one to several wells. The assumption was made that contaminants in the St. Peter aquifer are located under or immediately downgradient from the plant site. Because of a lack of sampling points in the St. Peter aquifer, this assumption can not be verified. Withdrawals from multiaquifer and production wells, and the influence of bedrock valleys probably have created a complex distribution of contamination in the St. Peter aquifer. The contaminants probably have already migrated considerable distances downgradient.

Steady-state simulations were conducted to estimate the effect of pumping hypothetical gradient-control wells on the potentiometric surface of the St. Peter aquifer in the summer of 1985 (fig. 10). Simulations of gradient-control alternatives were conducted as steady-state simulations using summer pumping rates because (1) spring and summer simulations approach equilibrium at the end of the pumping season, (2) differences between the spring and summer potentiometric surfaces are of the same magnitude as the degree of uncertainty in water levels measured in wells, (3) pumping stress is greatest during the summer season, and (4) the seasonal changes in pumping rates and boundary conditions do not significantly alter the general configuration of the potentiometric surface (figs. 9 and 10). Simulated gradient-control wells are located southeast of the plant site because simulations were limited to the downgradient movement of water flowing under the plant site.

The simplest simulated gradient-control option consisted of a well located downgradient from the plant site. The well was located approximately 3,100 ft southeast of the former plant site. Two pumping rates were simulated (figs. 14 and 15). Figure 14 shows the simulated potentiometric surface and associated flow lines for a well pumped at 75 gal/min. The flow lines shown on figure 14 indicate that this pumping rate is not sufficient to create a zone of contribution that intercepts all the flow under the area of the former plant site. Increasing the pumping rate to 150 gal/min (fig. 15) increased the width of the zone of contribution significantly.

Figures 16 and 17 show the potentiometric surface and flow lines for simulations including two gradient-control wells located about 3,000 ft southeast of the plant site. The wells are about 1,000 ft apart. Figure 16 shows the simulated potentiometric surface for pumping rates of 75 gal/min, figure 17 for rates of 50 gal/min. Both figures indicate that these pumping rates will create a zone of contribution that captures water flowing under the entire area of the plant site.



EXPLANATION

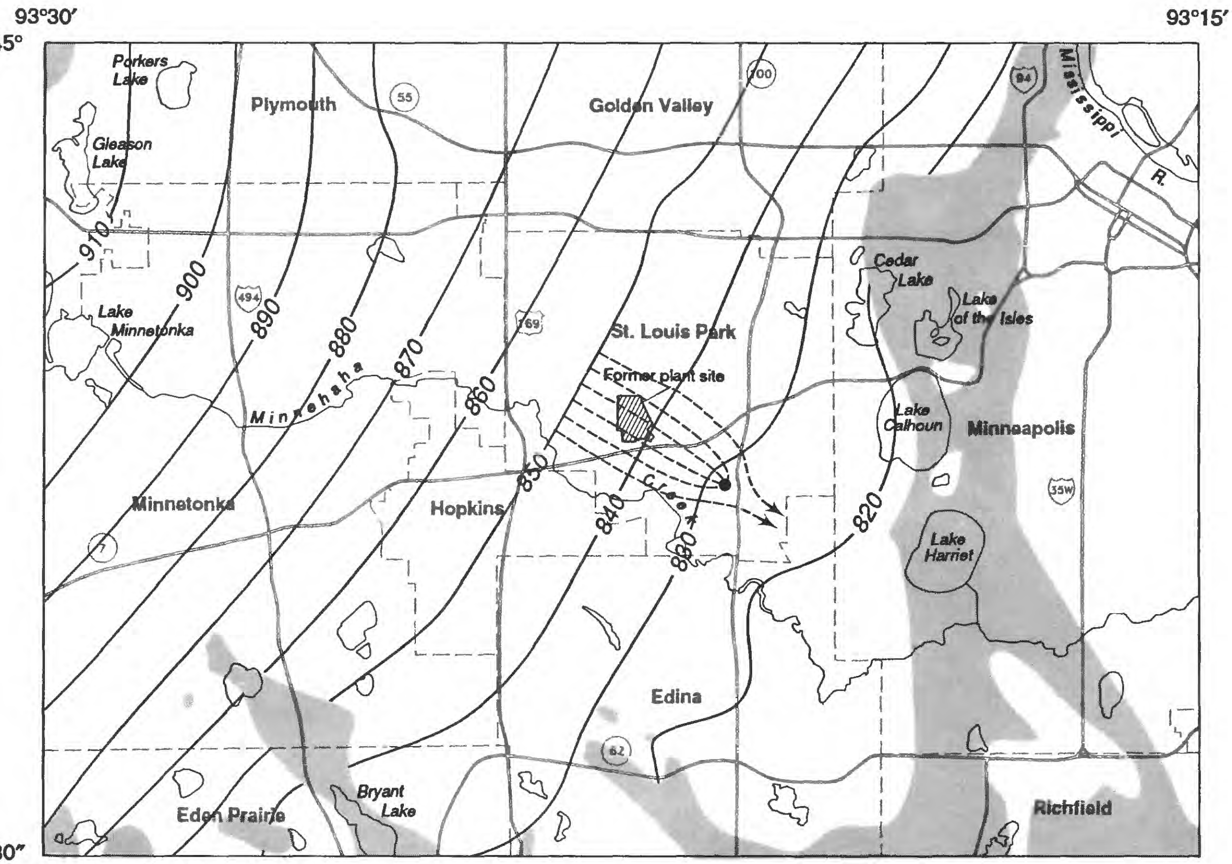
AREA WHERE ST. PETER AQUIFER IS MISSING

—850— SIMULATED POTENTIOMETRIC CONTOUR-- Shows altitude of potentiometric surface. Contour interval 10 feet. Datum is sea level

------> GROUND-WATER FLOW PATH

● LOCATION OF GRADIENT-CONTROL WELL

Figure 14.--Simulated potentiometric surface of the St. Peter aquifer, summer 1985, one well pumped at 75 gallons per minute.



Base from U.S. Geological Survey digital data, 1:100,000, 1985
Universal Transverse Mercator projection, Zone 15

EXPLANATION

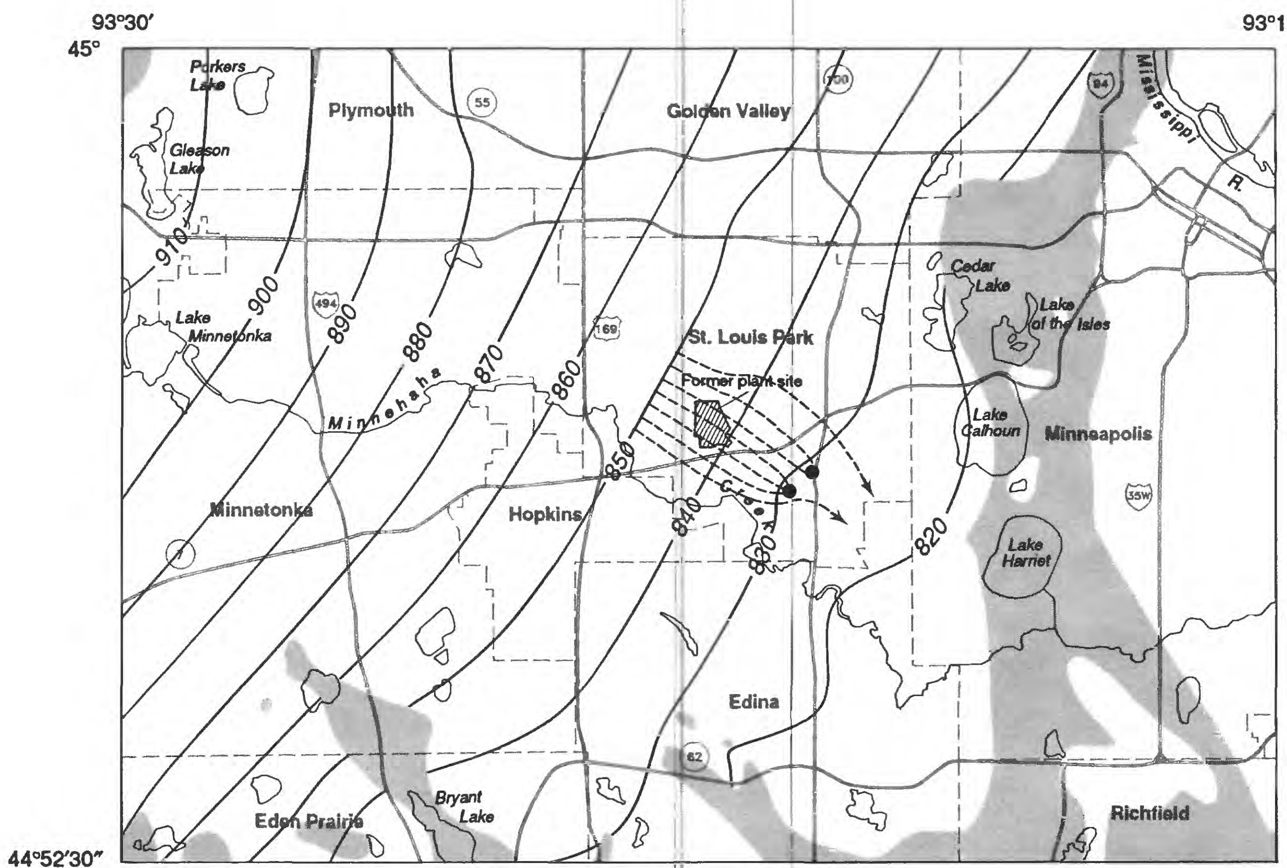
AREA WHERE ST. PETER AQUIFER IS MISSING

—*850*— SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude of potentiometric surface. Contour interval 10 feet. Datum is sea level

------➤ GROUND-WATER FLOW PATH

● LOCATION OF GRADIENT-CONTROL WELL

Figure 15.--Simulated potentiometric surface of the St. Peter aquifer, summer 1985, one well pumped at 150 gallons per minute.



EXPLANATION

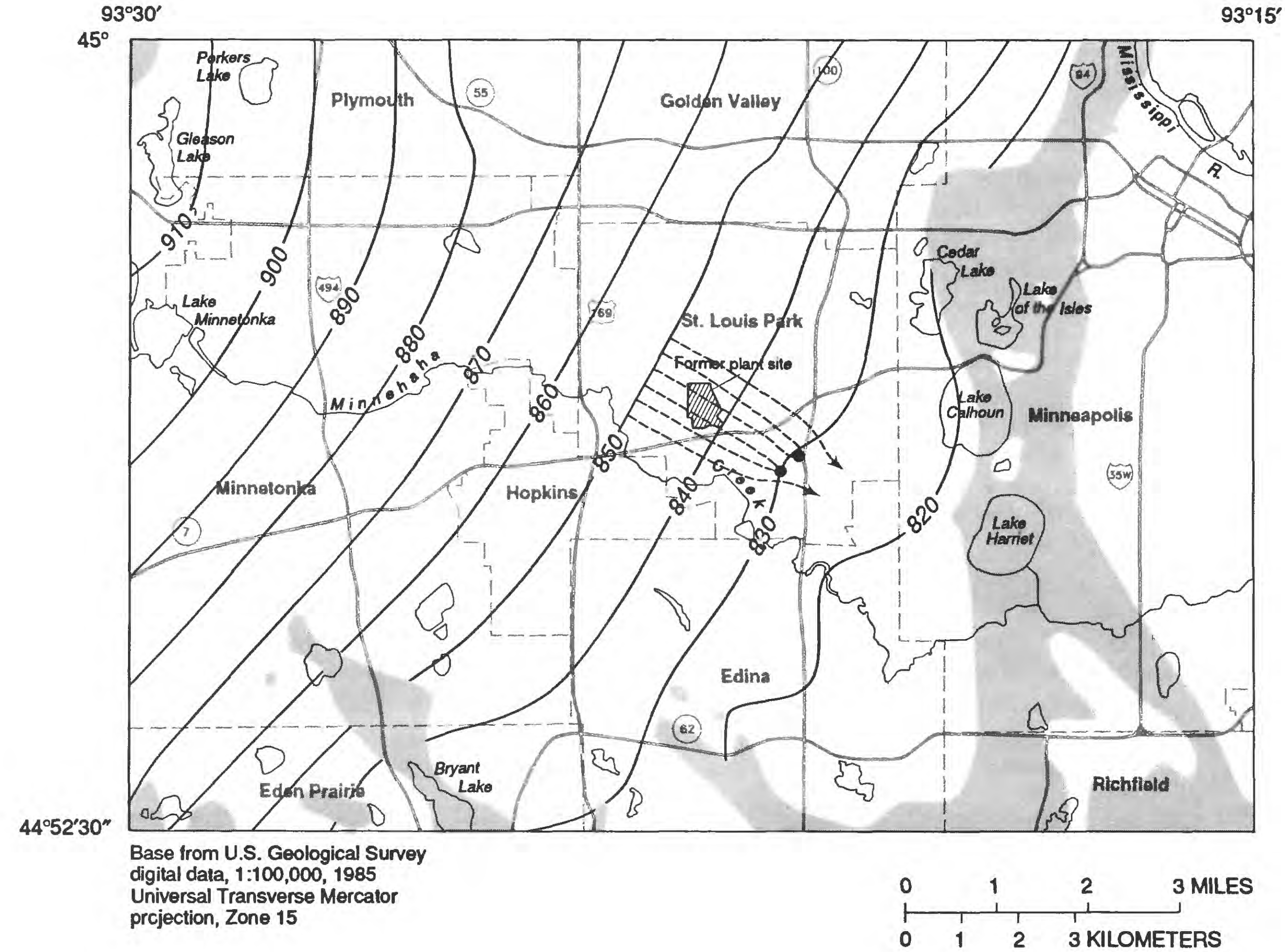
AREA WHERE ST. PETER AQUIFER IS MISSING

—*850*— SIMULATED POTENTIOMETRIC CONTOUR-- Shows altitude of potentiometric surface. Contour interval 10 feet. Datum is sea level

------> GROUND-WATER FLOW PATH

● LOCATION OF GRADIENT-CONTROL WELL

Figure 16.--Simulated potentiometric surface of the St. Peter aquifer, summer 1985, two wells each pumped at 75 gallons per minute.



EXPLANATION

AREA WHERE ST. PETER AQUIFER IS MISSING

—*850*— SIMULATED POTENTIOMETRIC CONTOUR-- Shows altitude of potentiometric surface. Contour interval 10 feet. Datum is sea level

------→ GROUND-WATER FLOW PATH

● LOCATION OF GRADIENT-CONTROL WELL

Figure 17.--Simulated potentiometric surface of the St. Peter aquifer, summer 1985, two wells each pumped at 50 gallons per minute.

Simulations indicate that each 50-gal/min incremental increase of pumping from proposed wells will increase the width of the zone of contribution in the St. Peter aquifer by approximately 900 ft in the area of the plant site. Because the plant site is about 1/2 mi wide, a total pumping rate of 150 gal/min downgradient from the plant site would be adequate to capture water in the St. Peter aquifer flowing under the plant site. The option of using two wells, each pumped at 75 gal/min (fig. 16), appears to be most efficient. Bedrock valleys located southeast of the plant site could be an additional source of contamination to the St. Peter aquifer through leakage from the overlying glacial-drift aquifer. Two additional wells located downgradient from the bedrock valleys would ensure that water moving downward into the St. Peter aquifer from overlying aquifers does not flow to the southeast.

SUMMARY AND CONCLUSIONS

Ground water in the St. Peter aquifer, St. Louis Park, Minnesota, was contaminated by chemicals from a coal-tar distillation and wood-preserving plant that operated during 1918-72. Coal-tar derivatives--a mixture of many compounds--are the major contaminants.

A three-dimensional, ground-water-flow model of the St. Peter and Prairie du Chien-Jordan aquifers in St. Louis Park, Minnesota was used to aid in understanding gradient-control options for the St. Peter aquifer. The original model was described in Stark and Hult (1985). The model described here was calibrated for steady state conditions by matching simulated heads to measured heads in the St. Peter aquifer in the spring of 1980.

The model was used to examine the effect of several gradient-control options for capturing water flowing in the St. Peter aquifer under the plant site. Two wells, located about 3,000 ft southeast of the plant site, each pumping at a rate of 75 gal/min, were found to be effective for that purpose.

The volume of contaminated water in the St. Peter aquifer is assumed to be primarily under and downgradient from the plant site. However, contaminants probably have been transported beyond the zone of contribution of these wells by a poorly understood and complex set of hydraulic conditions that prevail in the vicinity of the plant site.

Because the St. Peter aquifer is not currently used extensively for water supply within the model area, the potential effect on the potentiometeric surface from nearby wells are negligible. Future pumping from wells in the area could alter the effectiveness of the proposed gradient-control plan.

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