GROUND-WATER FLOW IN THE PRAIRIE DU CHIEN-JORDAN AQUIFER RELATED TO CONTAMINATION BY COAL-TAR DERIVATIVES, ST. LOUIS PARK, MINNESOTA

By J. R. Stark and M. F. Hult

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CONVERSION FACTORS

For readers who prefer to use metric (International System) units, conversion factors for the inch-pound units used in this report are listed below:

Multiply inch-pound unit	By	To obtain metric unit
foot (ft)	0.3048	meter (m)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
gallon per minute (gal/min)	0.06308	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
inch per year (in./yr)	25.40	millimeter per year (mm/yr)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)

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ABSTRACT

A three-dimensional, ground-water-flow model of the Prairie du Chien-Jordan aquifer and associated hydrogeologic units was developed to evaluate the movement of coal-tar derivatives from a coal-tar distillation and wood-preserving plant in St. Louis Park, Minnesota. A finite-difference grid was superimposed on the modeled area, which includes most of eastern Hennepin County. The individual cells are 400-foot squares in the center of the grid (St. Louis Park area); the cells increase in dimension toward the outside limits of the grid. Five geologic units are represented by four layers in the model. These units include the Jordan Sandstone, the Prairie du Chien Group (dolomite and sandy dolomite), the basal confining unit of the St. Peter Sandstone (silty and sandy shale), the St. Peter Sandstone, and glacial deposits in bedrock valleys.

The model was calibrated for steady-state conditions for a period before significant ground-water development (1885-1930) and for a period of significant pumping stress (winter conditions, 1970's). A transient calibration was accomplished by simulation of a period during which seasonal changes in potentiometric head in the Prairie du Chien-Jordan aquifer were significant (1977-80). Sensitivity testing indicated that leakage to the upper model layer and the vertical hydraulic conductivity of the basal confining unit of the St. Peter Sandstone were the model hydrologic properties which, when changed, resulted in the greatest changes in model-calculated water levels. The calibrated model generally calculates water levels that are within 10 feet of measured values.

Model simulations indicate that the potentiometric surface of the Prairie du Chien-Jordan aquifer would be raised by as much as 3 feet in the area of the plant site by water introduced into the aquifer through wells open to more than one aquifer system. The cones of impression created at these wells could have a significant impact on the transport of contaminants in the Prairie du Chien-Jordan.

The presence of coal-tar derivatives in the aquifer has been difficult to explain in wells located upgradient from the plant site to the north, west, and southwest. Simulations suggest that, during periods of heavy withdrawal from certain of these wells (SLP10, SLP15, and SLP5), local hydraulic gradients may have been altered, resulting in the potential for the movement of contaminants from the area of the plant site to the wells. Cones of impression at multi-aquifer wells near the plant site contributed to the alteration of local gradients.

Simulation of a proposed gradient-control plan, in which lateral homogeneity and isotropy of individual hydrogeologic units was assumed, indicates that the actions would be effective in limiting expansion of the contaminated volume in the Prairie du Chien-Jordan aquifer. The plan includes the control of withdrawal from five wells. The simulations also show, however, that model-calculated potentiometric surfaces are sensitive to changes in withdrawal rates at wells not intended to be under the control of the plan. Management of discharge from these wells also will be important to overall effectiveness of the remedial-action plan.

INTRODUCTION

Ground water in the Prairie du Chien-Jordan 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 complex mixture of more than 1,000 compounds--are the major contaminants. These compounds are, for the most part, denser than water. A class of these compounds--PAH (polynuclear aromatic hydrocarbons)--are of particular concern to human health because they are carcinogenic (U.S. Environmental Protection Agency, 1980). The use of several municipal water-supply wells has been discontinued because water from these wells contains PAH compounds. Remedial measures to limit the spread of contaminants in the Prairie du Chien-Jordan aquifer, are being planned by the MPCA (Minnesota Pollution Control Agency). A ground-water-flow model, developed during this study, is being used by the MPCA in locating well sites for contaminant-source control (to limit additional inputs of contaminants to the aquifer) and for gradient control (to limit further migration of contaminants in the aquifer) and in designing pumping rates for those wells.

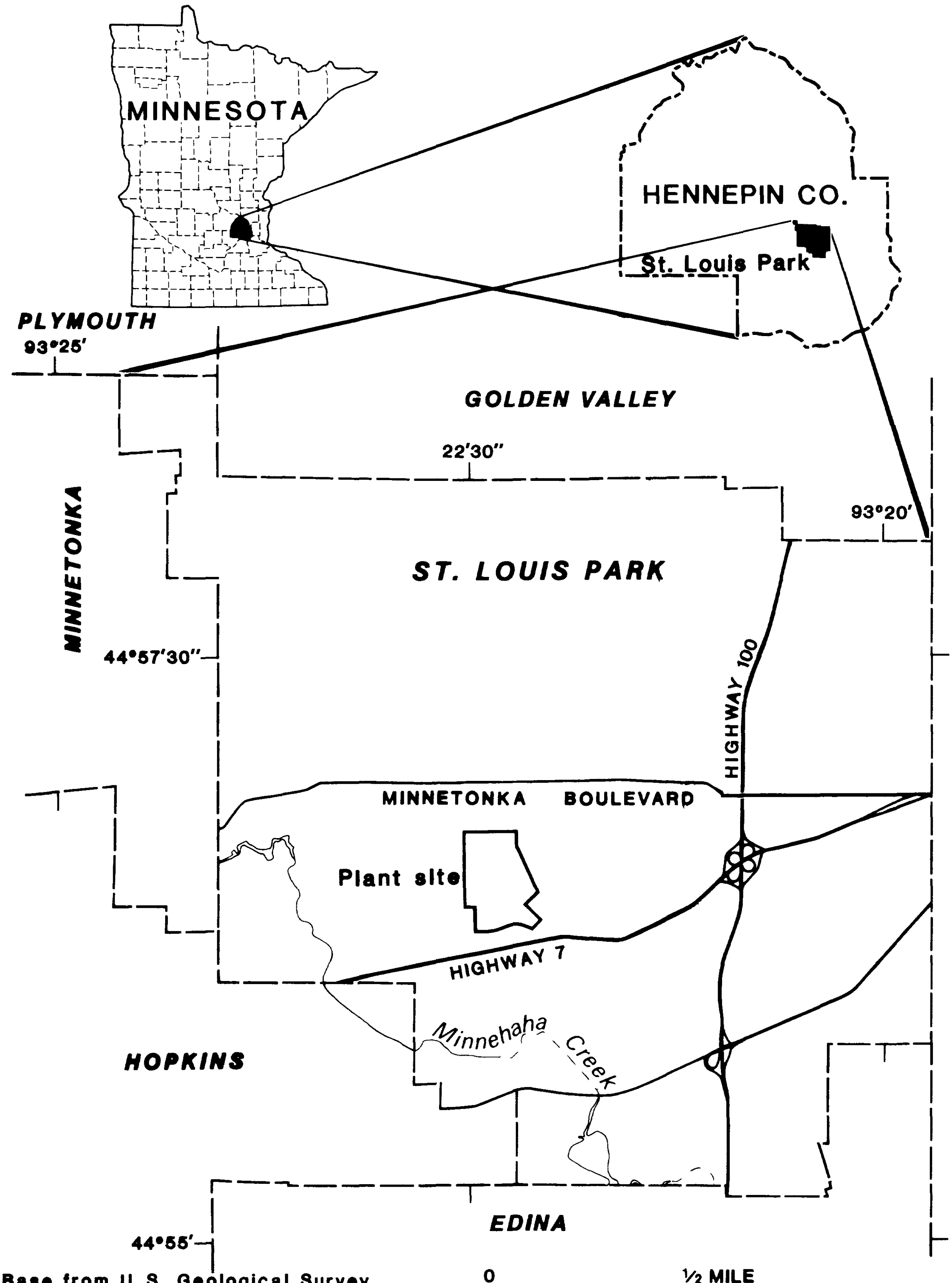
This report is one in a series of reports by the U.S. Geological Survey that document ground-water contamination at St. Louis Park. Hult and Schoenberg (1984) and Hult (U.S. Geological Survey, written commun., 1983) present an overview of the problem and summarize the current understanding of the ground-water hydrology of the area.

Purpose and Scope

This report describes the construction, calibration, testing, and application of a numerical model that simulates ground-water flow in the Prairie du Chien-Jordan aquifer in the St. Louis Park area and in hydrogeologic units that overlie and interact hydraulically with the aquifer, in order to study the movement of coal-tar derivatives in the aquifers. The report evaluates consequences of modifying current pumping strategies and increasing pumping by installing new wells. The hydrogeology of the area is presented as background for describing the model's construction.

Location and Description of Area

The site of the former coal-tar distillation and wood-preserving plant is in St. Louis Park, Hennepin County, Minn., (fig. 1). The city adjoins Minneapolis on the east and the cities of Golden Valley, Minnetonka, Hopkins and Edina on the north, west, south, and southeast, respectively.



Base from U. S. Geological Survey
Hopkins and Minneapolis South; both
maps 1:24,000, 1967 (Photorevised 1972)

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

In this report the term "plant site" refers to the approximately 80-acre tract on which the plant was located (fig. 1). The term "study area" refers to the geographic extent of the Prairie du Chien-Jordan aquifer in Hennepin County. This area is between Lake Minnetonka to the west, the Minnesota and Mississippi Rivers to the south and the east, and a latitude of 45° 05' to the north.

History of Contamination

Ground-water contaminants from a coal-tar distillation and wood-preserving plant have degraded the quality of water in several aquifer systems in the St. Louis Park area. The upper aquifer system in the drift and Platteville limestone has been contaminated by coal-tar derivatives. Hult and Schoenberg (1984) reported that these contaminants percolated to the water table from ponds and wetlands that received runoff and process water from the plant. Although this aquifer system is not extensively used for water supply, water from the system has contributed to contamination of deeper aquifers by downward leakage and by flow in multiaquifer wells which connected more than one aquifer.

The Prairie du Chien-Jordan aquifer, the most highly utilized aquifer in the Minneapolis-St. Paul Metropolitan Area, is relatively well protected from near-surface sources of contamination. In the St. Louis Park area, the aquifer is from 250 to 500 feet below land surface and is overlain by drift, two bedrock aquifers, and two bedrock confining units. Contamination of the Prairie du Chien-Jordan aquifer primarily resulted from direct discharges of coal-tar materials in wells open to the aquifer and by flow through wells open to the Prairie du Chien-Jordan and overlying aquifers (Hult and Schoenberg, 1984).

Contamination of the Prairie du Chien-Jordan aquifer was first documented in 1932 when the city of St. Louis Park completed its first municipal well, [St. Louis Park old well 1 (W112)] in the aquifer (Hult and Schoenberg, 1984). This well, located about 3,500 feet east of the plant site (fig. 2), produced water with a coal-tar taste. In 1933, efforts to reconstruct the well to eliminate the contamination problem failed and use of the well was discontinued. A driller's report from that time implied that the probable cause of contamination in the well was from wells at the plant site, which were being used to drain wastes from the plant into the ground (Hult and Schoenberg, 1984). Several other wells completed in the Prairie du Chien-Jordan aquifer during the 1930's, generally located to the east of the plant site, also produced water with a coal-tar taste and odor.

In 1946, St. Louis Park completed another municipal well, SLP4 (fig. 2), in the Prairie du Chien-Jordan aquifer (Hult and Schoenberg, 1984). Concentrations of phenolic compounds in water from the well were reported to be 0.10 mg/L (milligrams per liter) but decreased rapidly after several months of use. In 1953, the bore of a well (W23) on the plant site (fig. 2) that was open to the Prairie du Chien-Jordan aquifer, was found to contain coal tar. Evidence suggests that a spill into the well may have occurred approximately 1930 (Hult and Schoenberg, 1984). Efforts to remove the tar by cable-tool drilling techniques were unsuccessful, and a liner was installed in the well in an attempt

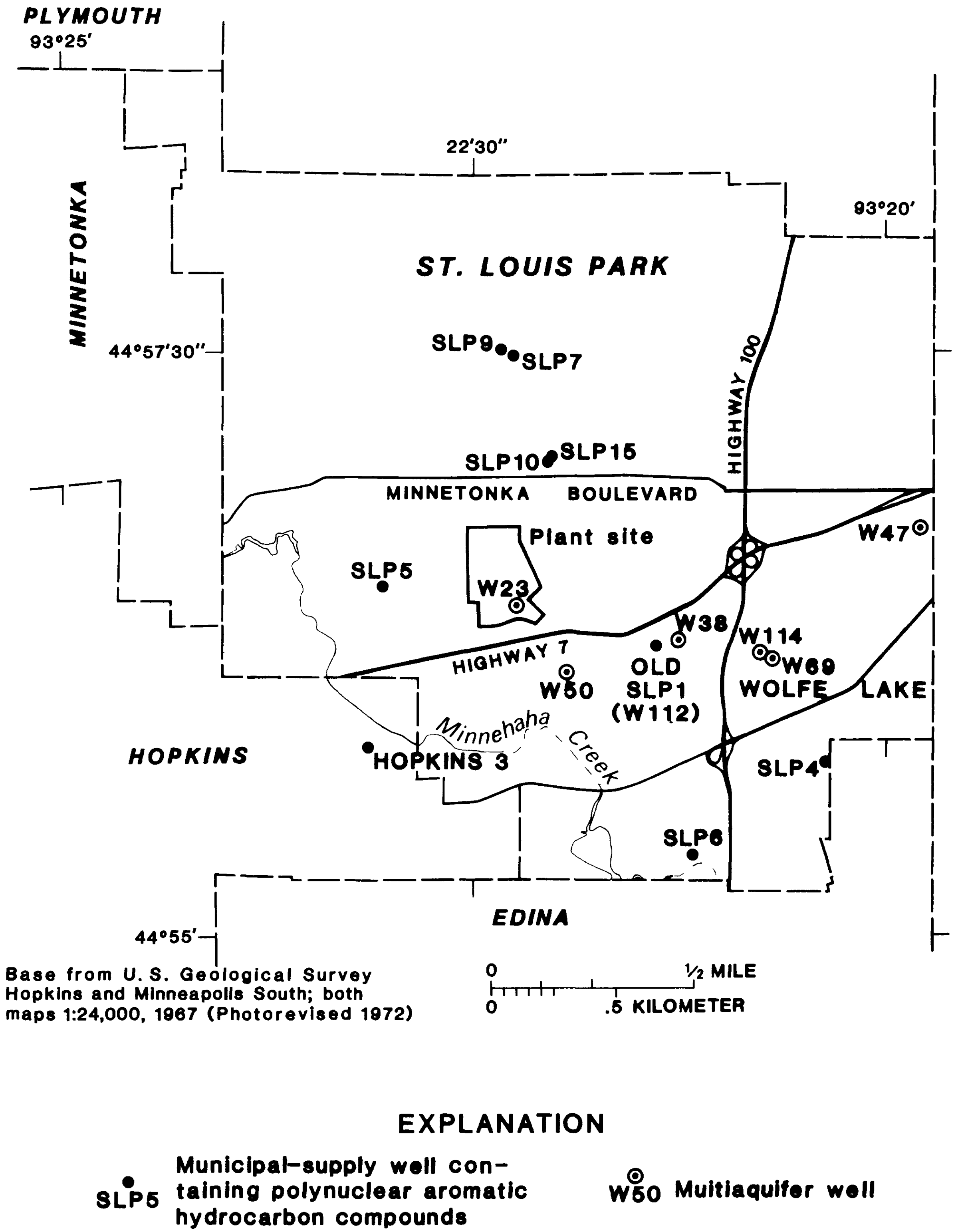


Figure 2.--Selected observation wells near the plant site

to keep contaminated water from entering the Prairie du Chien-Jordan aquifer. Sunde (1974) concluded that contamination of the deeper aquifers resulted from flow-through wells that penetrated more than one aquifer.

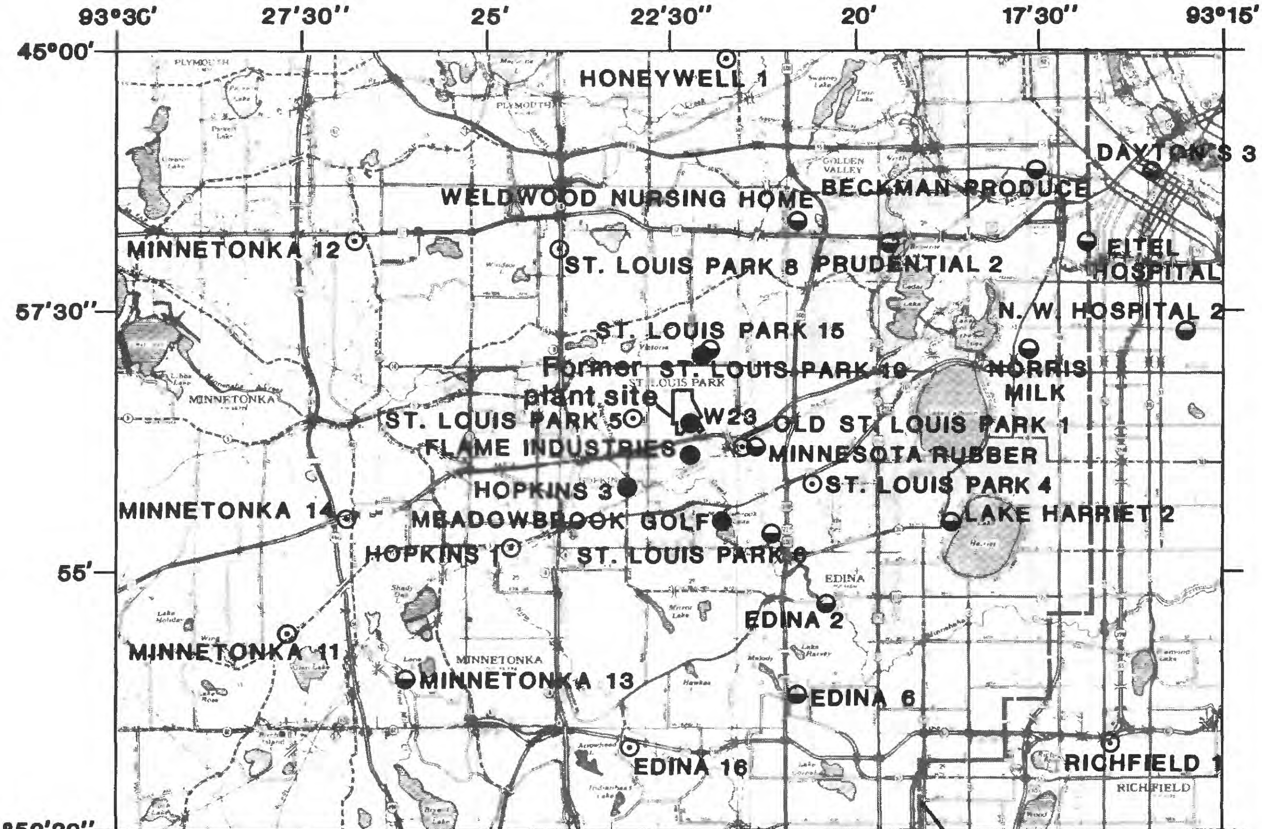
In 1978, PAH compounds were documented in water from five St. Louis Park municipal wells. Use of four of these wells (SLP7, SLP9, SLP10, and SLP15) was discontinued (fig. 2). During 1979 through 1980, three additional wells were removed from active use [SLP4, SLP5, and Hopkins 3; (fig. 2)]. The U.S. Geological Survey began a study in 1978 to evaluate the effects of multiaquifer wells. Six wells that connect the Prairie du Chien-Jordan aquifer with overlying aquifers were located and evaluated (fig. 2). Flow rates, estimated by geophysical logging and inspection with a television camera, ranged from 20 to 150 gal/min. The greatest flow rate was measured in well W23--the well on the plant site that was found, in 1983, to contain more than 100 feet of coal tar. Each of these wells had an effect on water levels near the well and, therefore, the local direction of water movement in the aquifers that were interconnected by the wells (Hult and Schoenberg, 1984). In addition, four of these wells were in areas where the bedrock aquifers are contaminated and were pathways for contaminant transport into the Prairie du Chien-Jordan aquifer. Each of these wells has been permanently or temporarily sealed (Hult and Schoenberg, 1984).

Contaminants in the Prairie du Chien-Jordan aquifer have moved at least 2 miles northeast and southeast of the plant site (fig. 3). The direction and rate of contaminant movement changes with time because hydraulic head in the Prairie du Chien-Jordan aquifer continually adjusts to stresses caused by ground-water withdrawals and flow through wells that connect more than one aquifer. Contaminants move rapidly through the upper part of the Prairie du Chien, which is a carbonate rock having fracture and solution-channel permeability and low effective porosity. Consequently, water pumped from wells completed in this aquifer has concentrations and composition of contaminants that commonly fluctuate with time.

Previous Investigations

Numerous studies have been made of various aspects of the contamination problems in St. Louis Park. In 1933, an investigation by McCarthy Well Company concluded that contamination was coming from the plant site through "several old wells being used to drain creosote away into the ground" (files of the U.S. Geological Survey, Minnesota District, St. Paul). A report by the Minnesota Department of Health (1938) identified nine wells in the area with either a phenolic or tar-like taste. Hickok (1969) reported that in 1946 the concentration of phenolic compounds in water from St. Louis Park well 4 (SLP4), completed in the Prairie du Chien-Jordan aquifer, was 0.10 mg/L.

Sunde (1974) concluded, in a general evaluation of the problem, that contamination in the deeply buried bedrock aquifers resulted from flow through wells connecting more than one aquifer. The Minnesota Department of Health (1974) reported on the water quality of private, industrial, and municipal wells in the area. A compilation of available geological information on the



Base from Minnesota Department of Highways General Highway Map of Hennepin County, 1977

0 1 2 MILES
0 1 2 3 KILOMETERS

EXPLANATION

DISTRIBUTION OF POLYNUCLEAR AROMATIC HYDROCARBON

● W23 — Sample contained at least 400 nanograms per liter of PAH analytes

◓ NORRIS MILK — All PAH analytes below detection limits for GC/MS (gas chromatography with mass spectrometry) methods used. Concentrations of one or more analytes greater than 28 nanograms per liter as measured by HPLC (high performance liquid chromatography)

⊙ EDINA 16 — All PAH analytes below detection limits for GC/MS methods used. Concentrations of individual PAH analytes measured by HPLC below 28 nanograms per liter.

Note: All samples were analyzed using gas chromatography with mass spectrometry (GS/MS). Extracts of samples that did not contain any of 12 specific PAH (polynuclear aromatic hydrocarbons) above the MDL (method detection limits) were reanalyzed using HPLC (high performance liquid chromatography)

Figure 3.--Distribution of PAH (polynuclear aromatic hydrocarbon) compounds in the Prairie du Chien-Jordan aquifer

St. Louis Park area was completed by Olson and others (1974). National Biocentric (1976a; 1976b) analyzed drift materials underlying the northern part of the site for organic contaminants.

Barr (1976; 1977) recommended specific remedial actions to control ground-water contamination in the drift. They also concluded that the occurrence of phenolic compounds in certain municipal wells completed in the Prairie du Chien-Jordan aquifer could not be explained. The Minnesota Department of Health (1977; 1978) measured the concentrations of PAH in municipal water supplies, assessed the health-risk implications, and outlined additional data needs.

In 1978, the U.S. Geological Survey began a study to evaluate the geology, hydrology, chemistry, and biology of the plant-site area. Several reports have been published or are in preparation. Hult and Schoenberg (1984) presented a preliminary evaluation of the contamination problem. Ehrlich and others (1982) discussed the degradation of phenolic contaminants in ground water by anerobic bacteria.

Hickok and others (1981) presented findings, preliminary designs, and expense estimates for remedial actions relating to ground-water and soil contamination. Environmental Research and Technology (1983) described a comprehensive plan for remedial action for the St. Louis Park problem.

HYDROGEOLOGY AND HYDROLOGY OF MODEL AREA

The Prairie du Chien-Jordan aquifer is part of a thick sequence of sedimentary rocks that were deposited in a north-south trending trough in the Precambrian rock surface. These sedimentary rocks, which range in age from Precambrian to Ordovician, occupy what commonly is referred to as the Twin Cities artesian basin (Guswa and others, 1982). The thickest sequence of these rocks lies over the deepest part of the basin, directly beneath the Twin Cities. There is no evidence of deposition in the Twin Cities area from Late Ordovician to Quaternary time. The present land surface is composed primarily of glacial drift.

Six hydrogeologic units, lying stratigraphically above the Mount Simon-Hinckley aquifer, have been defined from the geologic units that underlie the study area. The vertical distribution of the nine rock-stratigraphic units that comprise the hydrogeologic units in the Twin Cities area is illustrated in figure 4.

The Jordan Sandstone is a white to yellowish-white, fine- to medium-grained, quartz-rich sandstone. The Prairie du Chien Group consists of dolomite, shale, and sandy dolomite. Within the study area, the Prairie du Chien-Jordan aquifer ranges in thickness from 0 feet where the units have been removed by glacial or preglacial erosion to 160 feet. The aquifer overlies the St. Lawrence-Franconia confining unit, a thick sequence of siltstone, sandstone, shale and dolomite, and is overlain by the basal confining unit of the St. Peter aquifer, or by glacial drift, where the St. Peter has been removed by erosion. The relationship of these hydrogeologic units to the geologic units is illustrated in table 1. The hydrogeologic units lying stratigraphically below

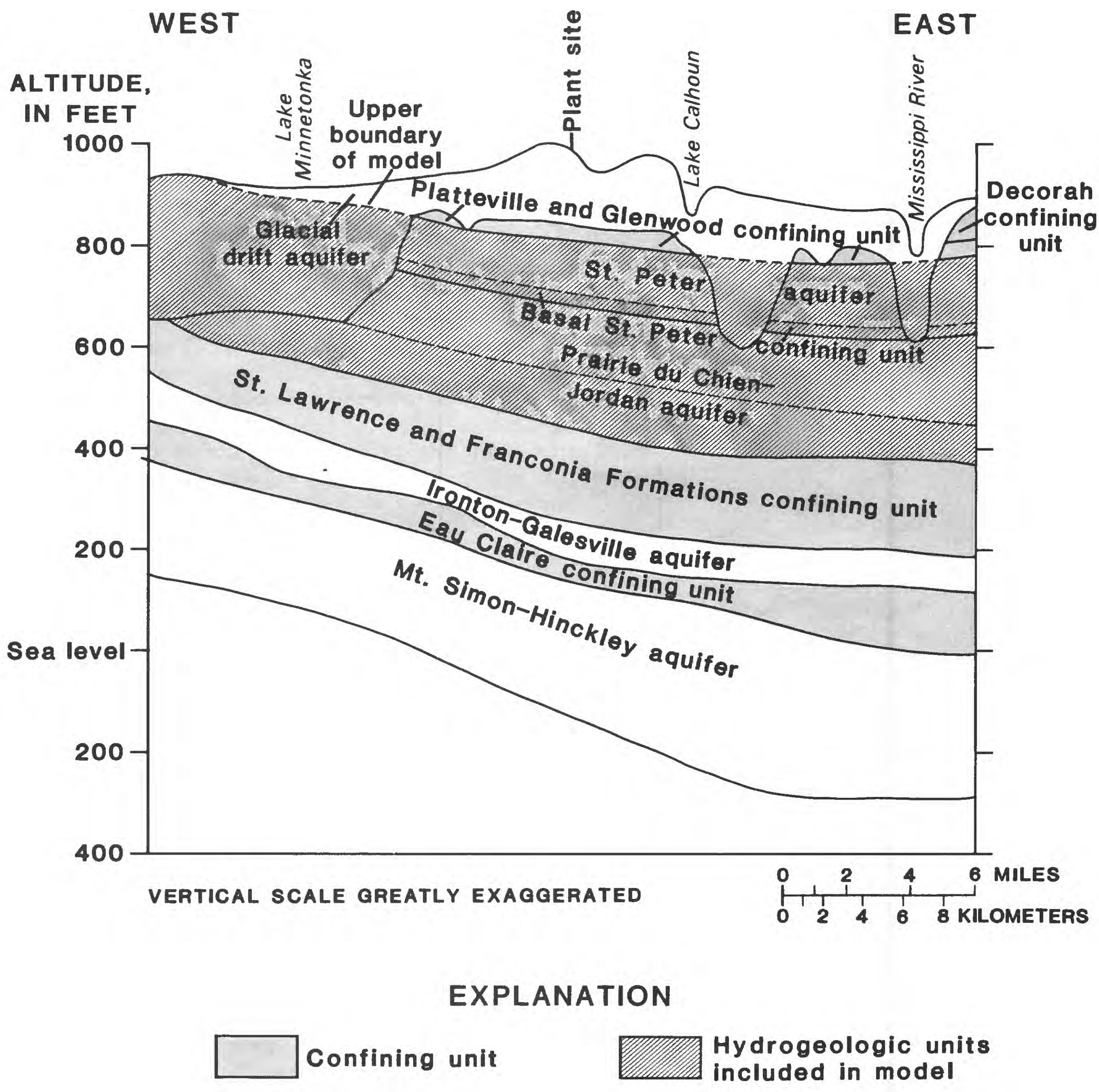


Figure 4.--Hydrogeologic units defined in the study area

Table 1.--Geologic and water-bearing

Geologic unit	Approximate range in thickness (feet)	Description
Glacial drift	50-400	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 is complex. Units have been differentiated in the immediate area of the plant site. These units include a poorly defined (unconfined) upper-drift aquifer, a middle-drift aquifer, and a lower-drift complex.
Decorah Shale	0-95	Shale, bluish-green to bluish-gray, blocky. Locally present in eastern part of study area.
Platteville Limestone	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. Present only in central part of study area. Dissected by erosion.
Glenwood Shale	0-18	Shale and claystone, green to buff, plastic to slightly fissil, lower 3 to 5 feet grade from claystone with disseminated sand grains to sandstone with clay matrix. Present only in central 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 consist of siltstone and shale. Generally present over most of the central part 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.
Jordan Sandstone	0-130	Sandstone, white to pink, fine- to coarse-grained, moderately well cemented, quartzose to dolomitic. Absent in extreme western and northern parts 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 beds within drift is poorly known outside the area of the plant site. Stratified well-sorted deposits of sand and gravel yield moderate to large supplies of water to wells (240-2,000 gallons per minute). Results from one aquifer test indicates that the transmissivity of the middle-drift aquifer near the plant site is about 9,000 square feet per day (Hult, U.S. Geological Survey, St. Paul, Minn., written commun., 1983).	Drift
Confining bed.	
Hydraulic conductivity primarily from fractures, open joints, and solution channels. Specific capacities of wells are generally between 10 and 100 (gallons per minute per feet of drawdown, if pumped at about 12 gallons per minute for 1 hour. Results from one aquifer test indicates that the transmissivity of the unit is about 9,000 square feet per day near the test site.	Decorah-Platteville-Glenwood confining unit
Very low hydraulic conductivity. Vertical hydraulic conductivity is estimated to be about 10^{-5} feet per day based on laboratory measurements of core samples.	
Most wells completed in the sandstone are of small diameter and used for domestic supply.	St. Peter aquifer
Confining beds near bottom of formation separate sandstone from 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.	
Confining bed, hydraulic characteristics are poorly known.	St. Lawrence-Franconia confining unit

the St. Lawrence-Franconia confining bed are not included in the table or in the model study because they are thought to be in poor hydraulic connection with overlying units.

Characteristics of Prairie du Chien-Jordan Aquifer

The Jordan Sandstone and the Prairie du Chien Group are defined as a single aquifer unit (Prairie du Chien-Jordan aquifer). The hydraulic connection between the two units is good and production wells commonly are open to both units. Although small differences in hydraulic head exist across the contact of the two subunits, distinct potentiometric surfaces can not be delineated with the available number and spacing of observation wells.

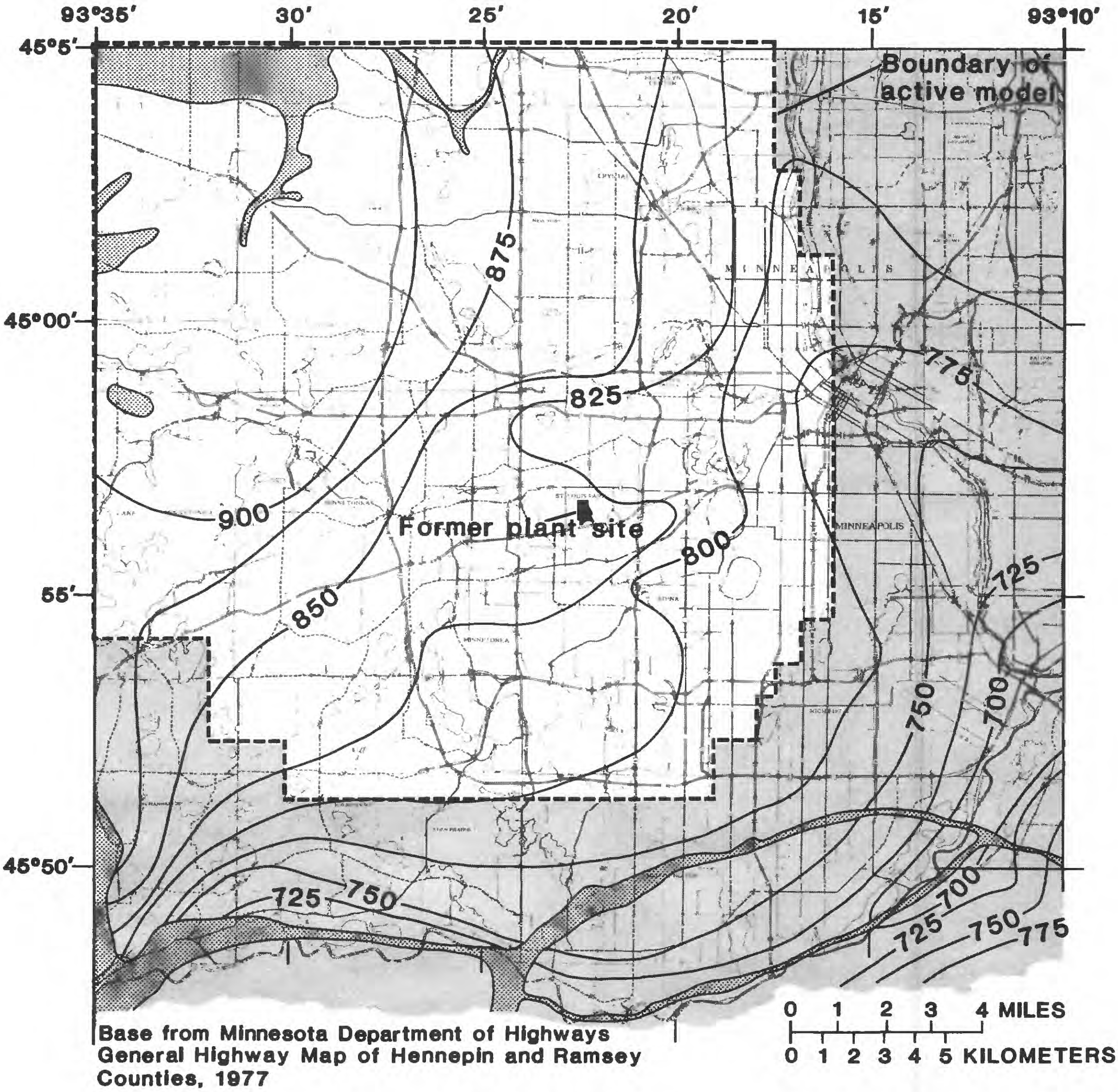
The hydraulic characteristics of the two subunits of the aquifer, however, are quite different. These differences influence the ways in which contaminants move through the subunits (M. F. Hult, U.S. Geological Survey, St. Paul, Minn., written commun., 1983). Permeability is chiefly due to intergranular porosity in the Jordan. In the Prairie du Chien, however, permeability is due mostly to fractures, joints, and solution cavities (secondary permeability). As a result, the Prairie du Chien has a lower effective porosity [about 6 percent compared with 32 percent for the Jordan (Norvitch and others, 1974)], has at least five orders-of-magnitude less surface area available for adsorption of contaminants (M. F. Hult, U.S. Geological Survey, St. Paul, Minn., written commun., 1983), and has more variability in permeability than the Jordan. Consequently, the Prairie du Chien has the potential for more rapid transport of contaminants.

In the study area, wells completed in the Jordan Sandstone generally yield more than 1,000 gal/min, whereas yields from wells completed in the Prairie du Chien can be as much as 1,800 gal/min (Guswa and others, 1982). Transmissivity values average about 7,000 ft^2/d in the Jordan Sandstone but the transmissivity of the Prairie du Chien changes with the degree of secondary permeability.

Ground-Water Flow

In Hennepin County, water in the Prairie du Chien-Jordan aquifer generally flows from west to east under the influence of a regional hydraulic gradient of about 10 ft/mi (fig. 5). This regional gradient increases, however, near the Mississippi and Minnesota Rivers. The aquifer is recharged by leakage from overlying units. Larson-Higdem and others (1975) have estimated that leakage to the aquifer, in Hennepin County, is about 3.5 inches per year and that about 1 inch of additional leakage occurs as the result of increased summer pumping and drawdown in the Prairie du Chien-Jordan aquifer. Discharge from the aquifer, in Hennepin County, is to unconsolidated sediments in the valleys of the Minnesota and Mississippi Rivers, to production wells completed in the aquifer, and to leakage to underlying units.

A locally persistent mound in the potentiometric surface of the Prairie du Chien-Jordan has been interpreted from water levels measured in wells W23 and W112 (fig. 6) (M. F. Hult, U.S. Geological Survey, St. Paul, Minn, written commun., 1983). This mound may be located between the plant site and St.



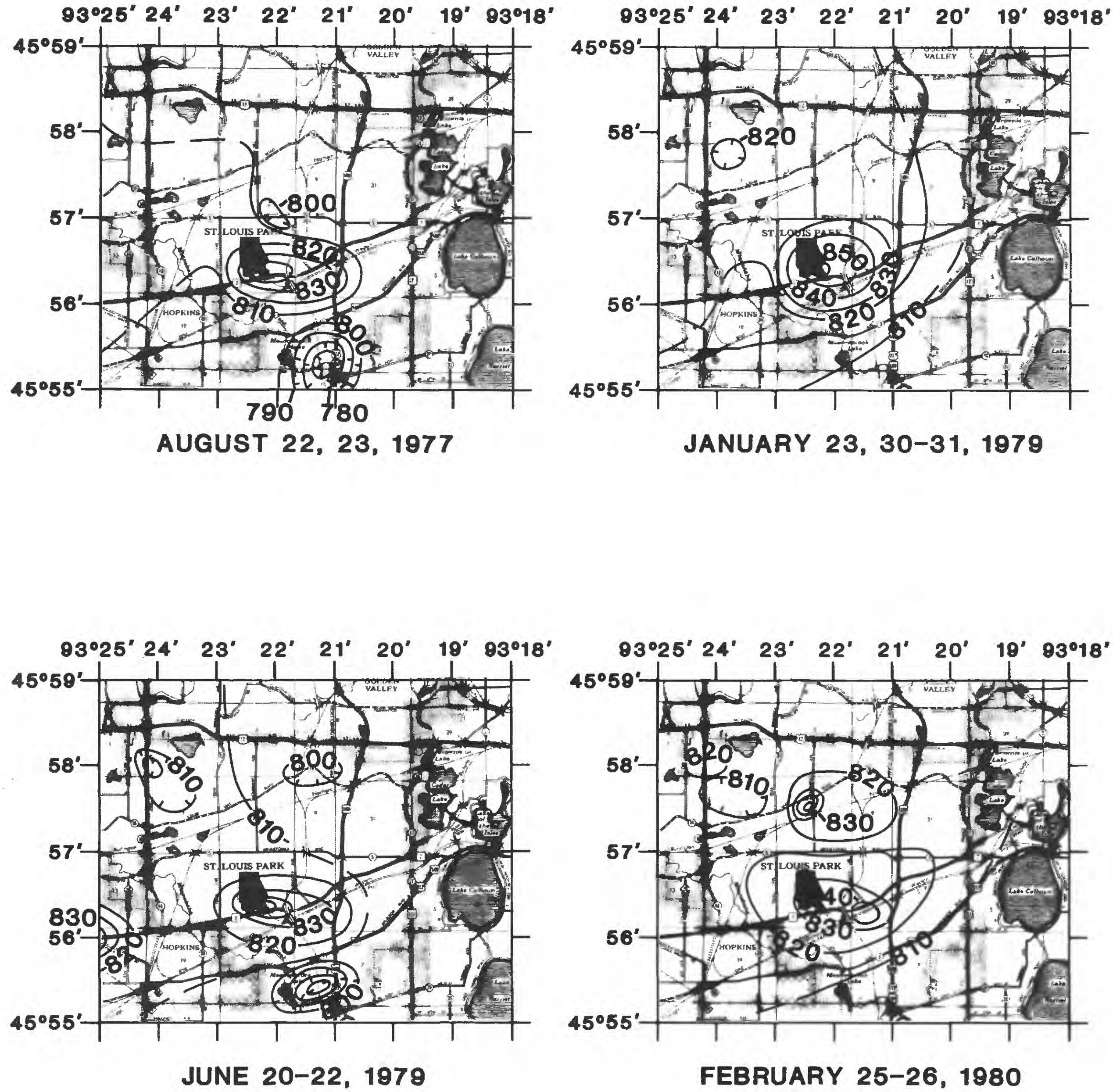
EXPLANATION

—725— Potentiometric contour showing altitude at which water levels would stand in tightly cased wells. Contour interval 25 feet. Datum is sea level

Areas where Prairie du Chien-Jordan aquifer has been removed by erosion

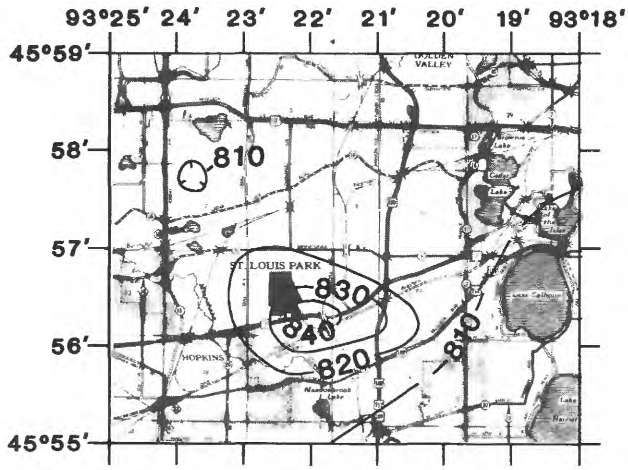
Area outside of active model area

Figure 5.--Potentiometric surface of the Prairie du Chien-Jordan aquifer, February-March 1980 (adapted from Schoenberg, 1984)



Base from Minnesota Department of Highways
General Highway Map of Hennepin County, 1977

Figure 6.--Potentiometric surfaces of the Prairie du Chien-Jordan



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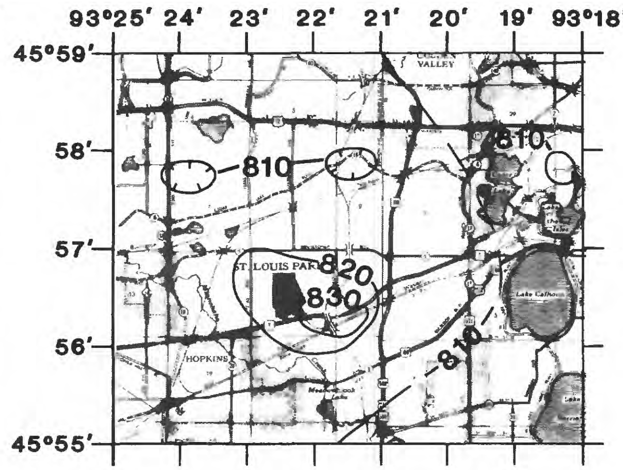

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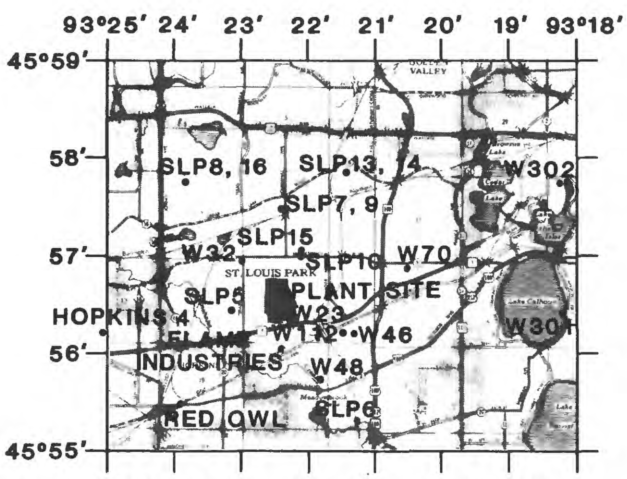


WELL NAME (NUMBER) AND
LOCATION OF WELLS MEASURED

EXPLANATION

— —810— Potentiometric contour showing line of equal altitude at which water levels would stand in tightly cased wells. Dashed where approximate. Contour interval 10 feet. Datum is sea level

0 1 2 MILES

0 1 2 3 KILOMETERS

aquifer near the plant site at selected periods from 1977-83

Louis Park old well 1 (W112), and related to discharge into the aquifer through multiaquifer wells. Flow into the Prairie du Chien-Jordan aquifer, from overlying aquifers, has been documented in six wells. Although flow in these wells was stopped in 1979, the mound remains. Other possible causes for the mound may have existed. These could include higher than normal leakage in the area due to erosion or fracturing of the basal St. Peter confining bed.

Ground-Water Withdrawals

The Prairie du Chien-Jordan aquifer supplies about 80 percent of the ground water used in Hennepin County (fig. 7). Within the study area, the volume of water pumped from the aquifer has increased during the century and currently averages about 24 Mgal/d. 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 is pumped from the study area for four major uses: (1) Municipal supply, (2) commercial (mostly for air-conditioning), (3) self-supplied industrial, and (4) irrigation (mostly for cemeteries and golf courses) (fig. 8). 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 due to conservation measures.

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

Mean yearly and seasonal ground-water-withdrawal data for about 100 high-capacity wells (fig. 9) was compiled for use in model simulations. Yearly data were used for steady-state simulations and seasonal data were used for transient simulations. Standard statistical methods (M. E. Schoenberg, U.S. Geological Survey, oral commun., 1983) were used to estimate seasonal withdrawals from wells for which only annual data were available. The method uses regression analysis to estimate monthly water use from annual values for each of the four water-use classes. Each class has a distinct seasonal pattern of water use. Commercial wells, for example, are pumped primarily during the summer because these wells are used mainly for air-conditioning.

Within each class in which monthly water-use data were available, pumpages were regressed against deviations from monthly normal precipitation and monthly normal temperature. If no regressed relationships could be determined, the mean percent of annual water use, based on reported monthly use during 1970-77, was used to estimate monthly pumpage for wells that had annual data. When regressed relationships were determined, the degree of departure from normal monthly temperature or precipitation or both was used to modify estimates based on wells with reported monthly use.

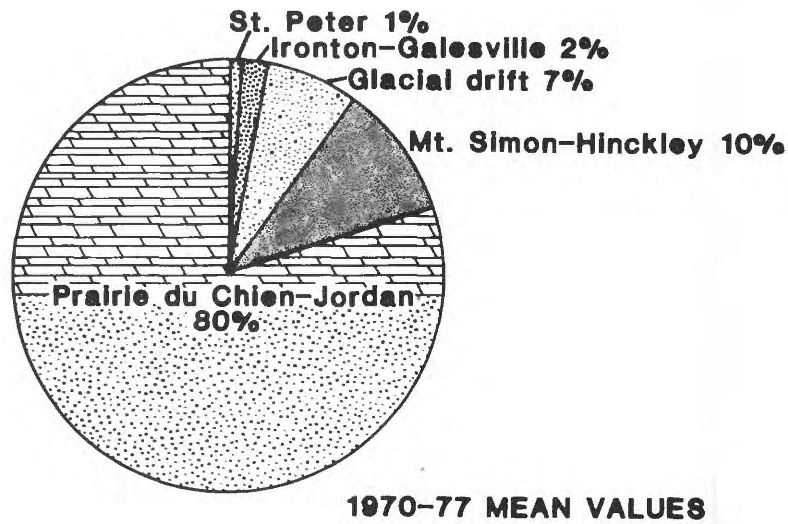


Figure 7.--Distribution of ground-water withdrawals by aquifer in Hennepin County

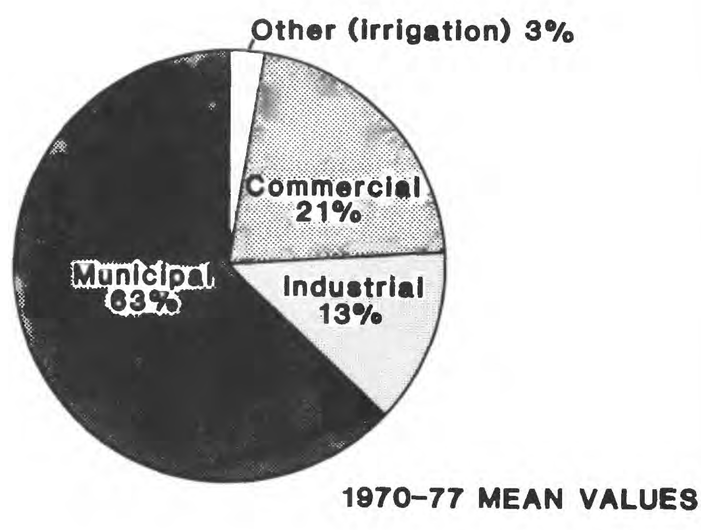
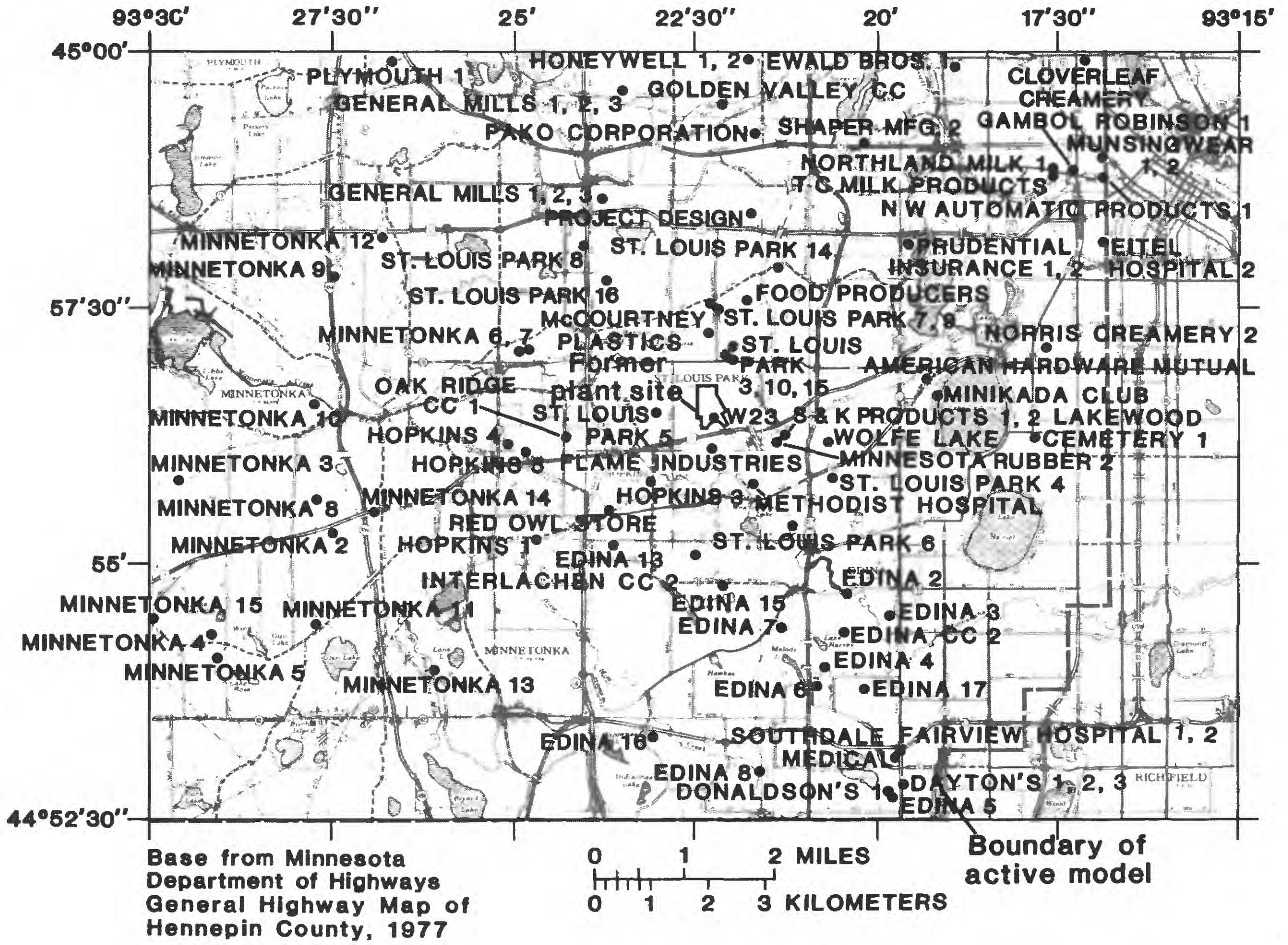


Figure 8.--Distribution of ground-water withdrawals by use type from the Prairie du Chien-Jordan aquifer in the study area



EXPLANATION

EDINA 6• Location and name of high-capacity production well simulated in model

Figure 9.--Location of high-capacity wells in the central part of the model area

Seasonal water-use estimates were created by summing monthly estimated or monthly reported water use or both within each pumping season (fig. 10). "Summer months," generally the period of highest pumpage, were defined as the period from May through September. Each calendar year, therefore, had three "pumping seasons:" (1) "Spring," January-April, (2) "summer," May-September, and (3) "fall," October-December.

Water-Level Changes

Withdrawals from the Prairie du Chien-Jordan aquifer have produced long-term (1885-1980) potentiometric-surface declines. In Hennepin County, the greatest water-level declines (as much as 50 feet) have occurred in the downtown Minneapolis area and in certain areas of St. Louis Park (fig. 11). In addition, water-level declines have occurred as a result of increased pumpage in the summer months (fig. 12). These short-term seasonal declines are as much as 50 feet in the downtown Minneapolis area and as much as 40 feet in certain areas of St. Louis Park. Changes in water levels at individual wells reflect both short- and long-term trends. A hydrograph of St. Louis Park old well 1 (fig. 13) shows seasonal changes and the trend in long-term changes since 1962.

GROUND-WATER-FLOW MODEL

The primary objective of this study was to develop a tool that could be used to simulate movement of ground water (and, hence, contaminants) under various pumping schemes at municipal, commercial, industrial, and gradient-control wells in the immediate vicinity of St. Louis Park. The model will be used by the MPCA to aid in locating and evaluating discharge rates for wells that will be used to control hydraulic gradients in the vicinity of contamination. The model will also be used to help understand how changing patterns of ground-water withdrawals influenced the movement of contaminants.

A computer model by Trescott (1975), later modified by Trescott and Larson (1976) and Torak (1982), was used for this study. The model solves finite-difference approximations to the ground-water-flow equation in three dimensions. The equations describe the flow of water through the aquifers and confining units at St. Louis Park in relation to 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 digital model. The conceptual model consists of a qualitative description of the known characteristics and behavior of the system. The major concepts of flow and associated assumptions for modeling are:

1. The Prairie du Chien-Jordan aquifer, basal confining part of the St. Peter Sandstone, and the St. Peter Sandstone, are recharged by leakage through overlying units, the glacial drift, and by lateral inflow.

2. At the scale of the 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.

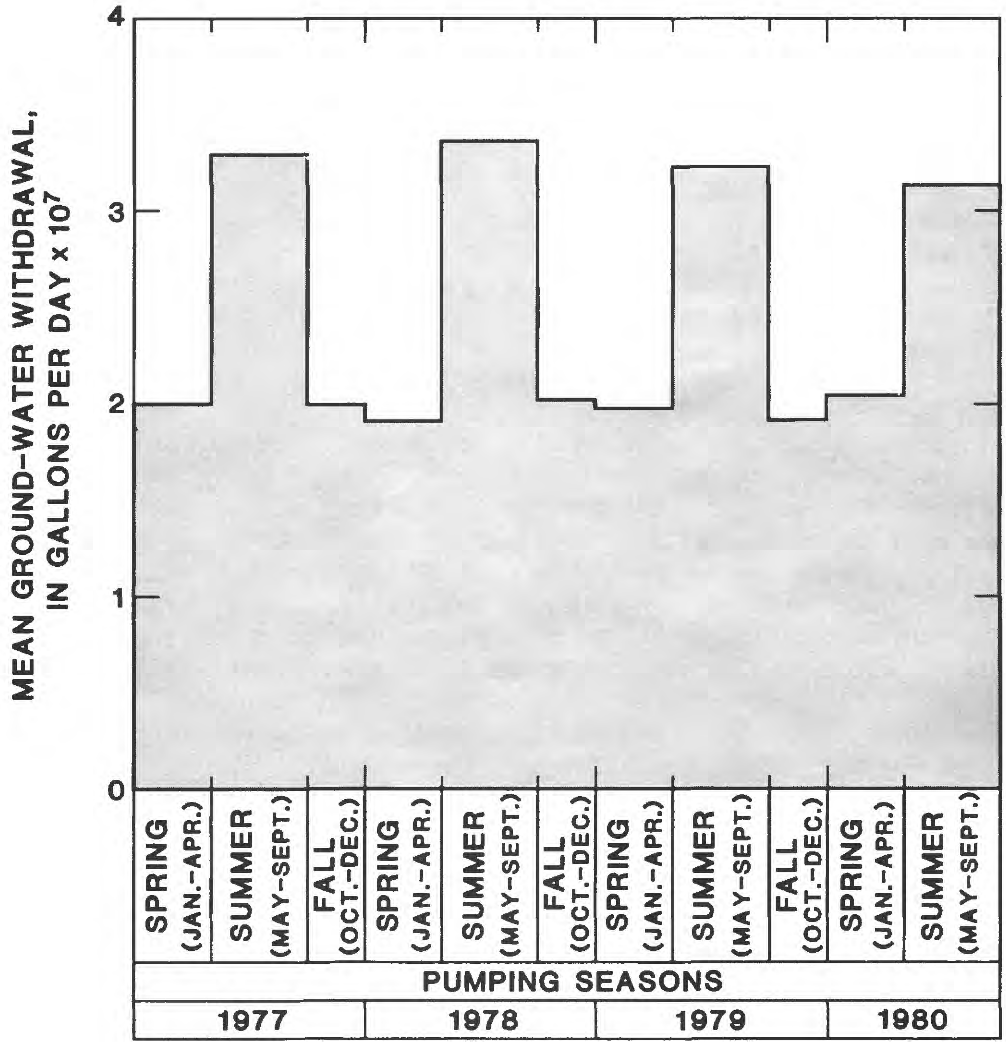
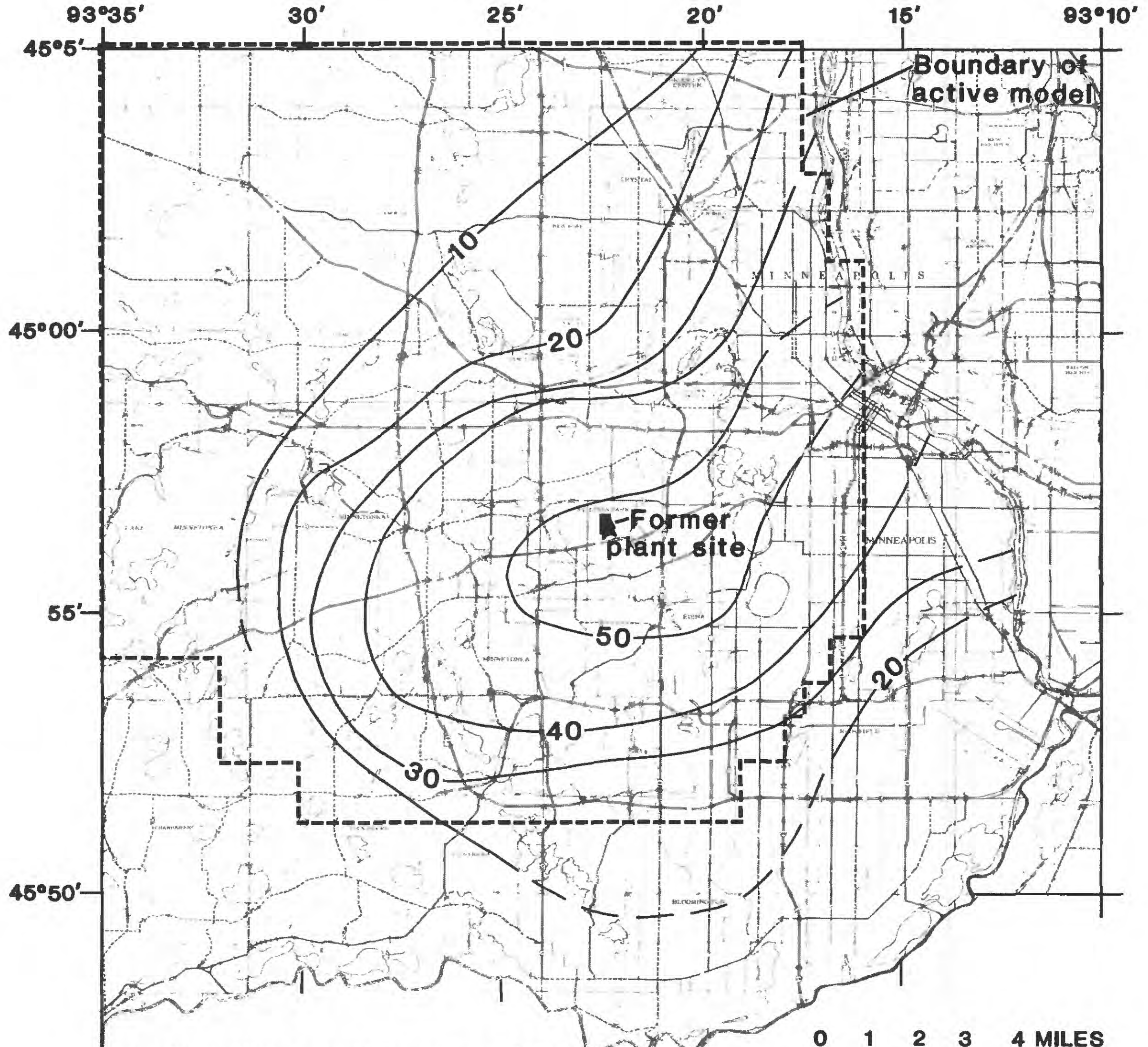


Figure 10.--Estimated ground-water withdrawals for study area by pumping season, 1977-80

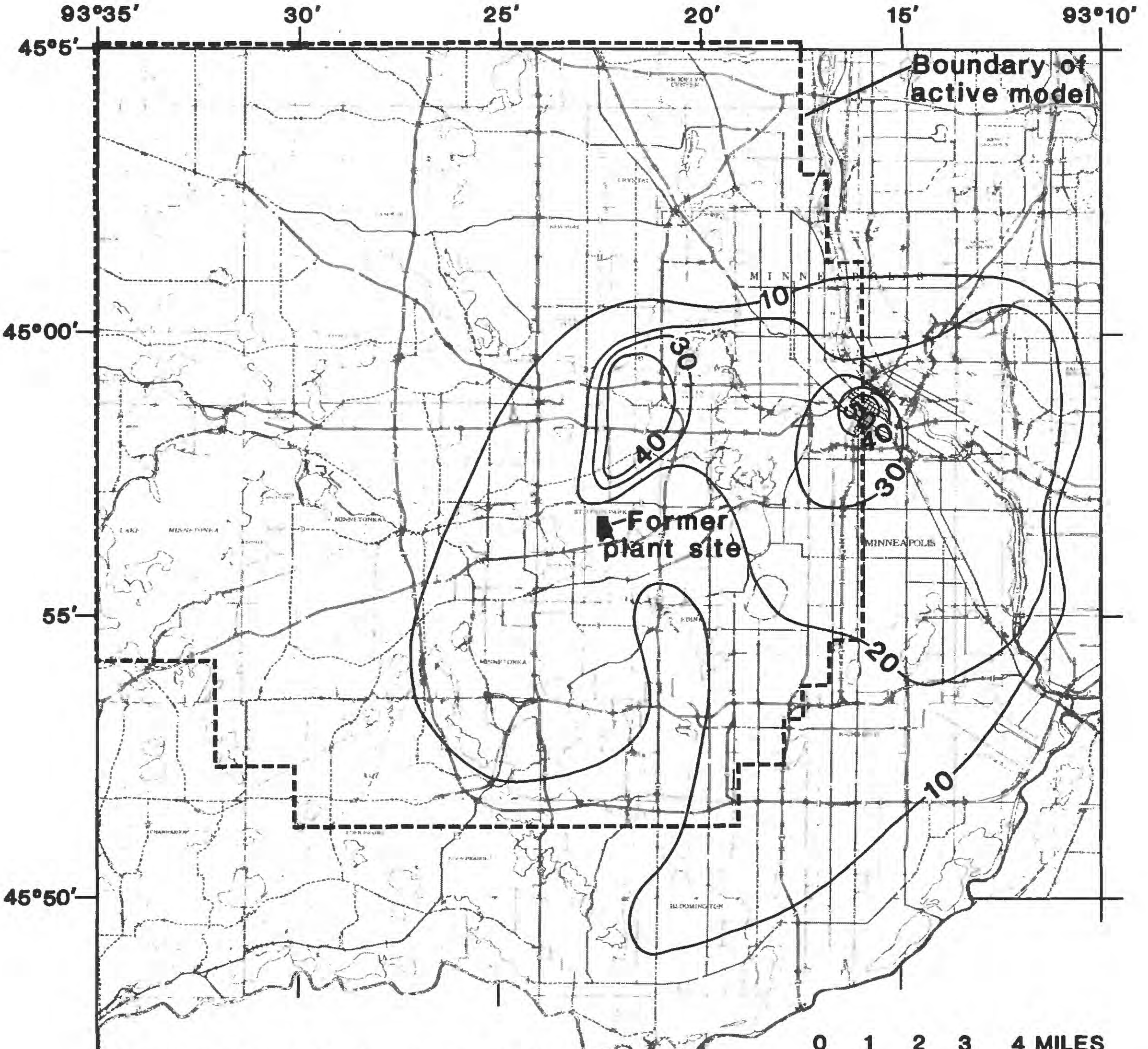


Base from Minnesota Department of Highways General Highway Map of Hennepin and Ramsey Counties, 1977

EXPLANATION

— —10— Line of equal potentiometric-surface decline in the Prairie du Chien-Jordan aquifer, 1885-1980 Dashed where approximate. Interval 10 feet

Figure 11.--Long-term potentiometric-surface decline in the Prairie du Chien-Jordan aquifer caused by ground-water withdrawal, 1885-1980 (adapted from Reeder, 1966, Schoenberg, 1984)



Base from Minnesota Department of Highways General Highway Map of Hennepin and Ramsey Counties, 1977

EXPLANATION

—20— Line of equal potentiometric-surface decline in the Prairie du Chien-Jordan aquifer, winter to summer, 1980. Interval 10 feet

Figure 12.--Seasonal potentiometric-surface decline in the Prairie du Chien-Jordan aquifer caused by ground-water withdrawal, winter to summer, 1980 (adapted from Schoenberg, 1984)

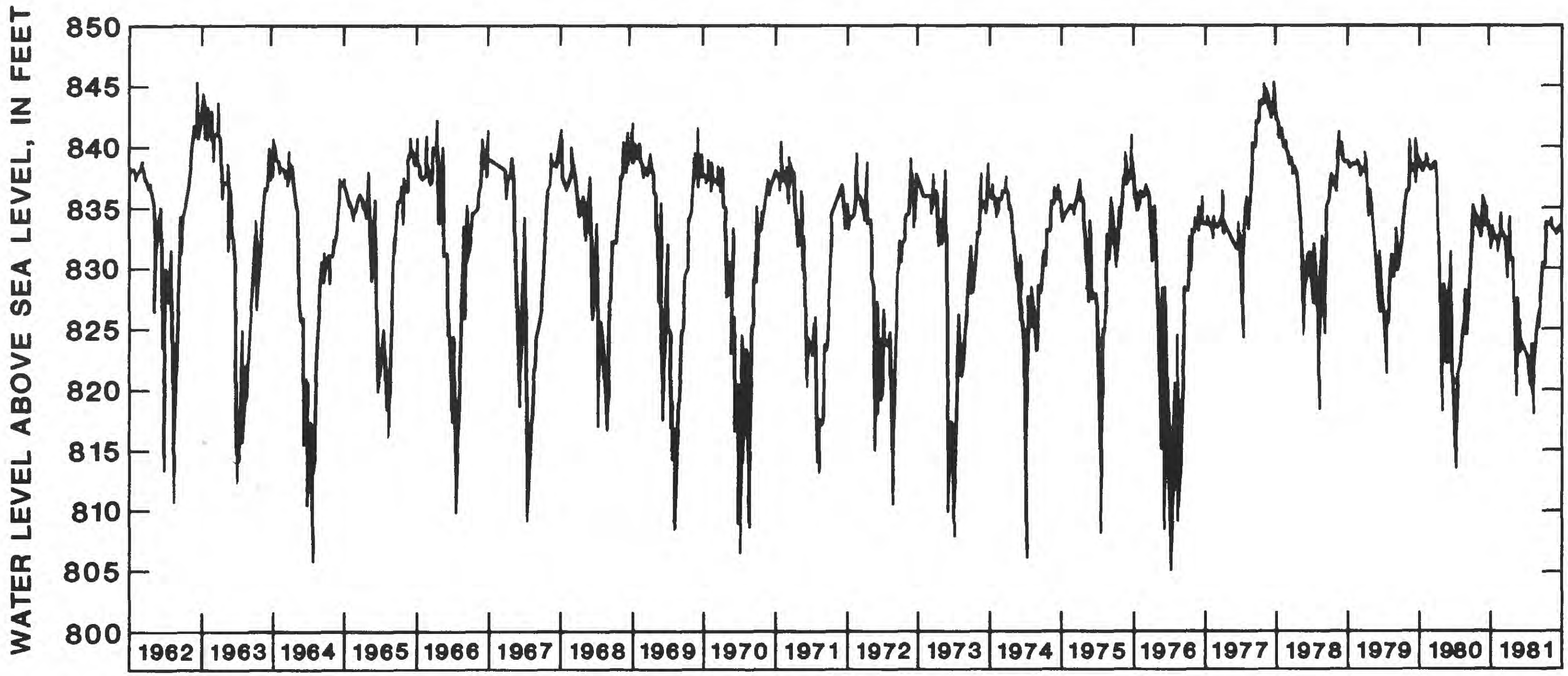


Figure 13.--Hydrograph of St. Louis Park old well 1 (W112)

3. Water is pumped from each of the aquifers in the system.

4. Aquifers discharge water to the Minnesota and Mississippi Rivers through glacial drift in the valleys.

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

6. Some natural hydrologic boundaries lie outside the modeled area and ground water flows laterally across arbitrarily imposed model boundaries.

7. The hydrogeologic units represented in the model include, in ascending order, the Jordan Sandstone of Cambrian age, the Prairie du Chien Group, the basal part of the St. Peter Sandstone, the St. Peter Sandstone both of Ordovician age, and glacial deposits of Pleistocene age. 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 Sandstone. The entire unconfined glacial-drift aquifer, therefore, is not simulated in the model-layer configuration. The lower model layer, representing the Jordan Sandstone, is considered to have an impermeable lower boundary because the St. Lawrence and Franconia confining units, (St. Lawrence and Franconia Formations of Cambrian Age) which underlie it, are considered to isolate it from aquifers that lie stratigraphically below.

The model is designed to simulate ground-water flow in the immediate vicinity of St. Louis Park. The area modeled is larger to include ground-water withdrawals from areas that affect hydraulic head in the St. Louis Park vicinity. Because the dimensions of cells increase toward the edges of the modeled area, hydrologic properties assigned to these cells are averaged over large areas.

Model Design

The modeled area, about 380 mi^2, was subdivided by use of a rectangular finite-difference grid with variable spacing (fig. 14). The grid contains 40 rows and 42 columns of cells that have horizontal dimensions ranging from 400 to 14,000 feet. The smallest cells generally are in the St. Louis Park area (central part of the grid) where the most detail is required. In the Trescott and Larson (1976) code, equations are formulated using a block-centered scheme where nodes are located at the centers of the grid blocks and represent 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. Specific nodes and cells are referenced by citing row (i), column (j), and layer (k).

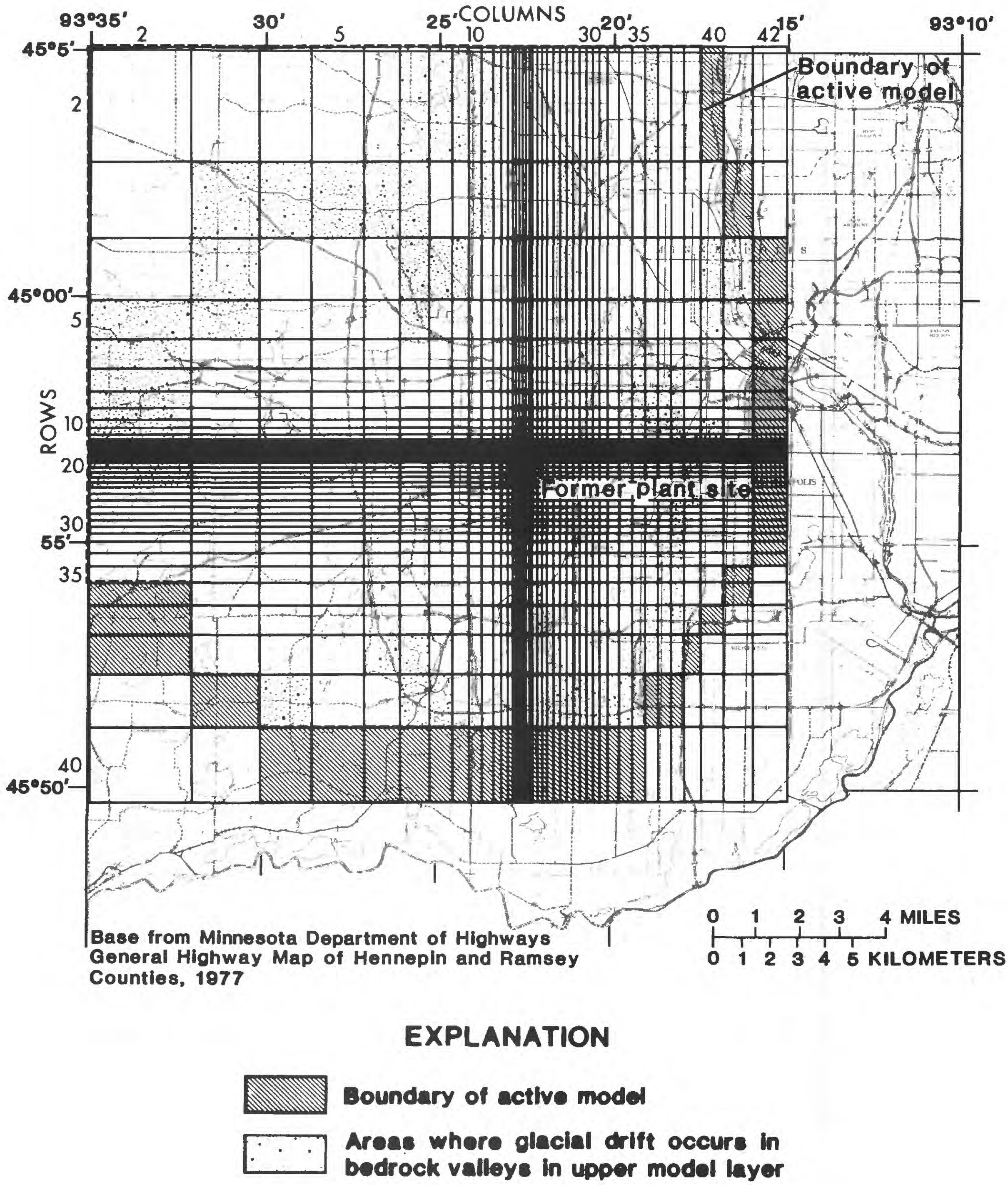


Figure 14.--Finite-difference grid

The model contains four layers that represent, in ascending order, (1) the Jordan Sandstone, (2) the Prairie du Chien Group, (3) the basal confining unit of the St. Peter Sandstone, and (4) the St. Peter Sandstone (fig 15). In addition, parts of each model layer contain cells that represent glacial drift in the bedrock valleys. For example, the St. Peter Sandstone is always in model layer 4, but this layer also contains drift. Drift occupies the part of the model where the bedrock units are missing because of erosion or nondeposition of the St. Peter.

The boundaries of the model grid simulate major hydrologic boundaries in the Prairie du Chien-Jordan aquifer. In the north and west, the boundaries represent the approximate lateral extent of the Prairie du Chien-Jordan aquifer. The potentiometric 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. The south and east boundaries of the model simulate flow conditions near the Minnesota and Mississippi Rivers. These boundaries were simulated as constant-head cells in which the heads were varied (depending upon the period being simulated) to represent head measured in the aquifers.

Geologic data from maps prepared by the Minnesota Geological Survey (1980) were used to assign hydrogeologic characteristics to each cell. This included the representation of cells in which glacial drift occurs in bedrock valleys. Initial values for hydraulic conductivity for each layer and leakage to the upper-most layer from overlying layers were the same as those being used in a regional ground-water-flow model presently being developed by the U.S. Geological Survey for the seven-county Twin Cities area (M. E. Schoenberg, U.S. Geological Survey, oral commun., 1983) (table 2). In areas where glacial drift occurs in cells in the upper model layer, leakage is from glacial deposits overlying the cell.

Model Calibration

Calibration of ground-water models is a matching process used to refine initial estimates of aquifer properties and boundary conditions. Input values of hydrologic properties are modified until model-calculated water levels satisfactorily approximate water levels measured in the field. Model-sensitivity analysis is often conducted during calibration to identify the relative effect of adjustments of hydrologic properties on calculated water levels.

Calibration and evaluation of the flow model was conducted for two steady-state (equilibrum) conditions and a transient condition. The steady-state simulations compute the head distribution in the system where inflow, such as leakage from overlying geologic units and lateral inflow to the system, is balanced by natural outflow from the system and pumpage. The transient simulations include the storage properties of the ground-water system, and, therefore, are time dependent.

The steady-state phases simulate (1) conditions prior to significant ground-water development (approximately 1885-1930) and (2) average winter conditions in the system during 1970-77, a period of large annual ground-water

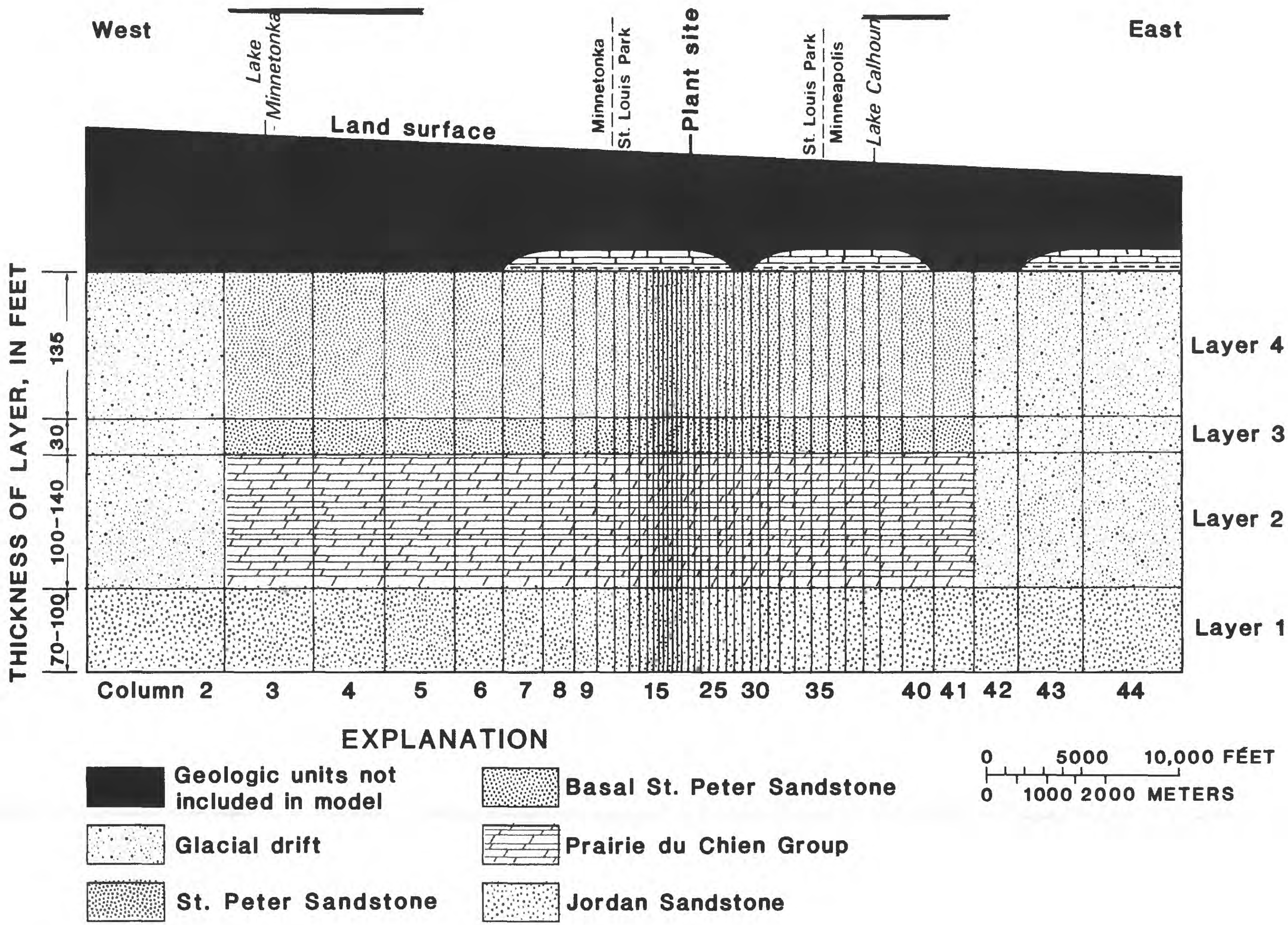


Figure 15.--West to east schematic hydrogeologic section through central part of model area showing model layers and hydrologic relationships

Table 2.--Initial values of hydrologic properties used in 1885 steady-state model

[K_z = vertical hydraulic conductivity, K_x = horizontal hydraulic conductivity, NA = not applicable]

Hydro-geologic unit	Horizontal hydraulic conductivity (ft/d)	Thickness (feet)	Anisotropy (K_z/K_x)	Leakage to uppermost layer (in./yr)
Drift	40	variable	0.1	NA
St. Peter aquifer (Layer 4)	20	135	.1	2.0
Basal St. Peter confining unit (Layer 3)	0.02	30	.1	NA
Prairie du Chien-Jordan aquifer (Layer 2)	40	125	.1	NA
Jordan (Layer 1)	40	80	.1	NA

withdrawal. Seasonally variable ground-water withdrawals from 1977-80, for which changes in potentiometric surfaces with time were documented, were used for transient calibration. Performance of the models was evaluated by comparing model-computed and observed water levels. Model performance was improved by 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 Simulation, 1885

The initial phase of model calibration involved simulating conditions in the Prairie du Chien and Jordan model layer for a period representing 1885-1930. Water-level data from this period were used to define boundary conditions and heads for the simulation, and to evaluate model performance. The earlier water levels generally are from the downtown Minneapolis area. Later 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 water levels before significant ground-water development.

Few water-level data are available for the St. Peter aquifer from 1885 to 1930. Therefore, head values assigned to constant-head cells at the boundaries of the Prairie du Chien and Jordan model layers also were assigned to boundary cells in the St. Peter model 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 presently are similar to water levels in the Prairie du Chien-Jordan aquifer and (2) available data suggest 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.

For the 1885 steady-state calibration, a sensitivity analysis of hydrologic properties was conducted. The degree to which model hydrologic properties can be adjusted, however, is related to the uncertainty associated with each property and must be considered.

During the sensitivity analysis, values of transmissivity and vertical hydraulic conductivity for each hydrogeologic unit in each model layer and leakage to the top layer were evaluated. 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 and drift) was found to be the most sensitive model hydrologic property. Variation of this property resulted in about a 5- to 10-foot difference in potentiometric levels in all layers. The model is relatively insensitive to changes in the values of other properties (table 3).

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 water levels matched measured water levels (best-match simulation). The significance of variable leakage rates to the upper model layer was examined early in the calibration process. Due to the relatively high transmissivity of all hydrogeologic units in the upper model layer, however, the effect of variable leakage was not found to be significant, and a lumped-parameter approach was considered to be acceptable. The model-computed water levels for all layers where head data are available in the Prairie du Chien-Jordan aquifer are generally within 10 feet of measured values (fig. 16). The model-computed water balance is shown in table 4. The number of water-level measurements for the preground-water-development period are few (about 10) and the model is relatively insensitive to adjustment of most properties.

Steady-State Simulation, 1970

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, it was a period of significant ground-water withdrawal, and, during this period, no significant long-term changes in potentiometric levels occurred in the system.

Table 3.--Sensitivity of Prairie du Chien model layer (layer 2) to changes in values of model hydrologic properties (1885 steady-state model)

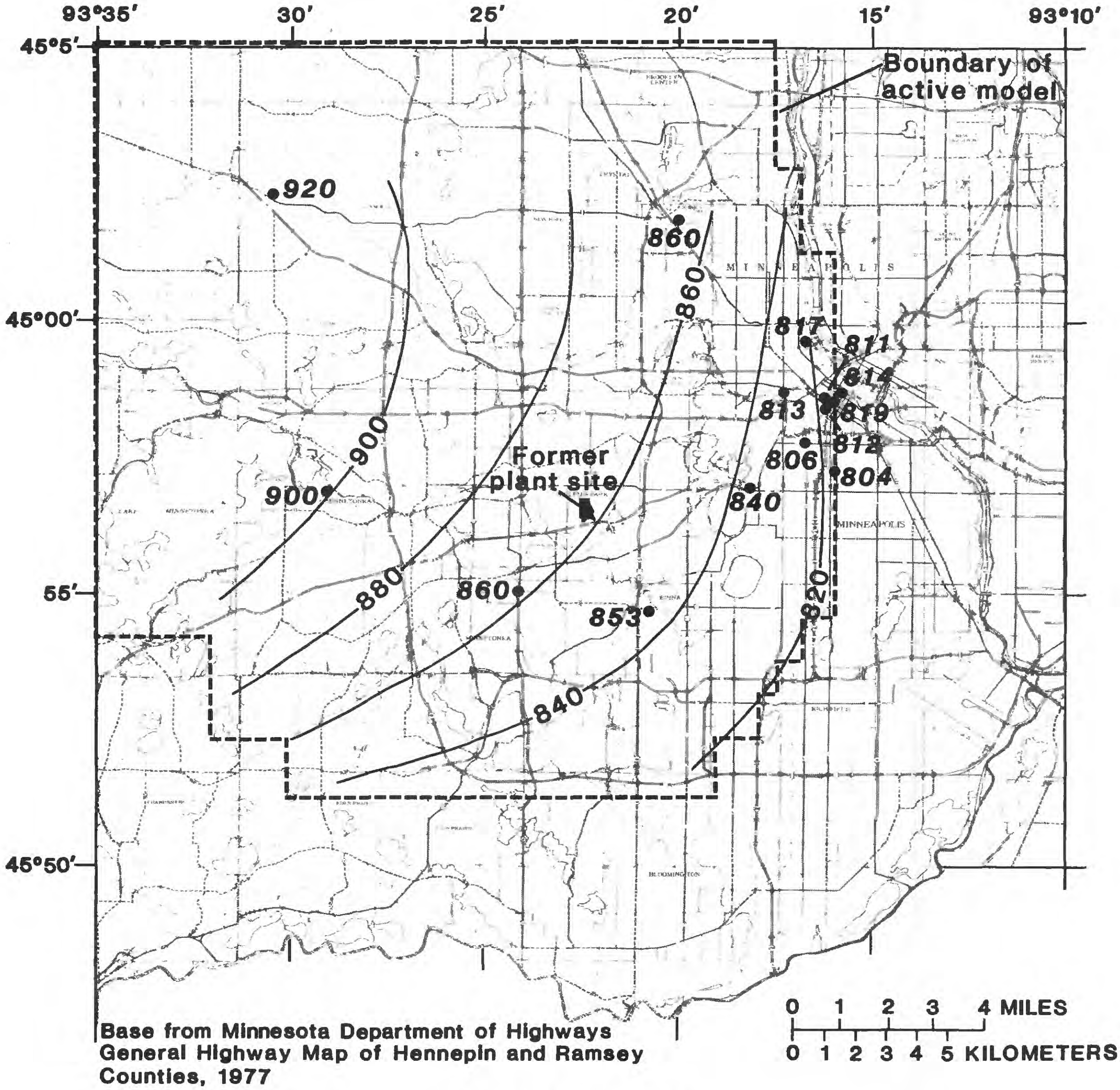
Property varied	Multi-plication factor	Hydrogeologic unit and model layer[1]	Mean deviation of water level[2] (feet)
Transmissivity	2.0	Jordan (L1)	-1.9
	.5	Jordan (L1)	+1.2
	2.0	Prairie du Chien (L2)	-2.3
	2.0	Basal St. Peter (L3)	-.3
	2.0	St. Peter (L4)	-1.4
Vertical hydraulic conductivity	.1	Jordan (L1)	-.4
	.1	Prairie du Chien (L2)	.0
	.1	Basal St. Peter	-.2
	.1	St. Peter	-.2
Leakage to top layer	2.0	L4	+6.9
	.5	L4	-3.1

[1] L1 = model layer 1.

[2] Mean deviation from values calculated by best-match simulation - deviation calculated at 10 cells in Prairie du Chien model layer where field data were available.

(+)-- deviation indicates calculated heads greater than best-matched simulation.

(-)-- deviation indicates calculated heads less than best-matched simulation.



EXPLANATION

—860— Simulated potentiometric contour, in feet above sea level. Contour interval 20 feet

•813 Well completed in the Prairie du Chien-Jordan aquifer, 1885–1930. Number is altitude of water level in feet above sea level

Figure 16.--Water-levels measured in wells completed in the Prairie du Chien-Jordan aquifer, 1885–1930 and model-calculated potentiometric surface of the Prairie du Chien model layer for the 1885 steady-state simulation

Table 4.--Computed water budget (1885 steady-state simulation)
[A dash indicates no sources or discharge for a budget component]

Budget component	Sources (cubic feet per second)	Discharges (cubic feet per second)
Leakage to top layer	31.38	---
Pumping	---	---
Constant head		
Layer 1 (lower layer)	3.77	13.15
Layer 2	6.31	21.09
Layer 3	---	---
Layer 4 (upper layer)	3.86	12.12
Total	45.32	46.36

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

Average annual ground-water pumpage for 1970-77 was incorporated into the model simulations. The simulated pumpage was 8.3 billion gallons per year from 121 high-capacity wells. Most of these wells simulate pumpage from the Jordan or Prairie du Chien model layers or both. Pumpage from wells that are open to only one of the two units was simulated for the corresponding model layer only. Simulated pumpage from wells open to both the Prairie du Chien and Jordan model layers were divided in relation to the transmissivities of the open intervals in each layer.

The sensitivity of the model to adjustments in values of model hydrologic properties was again investigated. Adjustments were made to the horizontal hydraulic conductivity of each hydrogeologic unit in each model layer and leakage to the top layer. All values, except leakage to the top layer, were increased and decreased by factors of 2.0. Leakage was varied by about 20 percent because the range of possible values was better 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 found to to be the most sensitive model properties (table 5).

Table 5.--Sensitivity of Prairie du Chien model layer (layer 2) to changes in values of model hydrologic properties (1970's steady-state simulation)

Property changed	Multi-plication factor	Hydrogeologic unit and model layer[1]	Mean deviation of water level[2] (feet)
Transmissivity	2.0	Jordan (L1)	-.8
	.5	Jordan (L1)	-.5
	2.0	Prairie du Chien (L2)	+1.0
	.5	Prairie du Chien (L2)	-2.1
Hydraulic conductivity	2.0	Drift (L2)	-.2
	2.0	basal St. Peter (L3)	+3.3
	.5	basal St. Peter (L3)	-4.1
	2.0	Drift (L3)	+1.0
	.5	Drift (L3)	+.4
	2.0	St. Peter (L4)	-.8
	.5	St. Peter (L4)	+.3
	2.0	Drift (L4)	+.1
	.5	Drift (L4)	-.2
Leakage to top layer	1.25	Drift and St. Peter (L4)	+2.2
	.80	Drift and St. Peter (L4)	-2.5

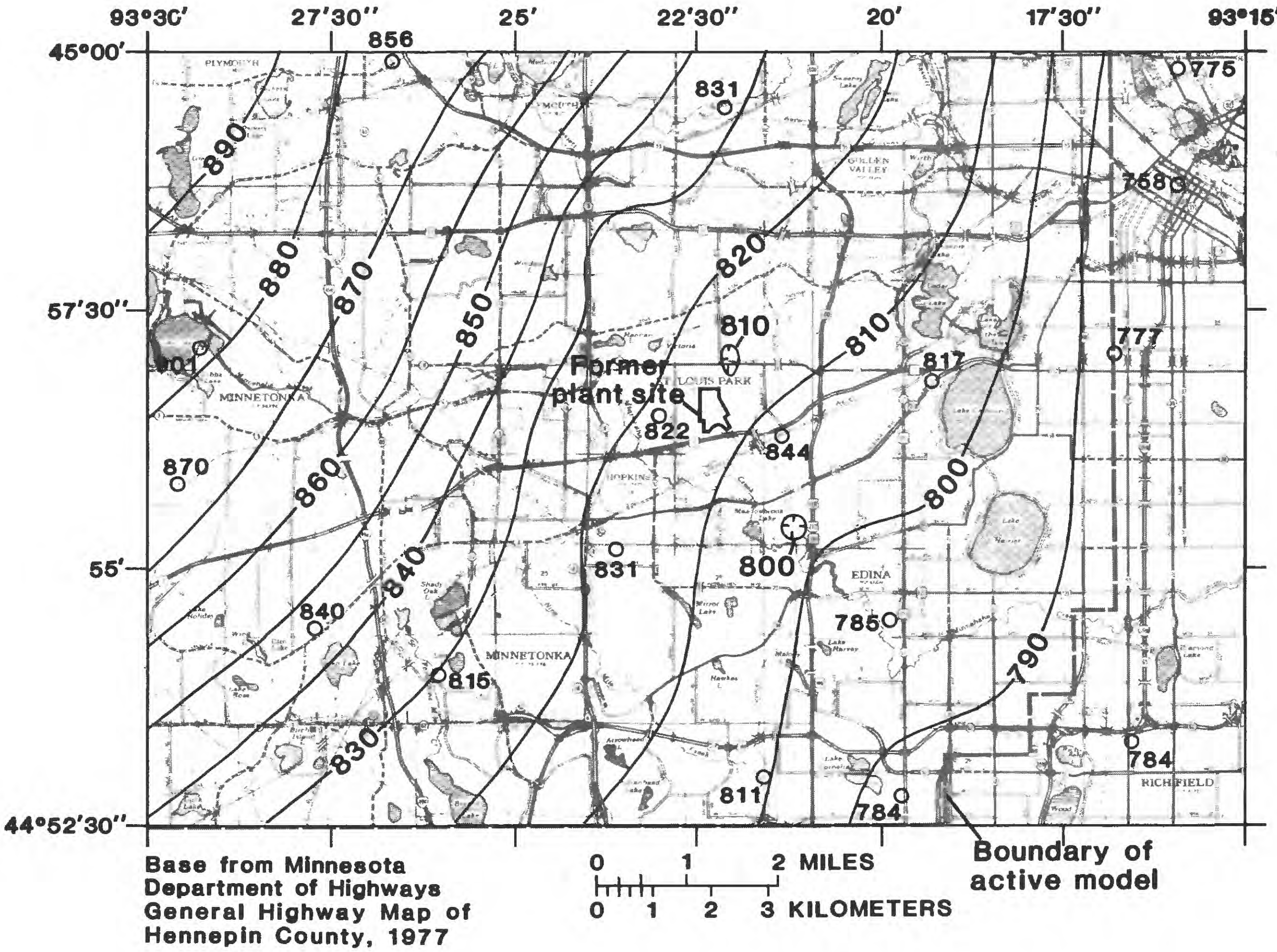
[1] L1 - model layer 1.

[2] Mean deviation from values calculated by reference simulation -- calculated at 19 cells in the Prairie du Chien layer where field data were available.

(+)-- deviation indicates calculated heads greater than reference simulation.

(-)-- deviation indicates calculated heads less than reference simulation.

Model calibration for 1970-77 was accomplished by adjusting selected model hydrologic properties until the average deviation between field-measured and model-calculated water levels was minimized. The model-calculated potentiometric surface in the Prairie du Chien model layer for the most satisfactory simulation for this period and water levels measured in the Prairie du Chien-Jordan aquifer during January and February 1978 are shown in figure 17. The average difference between model-calculated and field-measured water levels was 4 feet in the Prairie du Chien or Jordan model layers or both and 6 feet in the St. Peter model layer. Values of hydrologic properties used during the most satisfactory simulation are shown in table 6.



EXPLANATION

—810—	Simulated potentiometric surface. Contour interval is 10 feet. Datum is sea level
○ 831	Observation well. Number denotes altitude of water level of well, in feet, in Prairie du Chien–Jordan aquifer

Figure 17.--Model-calculated potentiometric surface for the Prairie du Chien model layer (layer 2) during steady-state simulation for central part of model area and water levels measured in wells in January-February 1978

Table 6.--Values of model hydrologic properties (1970's steady-state simulation)
[NA = not applicable]

Hydro-geologic unit	Horizontal hydraulic conductivity (ft/d)	Thickness (feet)	Anisotropy (K_Z/K_X)	Leakage (in./yr)
Drift	80-160	variable	$1.0\text{-}4.5\times10^{-5}$	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-Jordan aquifer (Layer 2)	36-56[1]	125	1	NA
Jordan (Layer 2)	18-25[1]	80	.1	NA

[1]Ranges in values reflect areal variation in thicknesses of unit.

The model-computed water budget for the simulation that most closely matches 1970-77 winter water levels is shown in table 7. This budget is significantly different from the model-calculated budget for the 1885 simulation period (table 4). Sources to the system and discharges from the system increased. Flow into the system, predominantly lateral inflow to the St. Peter aquifer (layer 4) and leakage to the top layer, reflects changes in vertical and horizontal gradients resulting from the general lowering of head in the aquifers caused by pumping. Increased lateral outflow resulted from constant-head cells along the south and east boundaries of the model in which specified head values were lowered to reflect the effects of pumping stress outside the modeled area.

Model-calculated water levels from the 1970-77 steady-state simulations, which include simulated injection of water into the Prairie du Chien aquifer at the multiaquifer well sites, do not match water levels measured at well W23 and St. Louis Park old well 1 (W112). Model-calculated water levels at these wells are about 35 to 45 feet lower than field-measured water levels. The disagreement between field-measured and model-calculated water levels at W23 and W112 is greater than at any other well in the model area.

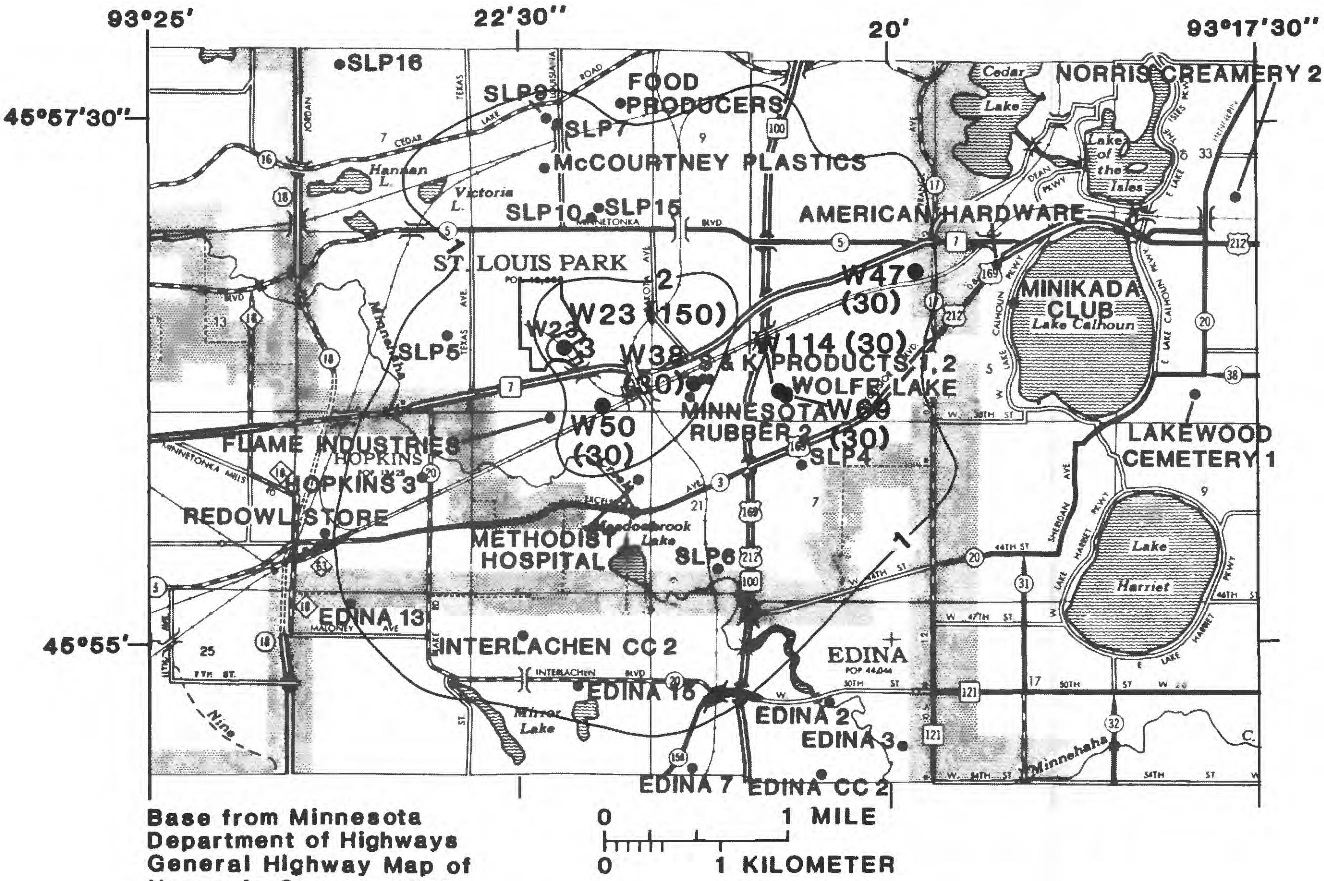
Table 7.--Computed water budget (1970's steady-state model)
[A dash indicates no sources or sinks for a budget component]

Budget component	Sources (cubic feet per second)	Discharges (cubic feet per second)
Leakage to top layer	57.74	---
Pumping		
Layer 1 (lower layer)	---	8.54
Layer 2	---	24.41
Layer 3	---	---
Layer 4 (upper layer)	---	1.61
Constant flux		
Layer 1	---	---
Layer 2	.60[1]	---
Layer 3	---	---
Layer 4	---	.60[2]
Constant head		
Layer 1	1.44	6.98
Layer 2	5.81	95.66
Layer 3	---	---
Layer 4	80.34	8.49
Total	145.93	146.29

[1] Simulates discharge into Prairie du Chien model layer through multiaquifer wells.
[2] Simulates discharge from St. Peter aquifer to multiaquifer wells.

A simulation was conducted to examine the importance of multiaquifer-well flow on the potentiometric surface of the Prairie du Chien-Jordan aquifer. The simulation was made using the calibrated version of the 1970-77 steady-state model. Figure 18 shows the model-calculated change in head in the Prairie du Chien layer due to multiaquifer-well flow. The simulated mound, which is from 0 to 3 feet high, compares poorly to the mound of at least 40 feet interpreted from field data (January and June 1979, fig. 6, compare water levels in W23 to water levels in adjacent wells).

In a different simulation, also using the calibrated 1970's steady-state model, constant heads were specified at model nodes in the Prairie du Chien model layer underlying wells W23 and St. Louis Park old well 1 (W112). Heads assigned to these nodes were identical to heads measured in W23 and St. Louis



Base from Minnesota
Department of Highways
General Highway Map of
Hennepin County, 1977

EXPLANATION

—2— Line of equal increase in potentiometric surface resulting from simulated multiaquifer flow. Interval 1 foot

● W50 (30) Well in which multiaquifer flow was measured. Number in parenthesis denotes the rate of flow into the Prairie du Chien-Jordan aquifer, in gallons per minute

•SLP16 High-flow production well in Prairie du Chien-Jordan aquifer

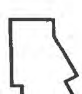

Former plant site

Figure 18.--Model-calculated mound in potentiometric surface of Prairie du Chien model layer (layer 2) due to multiaquifer-well flow into the aquifer

Park old well 1 in January 1979. Model-computed flows from the cells, representing wells W23 and St. Louis Park old well 1, respectively, into adjacent cells at steady state was about 1,900 and 1,300 gal/min. The sum of these flow rates is approximately an order-of-magnitude greater than measured multiaquifer flows.

Additional water-level measurement sites are needed to confirm the existence of the potentiometric high in the vicinity of the plant site. There are several possible explanations for the persistence of the potentiometric high and for the difference between model-computed and measured water levels. The possibilities include:

1. A steep, localized cone of impression resulting from well losses may have existed in the Prairie du Chien-Jordan aquifer before multiaquifer flow was stopped. Water levels measured in the well, therefore, may not have represented head conditions in the Prairie du Chien-Jordan aquifer in the immediate area around the well.

2. Multiaquifer flow in well W23 and other multiaquifer wells may have been significantly greater than measured due to flow around the outside of the casing or error in measurements.

3. Other multiaquifer wells may be present in the vicinity of the potentiometric high.

4. Leakage through the basal St. Peter confining bed may be anomalously high in the area due to erosion or fracturing of the basal St. Peter confining bed.

5. Uncertain head values because of the unknown well construction.

Transient Simulations

Transient simulations 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 significant seasonal changes in potentiometric surfaces had been documented.

To simulate transient conditions for 1977-80, 11 separate pumping seasons were specified to account for changing pumping rates in the modeled area. These pumping seasons also were specified to simulate potentiometric changes caused by pumping outside the south and east boundaries of the model area, primarily in downtown Minneapolis. Each year was divided into three "pumping seasons" that reflect seasonal variability in water withdrawals. These seasons are "spring" (January-April), "summer" (May-September), and "fall" (October-December). Average seasonal water use was simulated for each season. "Summer" water use, which averages about 33 Mgal/d, is about 1.7 times the average "spring" and "fall" rates of use (fig. 10). Because simulated ground-water withdrawals represent seasonal averages, and because continuous water-level data are not available for the aquifers, transient calibration of the system cannot be evaluated for time intervals shorter than a pumping season.

Potentiometric surfaces calculated for the 1970's steady-state simulation were used as a starting point for the first seasonal simulation (spring 1977) in each transient simulation. Subsequent seasonal simulations used final heads from simulation of the previous season as starting heads. Boundary-head values, assigned to constant-head cells in the Jordan and Prairie du Chien model layers, were modified before each seasonal simulation to reflect measured changes in head at the south and east boundaries of the model.

Model hydrologic-property values from the calibrated 1970's steady-state model were used as initial values for transient simulations. Values of aquifer storage coefficients, shown below, from Norvitch and others (1974) were used as initial values for aquifer storage.

Hydrogeologic unit	Storage coefficient
Drift	10^{-4}
St. Peter aquifer (Layer 4)	10^{-4}
Basal St. Peter confining unit (Layer 3)	10^{-5}
Prairie du Chien-Jordan aquifer (Layer 2)	4×10^{-4}
Jordan (Layer 1)	7×10^{-5}

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 (fig. 19). Tables 8 and 9, which show model-calculated water-balance statistics for a typical season, indicate that only 1 percent or less of model inflow comes from storage.

Values of hydrologic properties used during initial transient simulations gave the best model results (table 6).

Model-calculated water levels from transient simulations generally are within 10 feet of measured water levels. The largest differences between model-computed and measured water levels are at wells W23 and St. Louis Park old well 1 (W112). If data from these two points are not considered, the

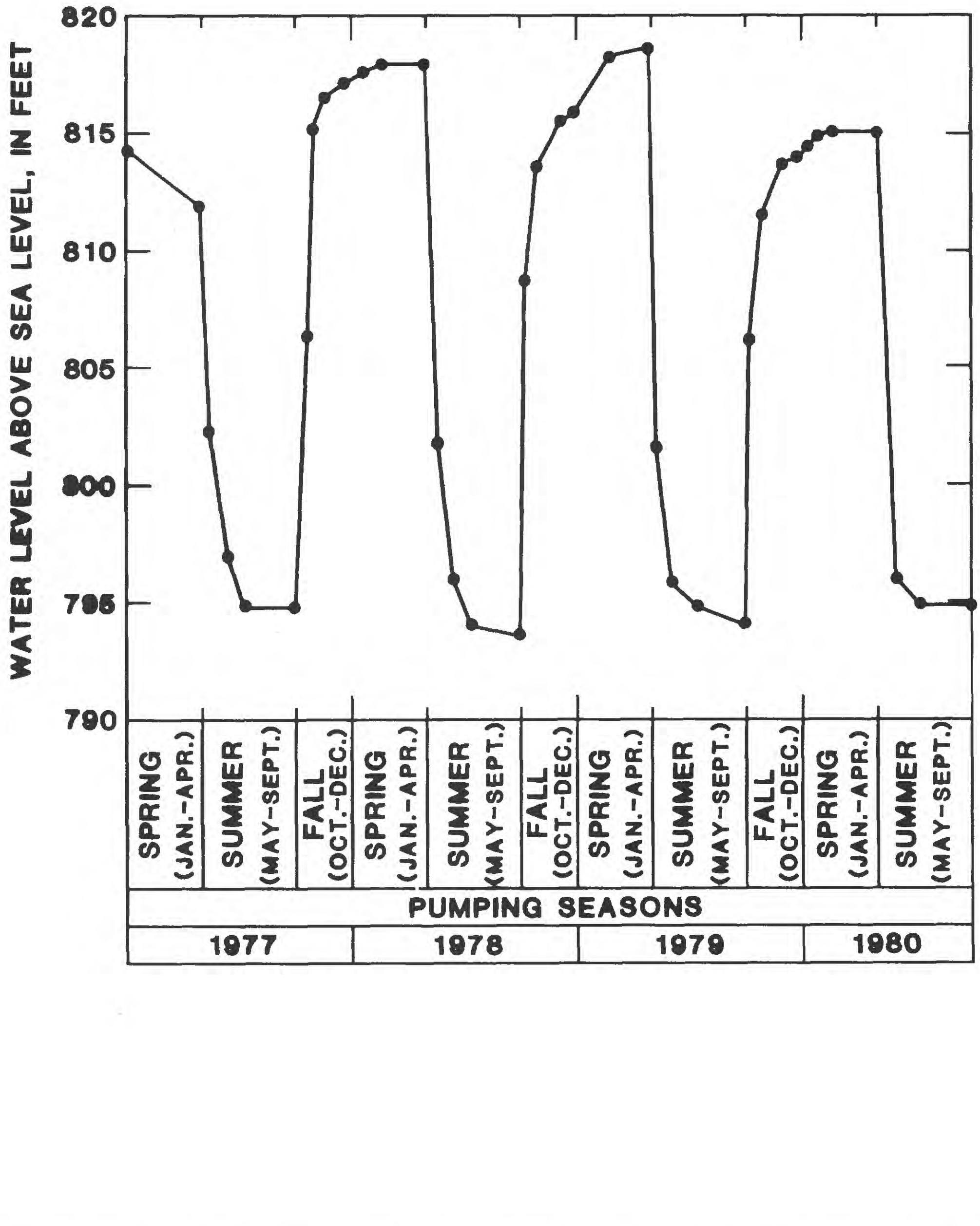


Figure 19.--Model-computed water levels in Prairie du Chien model layer (layer 2) at node 23,21 during transient simulation

Table 8.--Computed water budget for the earlier part of spring 1979 in the 1977-80 transient simulation[1]

[A dash indicates no sources or sinks for a budget component]

Budget component	Sources (cubic feet per second)	Discharges (cubic feet per second)
Storage		
Layer 1	0.14	---
Layer 2	.79	---
Layer 3	.02	---
Layer 4	.12	---
Leakage to top layer	57.74	---
Pumping		
Layer 1	---	6.99
Layer 2	---	21.18
Layer 3	---	---
Layer 4	---	2.11
Constant head		
Layer 1	1.43	7.53
Layer 2	5.82	98.65
Layer 3	0.00	0
Layer 4	80.95	8.73
Total	147.01	145.19

[1] Corresponds with period for which water-level data are available, January 30-31, 1979.

average difference between model-calculated and measured water levels is about 6 feet. Figures 20 and 21 show the model-calculated potentiometric surfaces and measured water levels for January and June 1979.

Transient-model water-balance statistics for January 1979 (table 9) are similar to water-balance statistics for the 1970-77 steady-state model (table 7). The similarities suggest that the system approaches steady-state conditions each winter and that the steady-state model may be used to approximate fall through spring conditions in the aquifer. These data also suggest that average yearly withdrawal data are a good approximation to withdrawal rates for the fall-spring pumping seasons. Differences between water-balance statistics for the June 1979 simulation (table 9) and for the January 1979 simulation (table 8) are due to the effects of increased summer withdrawals in the modeled area and changes in head at the boundaries that reflect increased withdrawals outside the modeled area.

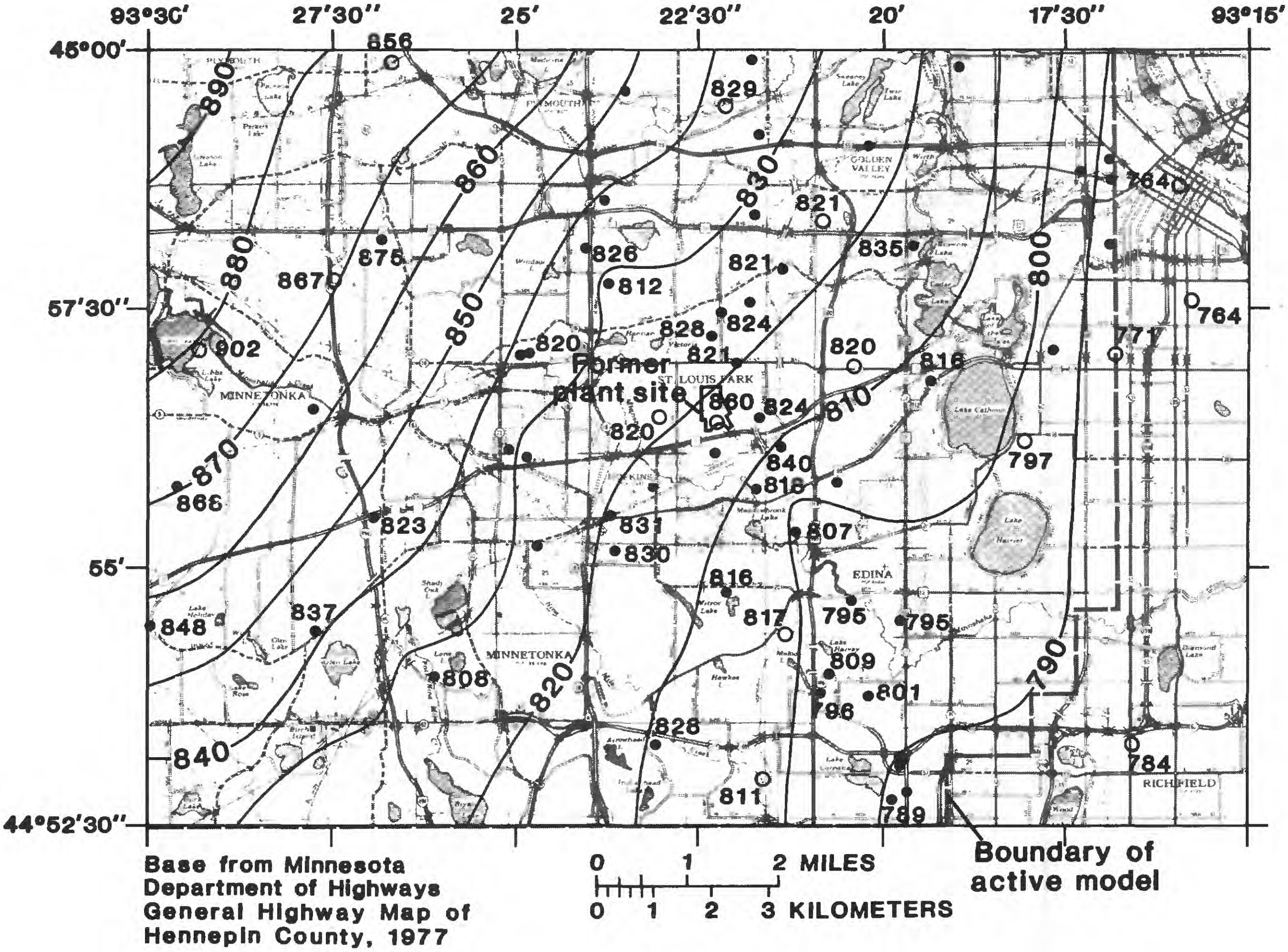
Table 9.--Computed water budget for the earlier part of summer 1979 in the 1977-80 transient simulation[1]

[A dash indicates no sources or sinks for a budget component]

Budget component	Sources (cubic feet per second)	Discharges (cubic feet per second)
Storage		
Layer 1	0.04	---
Layer 2	.10	---
Layer 3	0	---
Layer 4	.03	---
Leakage to top layer	57.74	---
Pumping		
Layer 1	---	11.38
Layer 2	---	36.01
Layer 3	---	0
Layer 4	---	2.51
Constant head		
Layer 1	2.11	7.53
Layer 2	8.31	103.28
Layer 3	0	0
Layer 4	97.14	5.19
Total	165.47	165.90

1 Corresponds with period for which water-level data are available, June 20-22, 1979.

The simulated potentiometric surface in the Prairie du Chien model layer is shown for summer and winter conditions on figures 20 and 21. In the area of the plant site, summer water levels are about 20 to 25 feet lower than winter water levels. However, gradients along streamlines, which average about 0.0025 through the plant site, do not vary significantly from summer to winter. Ground-water beneath the plant site generally flows to the south-southeast. The velocity of ground-water flow beneath the plant site in the Prairie du Chien is about 3 feet per day [assuming a gradient of 0.0025, hydraulic conductivity of 65 ft/d (table 6), and a porosity of 0.06 (Norvitch and others, 1974)].



EXPLANATION

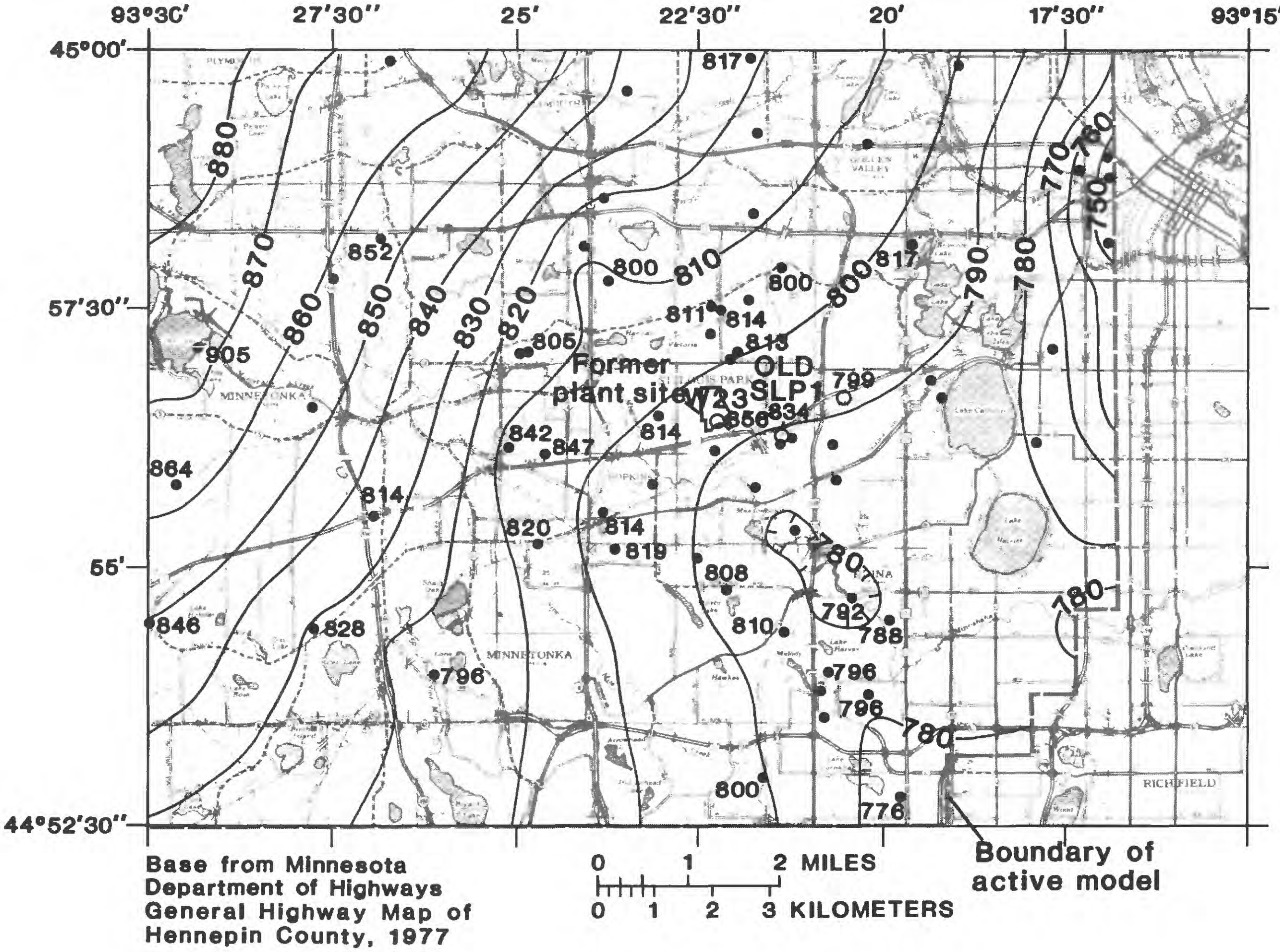
—810— Simulated potentiometric surface. Contour interval is 10 feet. Datum is sea level

● High-capacity production well

○ Observation well

820 Altitude of water level of well, in feet in Prairie du Chien-Jordan aquifer

Figure 20.--Model-calculated potentiometric surface for Prairie du Chien model layer (layer 2) for central part of the model area and water levels measured in wells, January 30-31, 1979



EXPLANATION

—780—	Simulated potentiometric surface. Contour interval is 10 feet. Datum is sea level
•	High-capacity production well
o	Observation well
814	Altitude of water level in well open to Prairie du Chien-Jordan aquifer, in feet

Figure 21.--Model-calculated potentiometric surface for Prairie du Chien model layer (layer 2) for central part of the model area and water levels measured in wells, June 20-22, 1979

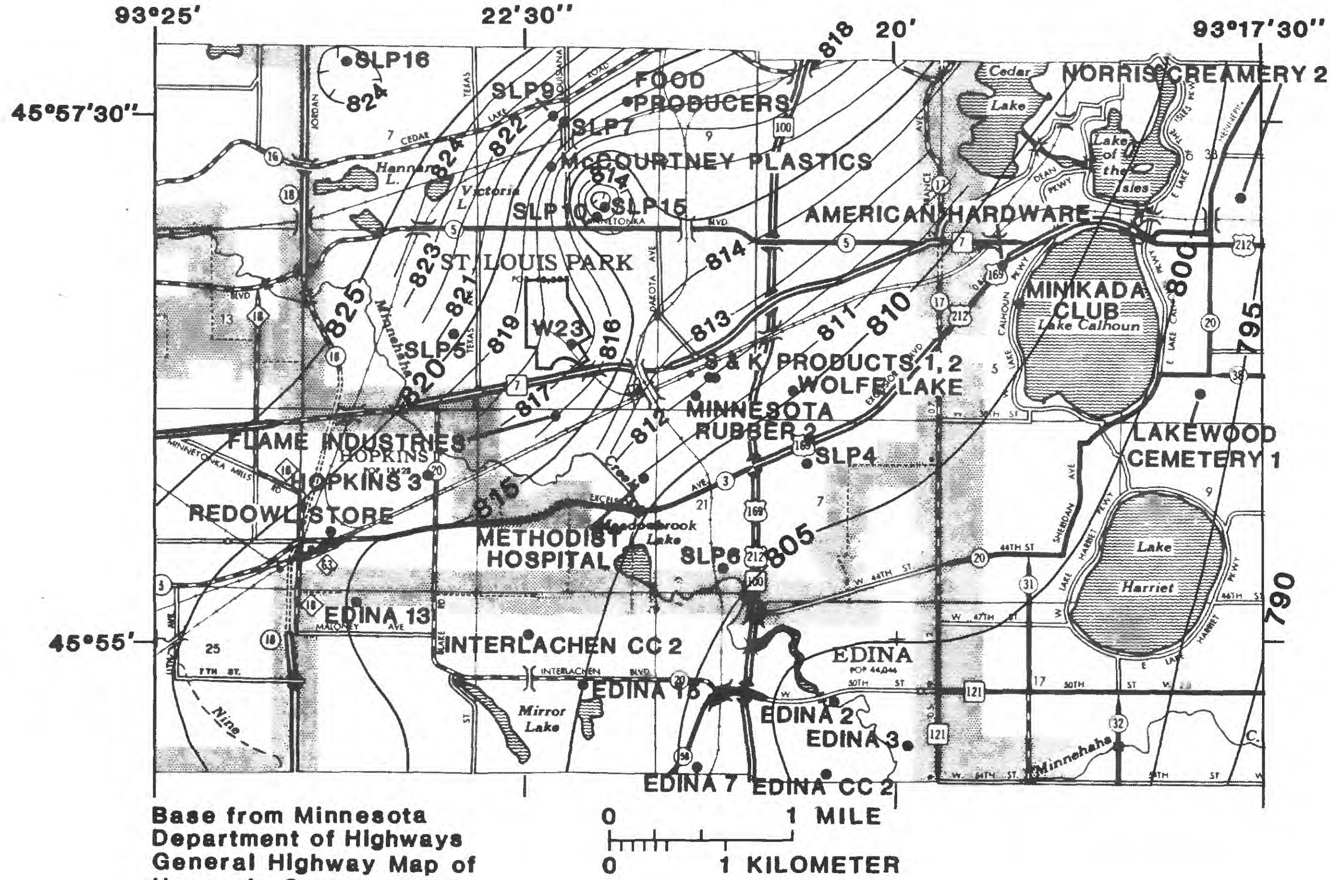
Implications of Model Results to Contaminant Transport

Calibrated simulations of the 1970's steady-state and 1977-80 transient models indicate that ground-water flow beneath the plant site is roughly parallel to the regional hydraulic gradient (east or southeast) (figs. 17, 20 and 21). These simulations included the influence of six multiaquifer wells, which injected water into the Prairie du Chien-Jordan aquifer from the basal part of the St. Peter Sandstone (Hult and Schoenberg, 1984). Withdrawal rates simulated at production wells during these simulations included mean annual values for the 1970's steady-state simulations and mean values for each season (transient simulations).

The presence of contaminants in the Prairie du Chien-Jordan aquifer in wells to the north (SLP10, 15, 7 and 9), west (SLP5) and southwest (Hopkins 3) of the plant site is difficult to explain by the flow-model results discussed so far. One possible explanation is that, during short periods of time, pumping stress varied significantly from average seasonal rates, and local ground-water gradients were significantly altered. Additional model simulations were made to examine some of these possibilities. The first of these simulated conditions of heavy pumping from SLP10 and SLP15 for a 1-month period (January 1977). The simulation included average monthly withdrawal rates for St. Louis Park municipal wells and average "spring" (January-April) rates for all other wells. Pumping rates simulated at St. Louis Park municipal wells are shown below:

WELL	MONTHLY PUMPING RATE (gallons per minute)
SLP 4	0
SLP 5	0
SLP 6	274
SLP 7	0
SLP 8	346
SLP 9	0
SLP10	176
SLP14	114
SLP15	580
SLP16	891

The results (fig. 22) indicate that during periods of heavy pumping from SLP10 and SLP15, local hydraulic gradients may have been altered, creating the potential for the transport of contaminants from the plant site to the wells. Near the plant site, the altitude of the model-calculated potentiometric surfaces in the Prairie du Chien and Jordan model layers were significantly influenced by flow into the aquifer through multiaquifer wells, particularily W23. The distance from the northeast corner of the plant site to SLP10 is about 2,000 feet. The simulated gradient along a streamline between these points, under conditions simulated for January 1977, is about 0.0025. If we assume a hydraulic conductivity of 65 ft/d (table 6) for the Prairie du Chien



Base from Minnesota Department of Highways General Highway Map of Hennepin County, 1977

EXPLANATION

—810— Simulated potentiometric surface. Contour interval 1 foot and 5 feet. Datum is sea level

•SLP16 High-flow production well in Prairie du Chien-Jordan aquifer

Former plant site

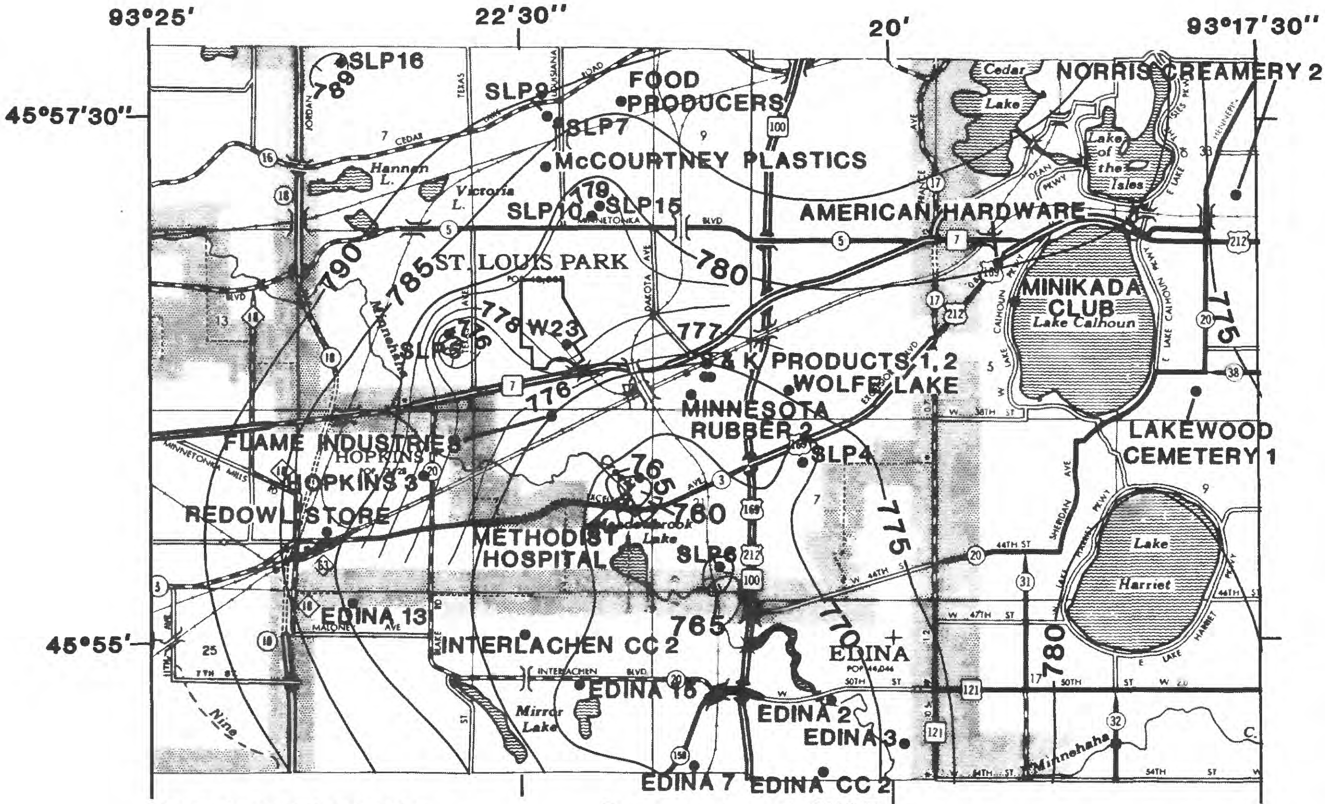
Figure 22.--Model-calculated potentiometric surface in the Prairie du Chien model layer (layer 2) for a period in which SLP10 and SLP15 were heavily pumped (January 1977)

model layer and a porosity of 6 percent (Norvitch and others, 1974), it would take ground water carrying contaminants about 2 years to flow, under this gradient, from the northeastern corner of the plant site to SLP10. The potentiometric surface shown on figure 22 does not indicate that a potential for the transport of contaminants was created from the assumed source of contamination in the southeast corner of the plant site (well W23) to wells SLP10 and SLP15. Variations in horizontal anisotropy of the Prairie du Chien-Jordan aquifer or short-term variations in local pumping may have had an influence on the migration of contaminants toward the northern part of the plant site.

A second simulation was made to examine ground-water gradients that may have resulted from a 1-month period of heavy pumping from SLP5 (August 1976). The simulation included the average monthly withdrawal rate for August 1976 for SLP5 (918 gal/min) and average "summer" (May-September) withdrawal rates for all other wells. The results (fig. 23) suggest that periods of heavy withdrawal from SLP5 may have created the potential for the transport of contaminants from the plant site to the well.

Several mechanisms for contamination of these "upgradient" wells have been presented by other investigators. Sunde (1974) suggested that the direction of ground-water flow from the plant site depended upon which wells in the area were being pumped at any given time. Barr (1977) constructed a ground-water-flow model which indicated that local pumping stress did not significantly alter the eastward component of ground-water flow through the site. These simulations, however, did not include the effects of multiaquifer wells which injected water into the Prairie du Chien model layer. Hult and Schoenberg (1984) presented data showing that multiaquifer flow in these wells significantly influenced the potentiometric surface of the Prairie du Chien-Jordan aquifer near the plant site. These data indicated that the water levels in well W23 were higher than water levels in all nearby surrounding wells in the aquifer, and that this cone of impression was created by water moving into the Prairie du Chien-Jordan aquifer from the overlying St. Peter aquifer through the bore of the well W23. The presence of this cone of impression, coupled with variable pumping at surrounding wells, was thought to have been sufficient to induce flow in all directions from well W23. Environmental Research and Technology (1983) used an analytical model to simulate the effects of production and multiaquifer wells on the potentiometric surface of the Prairie du Chien-Jordan aquifer near the plant site. When multiaquifer flow was not included in the simulations, results were similar to that of Barr (1977). In a second series of simulations, 21 "likely" multiaquifer-well sites were added, each injecting 150 gal/min into the aquifer. The potentiometric high created by these wells was found to be sufficient to induce flow from the plant site toward any of the nearby municipal wells if each of the wells in a particular area were pumped at full capacity to equilibrium.

Additional data are required to completely answer the question of the source of contamination in wells to the north, west, and southwest of the plant site. Observation wells are inadequate in number and wells currently used for observation are frequently pumped production wells that are not ideal for monitoring water levels. A second significant factor could be the effect of anisotropy in the Prairie du Chien portion of the Prairie du Chien-Jordan aquifer. Finally, weekly well-production data would be required to simulate



EXPLANATION

—785— Simulated potentiometric surface. Contour interval 1 foot and 5 feet. Datum is sea level

•SLP16 High-flow production well in Prairie du Chien-Jordan aquifer

 Former plant site

Figure 23.--Model-calculated potentiometric surface in the Prairie du Chien model layer (layer 2) for a period in which SLP5 was heavily pumped (August 1976)

the variable pumping in the St. Louis Park area and the resulting gradient changes.

Simulation of a Proposed Remedial-Action Plan

Several plans for contaminant-source and hydraulic-gradient control in the Prairie du Chien-Jordan aquifer have been proposed by the MPCA. The intent of these plans is to eliminate additional introduction of contamination from the principal source (well W23) and to limit the expansion of, or reduce, the contaminated volume. Under one of these plans, source control would consist of pumping well W23 at 50 gal/min, and discharging the water to the sanitary sewers.

Gradient control, under this plan, would consist of controlling the discharge from four wells: SLP4, SLP10, SLP15, and a new well to be constructed near the St. Louis Park City Hall. This new well and SLP4 would each be pumped continuously at 750 gal/min. Water pumped from these wells would be discharged directly to waste. Water pumped from SLP10 and SLP15 would be treated with GAC, to remove PAH, and discharged to the St. Louis Park water-distribution system.

Transient simulations were conducted to calculate the elevation of the potentiometric surface, in the Prairie du Chien-Jordan model layer, that could result from the remedial plan. Values of hydraulic head assigned at model boundaries and withdrawal rates, for most wells, are from 1980 data. Well discharge rates, for wells in the immediate vicinity of the site, are shown in table 10. Lateral (horizontal) isotropy was assumed for these simulations, but the relative head distributions predicted for the area between control wells and the plant site probably are valid even though the system may be anisotropic locally. Figures 24 and 25 show the calculated surfaces for typical "spring" and "summer" pumping seasons. During summer pumping seasons (fig. 25), increased withdrawal from the Methodist Hospital well significantly changes the ground-water flow to a southeast direction past the plant site. Pumping of the Methodist Hospital well effectively provides a barrier to flow to SLP6. During winter pumping conditions (fig 24), reduction of withdrawal from the Methodist Hospital well and other seasonal changes results in a shift in flow direction past the plant site to the east-southeast. Water flows toward the drawdown cone produced by SLP4 and barrier control to SLP6 is no longer provided by the Methodist Hospital well. For both pumping seasons, withdrawals from the proposed new well generally affects flow and the potentiometric surface northeast of the plant site.

Model-calibrated potentiometric surfaces are sensitive to changes in discharge rates at wells not intended to be directly controlled by the plan for remedial action. For example, when pumping from the Methodist Hospital well is not included in the "summer" pumping conditions (fig. 26), the direction of flow past the plant site shifts to the east toward the vicinity of SLP4 (examine figures 25 and 26 in the area bounded by W23, Methodist Hospital, SLP6 and SLP4). Barrier control is no longer provided to SLP6 by the Methodist Hospital well. The results of these simulations show that management of discharge from all wells in the immediate area is important. The Methodist

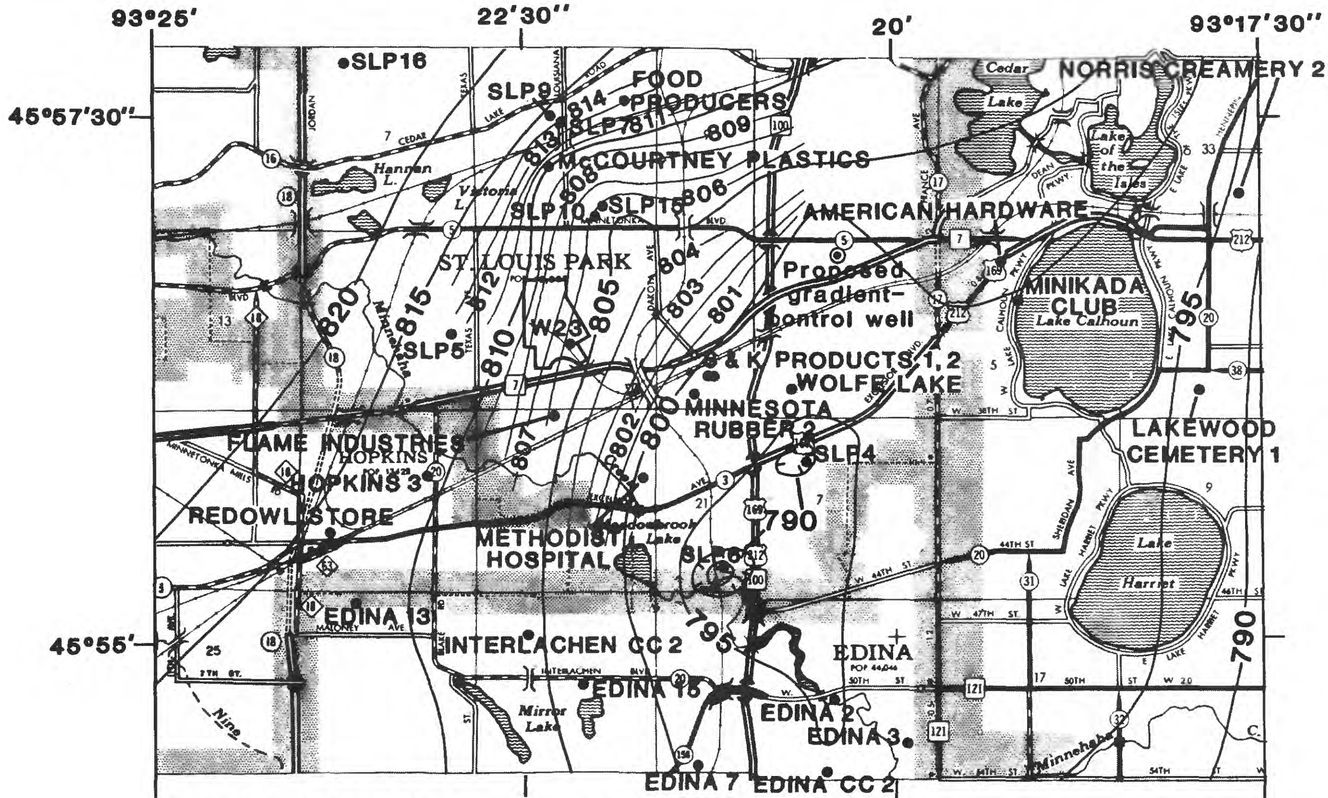
Table 10.--Withdrawal rates for remedial-action simulations

Well name	Pumping rate (gallons per minute)[1] Spring 1980	Summer 1980
SLP 5	167	320
SLP 6	1,100	660
SLP 7	40*	40*
SLP 8	570	910
SLP 9	93*	93*
SLP 10***	188*	188*
SLP 14	160	260
SLP 15	410*	410*
SLP 16	400	650
Flame Industries	26	30
Hopkins 3	300	485
Methodist Hospital	162	785
Minnesota Rubber	146	155
McCourtney Plastics	256	194
Food Producers	20	30
W23**	50	50
Proposed well***	750	750
SLP 4***	750	750

1/ Based on 1980 seasonal water-use data unless otherwise noted.
* 1970-77 mean annual rate.
** planned as source-control well.
*** planned as gradient-control well.

Hospital well provides barrier control for flow to SLP6, but captures flow, and possibly contaminants, that would otherwise be withdrawn from SLP4. When pumping from the well is stopped, as it is each winter, contaminants in the vicinity of the well have the potential to move toward SLP6.

Documentation of the apparent potentiometric high in the Prairie du Chien-Jordan aquifer in the vicinity of the plant site may be critical to the effectiveness of proposed gradient-control actions. The failure of the model to reproduce this feature does not necessarily mean that water-level measurements in W23 or St. Louis Park old well 1 (W112) are suspect or that the interpretation of water levels is wholly incorrect. It may imply that additional multi-aquifer wells exist, or that leakage into the Prairie du Chien-Jordan aquifer is anomalously high in the area.



Base from Minnesota Department of Highways General Highway Map of Hennepin County, 1977

0 1 MILE
0 1 KILOMETER

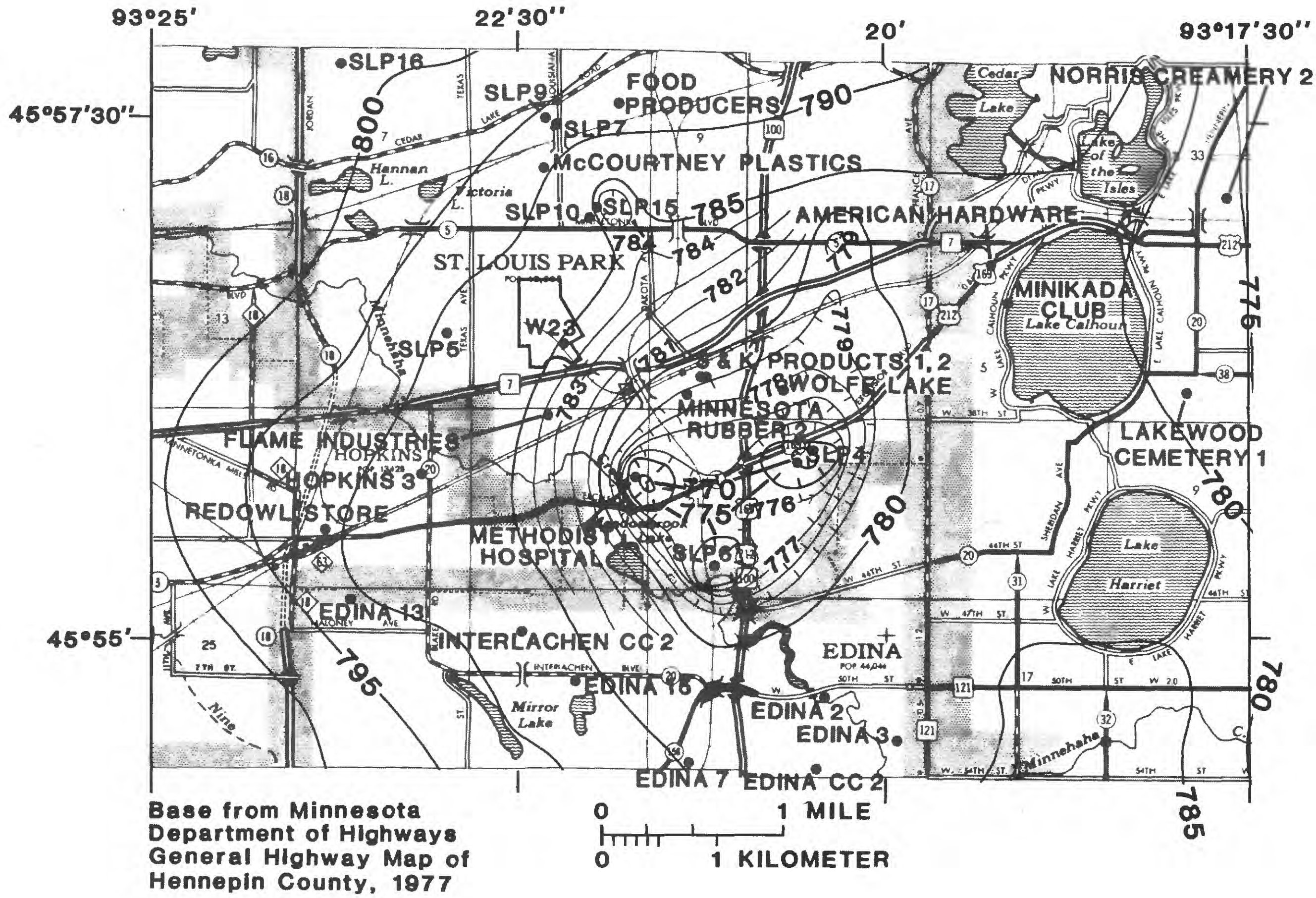
EXPLANATION

—785— Simulated potentiometric surface. Contour interval 1 foot and 5 feet. Datum is sea level

•SLP16 High-flow production well in Prairie du Chien-Jordan aquifer

Former plant site

Figure 24.--Model-calculated potentiometric surface in the Prairie du Chien model layer (layer 2) under proposed remedial-action plan--"spring" pumping conditions (January-April)



EXPLANATION

—780— Simulated potentiometric surface. Contour interval 1 foot and 5 feet. Datum is sea level

•SLP16 High-flow production well in Prairie du Chien-Jordan aquifer

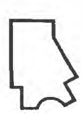
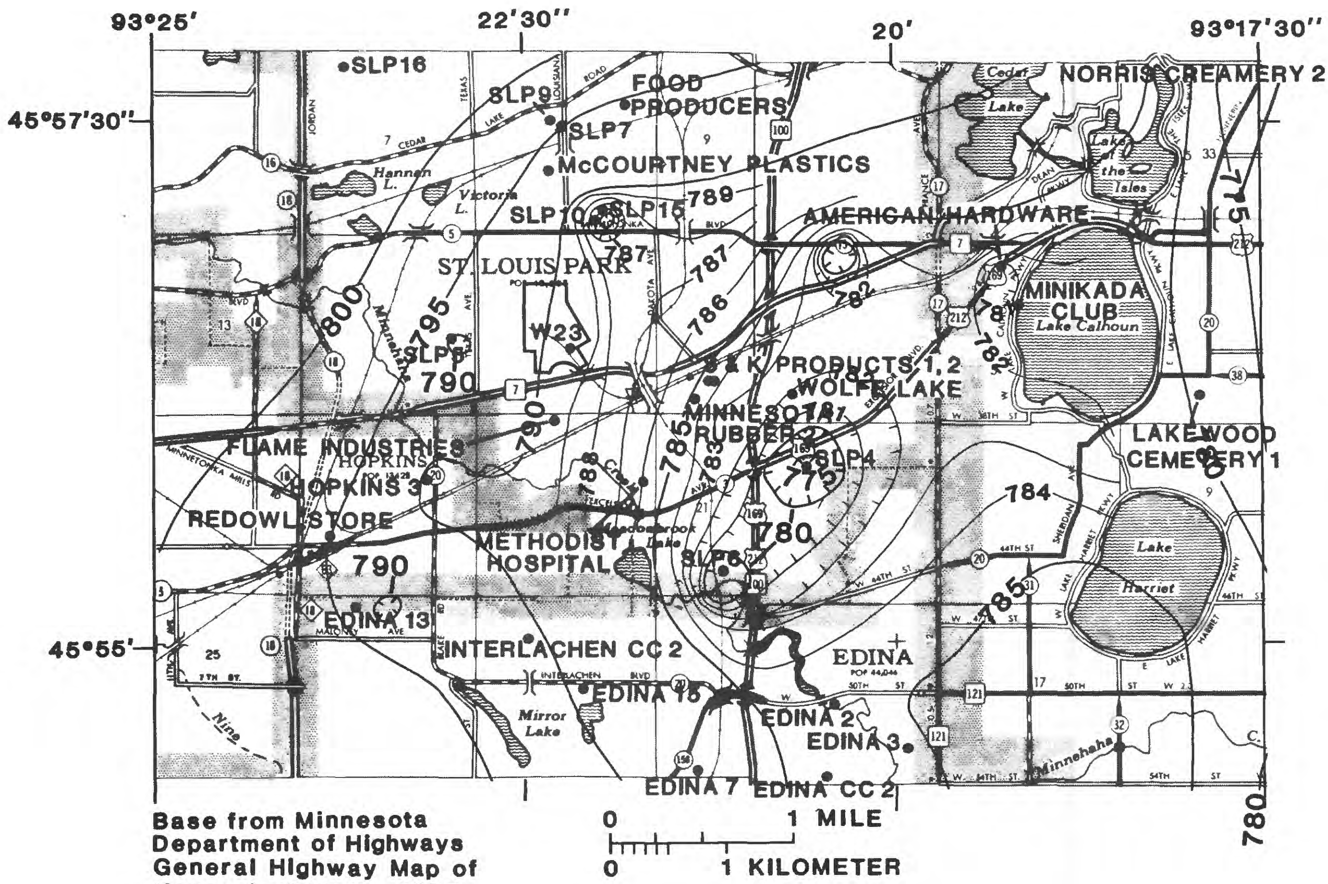
 Former plant site

Figure 25.--Model-calculated potentiometric surface in the Prairie du Chien model layer (layer 2) under proposed remedial-action plan-- "summer" pumping conditions (May-September)



EXPLANATION

—780— Simulated potentiometric surface. Contour interval 1 foot and 5 feet. Datum is sea level

•SLP16 High-flow production well in Prairie du Chien-Jordan aquifer

Former plant site

Figure 26.--Model-calculated potentiometric surface in the Prairie du Chien model layer (layer 2) under proposed remedial-action plan with no pumping from Methodist Hospital well--"summer" pumping conditions (May-September)

SUMARY AND CONCLUSIONS

A three-dimensional, ground-water-flow model of the Prairie du Chien-Jordan aquifer, St. Louis Park, Minnesota, was developed to aid in understanding the transport of ground-water contaminants (coal-tar derivatives) from a coal-tar distillation and wood-preserving plant. The modeled area, which includes most of eastern Hennepin County, was divided into a finite-difference grid containing 40 rows and 42 columns of cells. The dimensions of individual cells increases from the center of the grid (St. Louis Park area), where the cells represent squares with 400-foot sides.

Five geologic units are represented in the model. They include, in ascending order, the Jordan Sandstone, the Prairie du Chien Group (dolomite and sandy dolomite), the basal part of the St. Peter Sandstone (silty and sandy shale), the St. Peter Sandstone, and glacial deposits.

Initial values for model hydrologic properties were derived from available information. Ground-water withdrawal information from about 100 high-capacity wells was obtained from a data base constructed for a simulation model of the Twin Cities Metropolitan Area by the U.S. Geological Survey.

The model was calibrated during three phases. Steady-state calibration consisted of simulating a period before significant ground-water development (1885-1930) and a period of significant pumping stress (1970-77). Transient calibration was accomplished by simulating a period during which seasonal changes in potentiometric head were significant (1977-80). Sensitivity testing was used to aid in calibration by identifying model properties which, when changed, would result in the desired magnitude and direction of change in computed water levels. Leakage to the upper model layer and the vertical hydraulic conductivity of the basal confining unit of the St. Peter Sandstone were found to be the most sensitive model properties. The calibrated model calculates water levels to within 10 feet of most measured water levels.

The model was used to examine the impact of water discharged into the Prairie du Chien-Jordan aquifer through wells open to more than one aquifer. Simulations indicate that the potentiometric surface may have been elevated by as much as 3 feet by water introduced through the multiaquifer wells. This increase in the potentiometric surface is much less than indicated by measurements made in the multiaquifer wells, implying that water levels measured in the multiaquifer wells may not have represented hydraulic-head conditions in the aquifer immediately surrounding the wells.

The calibrated model was also used to gain a better understanding of the movement of coal-tar derivatives to wells north, west, and southwest of the plant site. The occurrence of contaminants in water pumped from these wells has been difficult to explain because they are located upgradient from the plant. Simulations suggest that, during periods of heavy withdrawal from certain of these wells, local hydraulic gradients may have been altered, resulting in the potential for movement of contaminants from the area of the plant to the wells. Cones of impression at multiaquifer wells near the plant site contributed to the reversal of local hydraulic gradients.

The simulated impact on the potentiometric surface of the Prairie du Chien-Jordan aquifer, resulting from a proposed gradient-control plan using five discharge wells, suggests that the plan will be effective in limiting the expansion of the contaminated volume. The simulations also indicate that manipulation of withdrawals from nearby wells, not controlled under the remedial-action plan, could alter the effectiveness of the gradient-control measures.

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