HYDROGEOLOGY OF SAND-PLAIN AQUIFERS IN CARLTON, KANABEC, AND PINE COUNTIES, EAST-CENTRAL MINNESOTA

By. C. F. Myette

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 85-4334

Prepared in cooperation with the

ONANEGOZIE RESOURCE CONSERVATION

AND DEVELOPMENT PROJECT and the

MINNESOTA DEPARTMENT OF NATURAL RESOURCES

St. Paul, Minnesota

1986

UNITED STATES DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS AND ABBREVIATIONS

For the convenience of readers who may prefer to use metric (International System) units rather than the inch pound units used in this report, values may be converted by using the following factors:

Multiply	By	To obtain
acre	0.4047	hectare (ha)
foot (ft)	0.3048	meter (m)
foot per second (ft/s)	0.3048	meter per second (m/s)
foot per day	0.3048	meter per day (m/d)
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per mile ($ft^3/s \cdot mi$)	0.04557	cubic meter per second per kilometer ($m^3/s \cdot km$)
gallon (gal)	3.785	liter (L)
gallon per minute (gal/min)	0.06308	liter per second (L/s)
million gallons per year (Mgal/yr)	3,785	cubic meters per year (m^3/yr)
billion gallons per year (Bgal/yr)	3,785,011	cubic meters per year (m^3/yr)
inch (in.)	25.4	millimeter (mm)
inch per year (in./yr)	25.4	millimeter per year (mm/yr)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)

HYDROGEOLOGY OF SAND-PLAIN AQUIFERS IN CARLTON, KANABEC, AND PINE COUNTIES, EAST-CENTRAL MINNESOTA

By C. F. Myette

ABSTRACT

Sand-plain aquifers in parts of Carlton, Kanabec, and Pine Counties in east-central Minnesota constitute a major aquifer system. They consist predominantly of fine to medium outwash sand with a combined areal extent of nearly 500 square miles. Saturated thickness in localized areas is as much as 90 feet. Depth to water generally is less than 20 feet. Transmissivities range from about 100 to 25,000 feet squared per day. Yields to properly constructed wells locally may exceed 2,000 gallons per minute. A reconnaissance of sandstone units underlying the outwash indicates that transmissivities of the sandstone aquifers range from 1,850 to 2,200 feet squared per day, and specific capacities range from 9 to 12 gallons per minute per foot of drawdown. Locally, wells may be capable of supplying several hundred gallons per minute. Regionally, the sand-plain and sandstone aquifers are poorly connected hydraulically at all locations tested except in a small localized area near Quamba in Kanabec County.

Ground water in the sand-plain aquifers can be classified chemically, based on predominant ions, as a calcium bicarbonate type that is moderately hard. Concentrations of dissolved solids range from 30 to 610 milligrams per liter. Except for locally high concentrations of iron and manganese, the quality of water is within State drinking-water standards and is suitable for most uses. There are no major differences between the quality of water in the sand-plain and sandstone aquifers.

Ground-water flow, aquifer response, aquifer development, and drought conditions were simulated for sand-plain aquifers areally extensive enough to be hydrologically significant. Simulation of expanded ground-water development and drought in northern Pine County indicates that regional ground-water levels may be lowered as much as 12 feet and ground-water discharge to streams may be reduced as much as 42 percent. Simulation of expanded development and drought in southern Pine County indicates that regional ground-water levels may be lowered as much as 25 feet and ground-water discharge to streams may be reduced as much as 65 percent. The simulations also indicate that each area, especially the northern Pine County area, will support substantial additional development without dewatering the aquifer or reducing streamflow significantly.

INTRODUCTION

Rapid urban, industrial, and agricultural development in Carlton, Kanabec, and Pine Counties has led to questions about ground-water availability and protection from contamination caused by improper land-use practices. Although many wells had been completed in the sand-plain and sandstone aquifers, little quantitative hydrogeologic data was available to guide development and management of water supplies. The Onanegozie Resource Conservation and Development Commission and the Minnesota Department of Natural Resources, realizing this need, requested the U.S. Geological Survey to conduct a water-resources study of the area.

Purpose and Scope

This report presents the results of a study to evaluate the hydrogeology and water quality of the major sand-plain aquifers in Carlton, Kanabec, and Pine Counties and to provide reconnaissance-level information on hydraulic characteristics and water quality of the sandstone aquifers in the area.

Specific objectives of the report are to (1) define the areal extent and saturated thickness of the sand-plain aquifers, (2) determine the availability and chemical quality of water from the sand-plain aquifers, (3) determine the potential effects of ground-water development on regional water levels and the effect on streams draining the sand plains, and (4) conduct a reconnaissance of the hydraulic characteristics and chemical quality of water from wells in the sandstone aquifers.

The study was limited in scope to an evaluation of major sand-plain aquifers and a reconnaissance of sandstone aquifers within the three-county area. Adequate supplies of water also may be obtained from wells completed in sand and gravel deposits buried within the drift and in fractures in basement rock. However, study of buried drift and basement-rock aquifers is beyond the scope of this investigation.

Simulations of ground-water flow are limited to sand-plain aquifers that have hydraulic properties and sufficient areal extent to be capable of supplying large quantities of water. Sandstone aquifers were not modeled because of the limited hydrogeologic data available.

Location and Description of the Study Area

The study area comprises Carlton, Pine, and Kanabec Counties in east-central Minnesota (fig. 1). It is drained by the St. Louis, Kettle, Snake, and St. Croix Rivers. Mean annual precipitation ranges from 27.5 in. near Cloquet to 28.9 in. near Mora and Pine City. Evapotranspiration rates range from 17.8 in. near Cloquet to 20.4 in. near Mora and Pine City (Helgesen and others, 1973; Lindholm and others, 1974, 1979; Olcott and others, 1978). Total areal extent of the sand-plain aquifers within the three counties is about 500 mi^2. The sandstone aquifers subcrop in an elongate shape that trends northeast-southwest and covers approximately 900 mi^2.

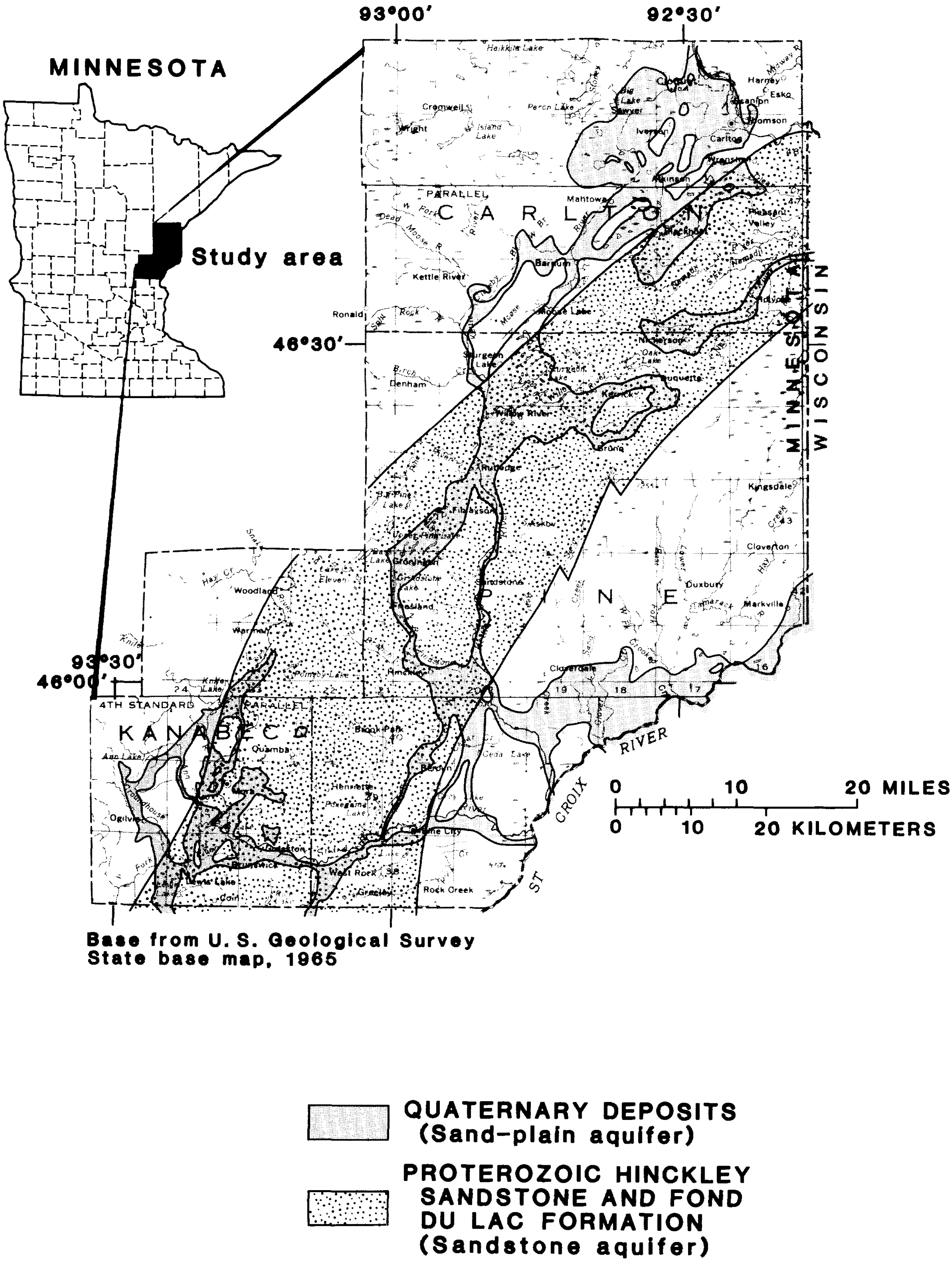


Figure 1.--Location and geology of study area (modified from Sims and Morey, 1972, pl. 1)

Previous Investigations

The earliest account of hydrogeologic investigations was by Winchell and others (1899) in which they describe the geology and drainage in the Carlton County area. Leverett and Sardeson (1917) described principal surficial features and general climatic conditions in northeastern Minnesota. Principal geologic structure was described by Leverett (1932), Thiel (1947), and Sims and Morey (1972). Principal glacial features were described by Leverett (1932), Wright (1956), Wright and Frey (1965), Wright and Ruhe (1965), Wright and others (1970), Sims and Morey (1972), and Wright (1973). The earliest reference to ground-water resources was by Thiel (1947) in which he discusses regional aquifers and municipal water supplies and chemical analysis of selected wells in each county. More detailed studies of hydrogeology and local well yields were done by Akin and Jones (1951) near Cloquet in Carlton County. Some of the latest studies that make generalizations about the climate, geology and water resources by drainage basin were part of the State "Hydrologic Atlas" series by Helgesen and others (1973), Lindholm and others (1974, 1979), and Olcott and others (1978). Within each of the atlases, the authors describe the major aquifers and their hydraulic characteristics, drainage areas and streamflow characteristics, the hydrologic budget, and chemical analyses of surface and ground water.

Methods of Investigation

Data for this report were collected and compiled from October 1979 to September 1982. Hydrogeologic maps were prepared from local soils maps, several hundred driller's logs, aerial photographs, and lithologic descriptions of about 750 augered test holes.

Sixty-seven of the test holes were completed with steel casings and screens and used to establish a regional observation-well network. Water-table maps were constructed based on water-level data obtained from logs of augered test holes and from observation wells. Hydrographs for each of the observation wells were based on periodic measurements and used to estimate seasonal and annual ground-water recharge, discharge, and storage characteristics of the aquifers. Water-quality samples were taken from each of the 67 wells in sand-plain aquifers and from 3 wells completed in sandstone aquifers. The data were used to establish regional baseline water quality for the sand-plain aquifers and, to a limited extent, the sandstone aquifers.

Hydraulic conductivities and transmissivities were estimated for each test hole based on sieve analyses and visual observations of grain size. To further aid in understanding the hydraulic properties of the aquifers, six aquifer tests were performed and analyzed to determine transmissivities and storage coefficients, which were used as a guide for estimating hydraulic properties of similar geologic materials.

Flow data were collected and compiled for the major streams. Frequency curves and low-flow data were used to evaluate the degree of hydraulic connection between the ground-water and surface-water systems.

Finite-difference, numerical models, based on a computer program by Trescott and others (1976), were constructed for parts of Pine County to simulate ground-water flow in the sand-plain aquifers and the hydraulic response of the system to withdrawals of ground water and to climatic changes.

Test-Hole and Well-Numbering System

Wells are identified by a unique 15-digit station number. The first 13 digits are based on the latitude and longitude coordinates and the last two digits are sequential numbers used to differentiate between stations having the same latitude and longitude. Wells and test holes also can be located by a local system of numbers and letters that represent the township, range, section, three letters designating quarter-quarter-quarter sections, and a two-digit sequential number that differentiates between stations having the same quarter-quarter-quarter section. The example in figure 2 shows site 040N18W18DBC01 (Pine County) to be in SW^1/4NW^1/4SE^1/4, sec. 18, T. 40 N., R. 18 W. The sequence number shows it to be the first well in the 10-acre quarter-quarter-quarter section.

Acknowledgments

The U.S. Geological Survey extends its appreciation to the U.S. Soil Conservation Service in Carlton, Kanabec, and Pine Counties for help in identifying local soil types. Special appreciation also is extended to property owners who allowed test holes and observation wells to be placed on their property and aquifer tests to be performed at some of those well sites. We also thank the cities of Cloquet, Hinckley, and Finlayson for the use of municipal wells for aquifer tests. The U.S. Geological Survey especially acknowledges the Onanegozie Resource Conservation and Development Commission and the Minnesota Department of Natural Resources for cooperation in this project.

HYDROGEOLOGY

Bedrock in the study area is composed of dense, poorly fractured, metamorphosed granite, interlayered volcanics and basalts, metasediments, and highly fractured and loosely cemented sandstones. These rocks are covered by glacial deposits that range from 0 to 400 ft thick (Helgesen and others, 1973; Lindholm and others, 1974, 1979; Olcott and others, 1978).

Crystalline bedrock generally occurs within 300 ft of the land surface and crops out locally throughout the three-county area (Thiel, 1947). Micaceous schist of the Thomson Formation is exposed near Barnum (Carlton County) and metasedimentary rocks can be observed near Denham (Pine County). Basic volcanic basalts underlie the area from southeastern Carlton County southward to the southern Pine County border with outcrops near Pine City and Cross Lake (Thiel, 1947). The Thomson Formation (slate) underlies most of Carlton County and parts of northwest Pine County. Typically, the crystalline bedrock formations are dense, with fractures providing the only storage of water. Yields to individual wells rarely exceed 10 gal/min.

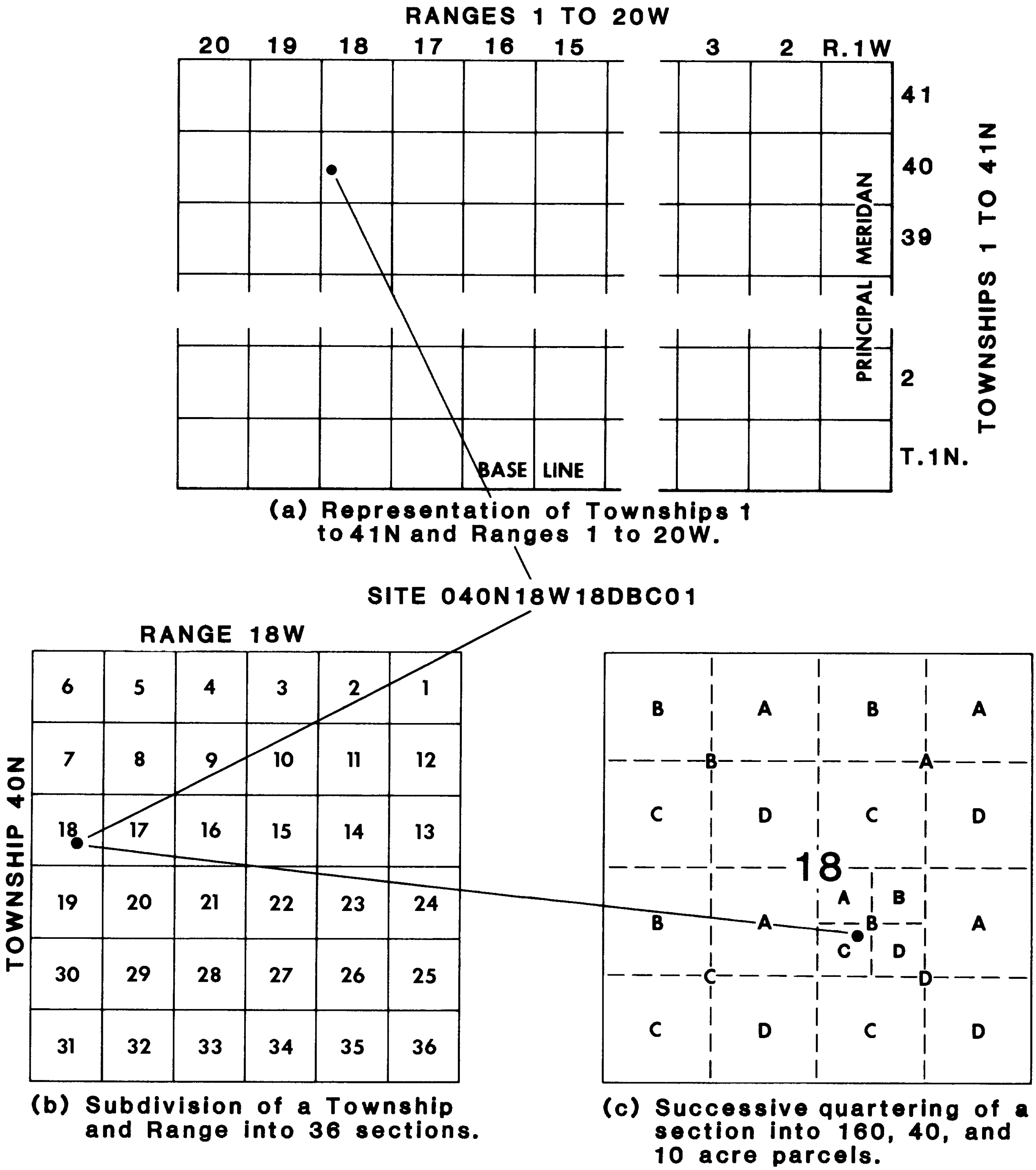


Figure 2.--Local test-hole and well-numbering system

Precambrian sandstone of the Hinckley and Fond du Lac Formation underlie part of each county in a band trending northeast to southwest. The Fond du Lac Formation crops out in Carlton County near Cloquet and Fond du Lac. Outcrops of the Hinckley Sandstone can be found near Sandstone, Askov, and Holyoke (Thiel, 1947). Depth to the sandstone formations generally ranges from 0 to 100 ft below land surface; they may be several thousand feet in thickness (Thiel, 1947). The sandstones generally are highly fractured and loosely cemented, providing for storage of large quantities of water. Yields to individual wells may exceed several hundred gal/min.

The Mount Simon Sandstone of Cambrian age underlies part of southeastern Pine County and crops out along the Snake River valley. In parts of the county, the Mount Simon Sandstone overlies the Hinckley Sandstone and in other areas lies directly over the igneous rocks (Thiel, 1947). Yields to individual wells locally may be large. Approximate boundaries of bedrock are shown in figure 3.

A complex series of glaciation has left virtually the entire study area covered by unconsolidated glacial drift deposits of Pleistocene age. The deposits consist mainly of till, lake deposits, stratified outwash, and ice-contact deposits. Most of the study area is covered by red drift from the Superior ice lobe. The extreme southwest corner of Pine County, however, is covered by gray drift from the Grantsberg ice sublobe. Approximate areal extent of the surficial deposits is shown in figure 4.

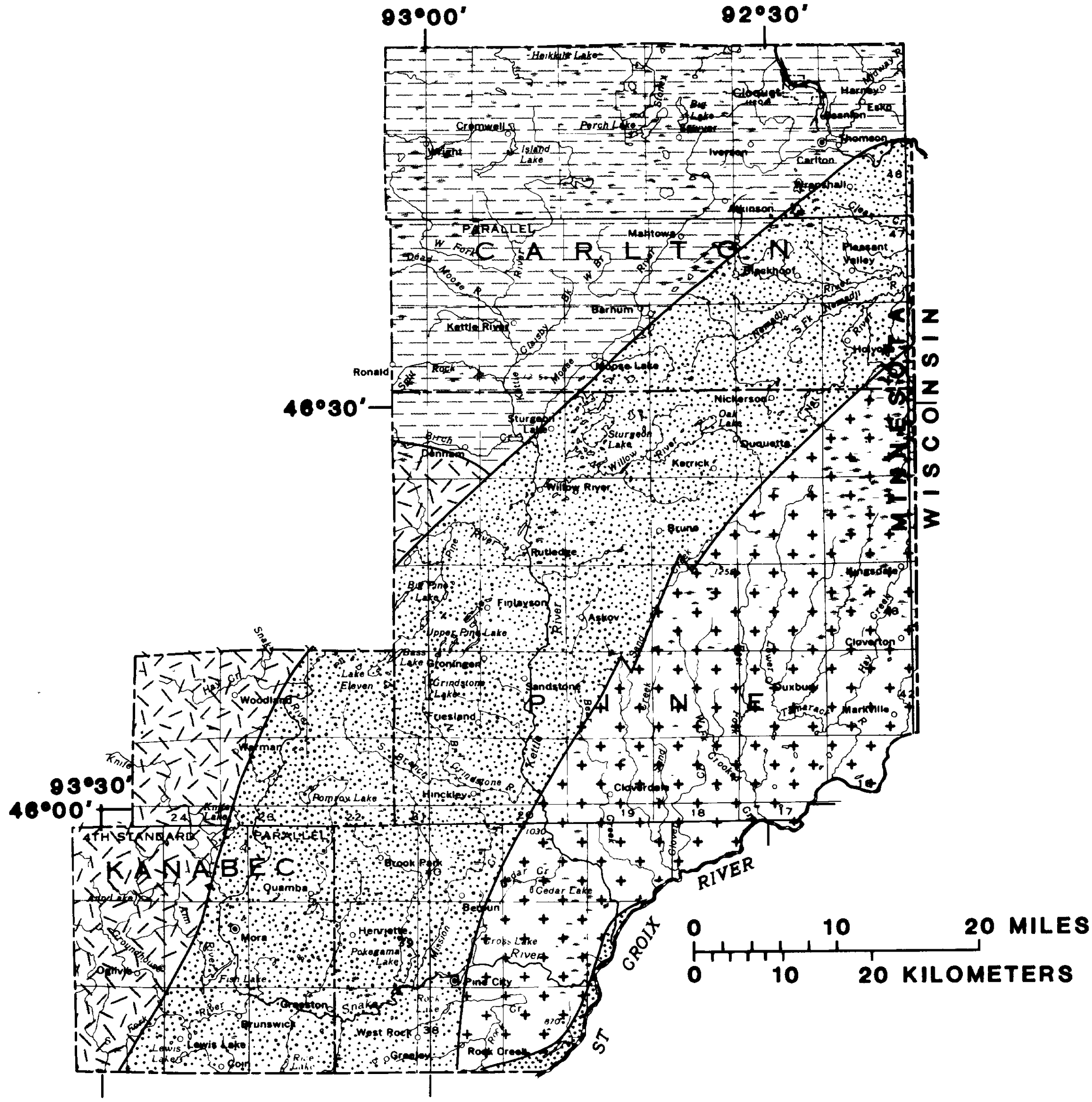
Till is an unsorted mixture of rock, silt, and clay, while lake deposits are sorted mixtures of silt and clay. Both till and lake deposits have low hydraulic conductivity and yield little water to wells.

The sand-plain aquifers are composed of outwash, well-sorted sand and gravel deposited during retreat of the glaciers. Outwash, consisting of very fine sand to coarse gravel, ranges in thickness from a featheredge near till boundaries to about 120 ft. Yields to wells completed in the sand-plain aquifers range from less than 10 to more than 2,000 gal/min. These sand and gravel deposits have the greatest potential for development of ground-water supplies within the drift because they generally have a high hydraulic conductivity.

In parts of the study area, sand, gravel, and till deposited by melting ice blocks form small, discontinuous, irregularly shaped topographic features, such as ice-contact ridges and valleys. These features, because of their composition and small size, have unpredictable water-yielding characteristics. In general, the deposits are not a large source of water and have not been investigated for this study.

Aquifer Distribution

The aquifers within the study area best suited for ground-water development are the sand-plains aquifers. Plate 1 shows the areal extent of the sand-plain aquifers. The aquifers trend from the northeastern corner of Carlton County southwest to the southwestern corner of Kanabec County. They also extend from southwestern Kanabec County to southeastern Pine County.



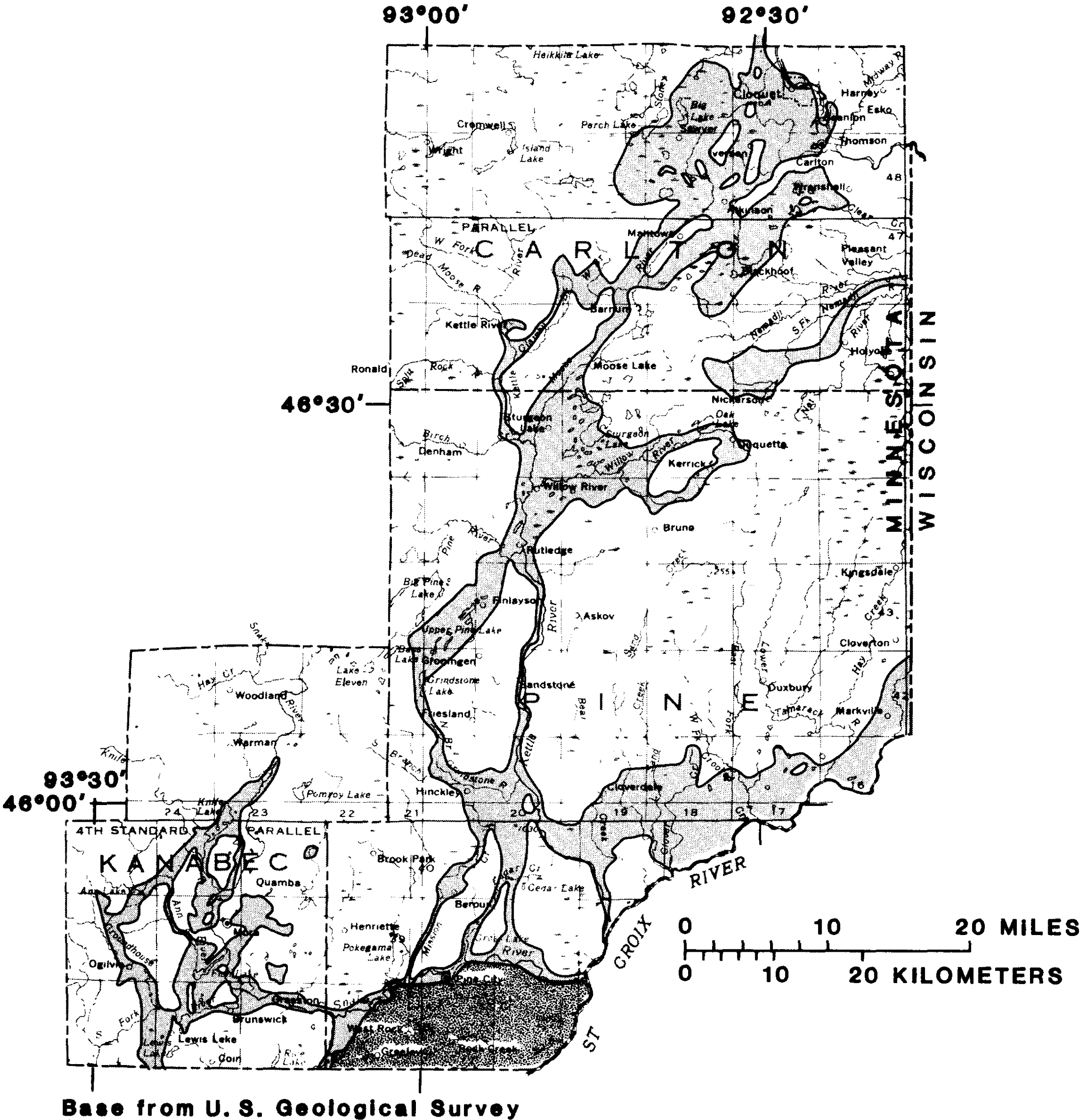
Base from U. S. Geological Survey
State base map, 1965

EXPLANATION

BEDROCK GEOLOGY

CAMBRIAN	CAMBRIAN ROCKS (Mt. Simon Sandstone)
LATE PROTEROZOIC	HINCKLEY SANDSTONE AND FOND DU LAC FORMATION
MIDDLE PROTEROZOIC	VOLCANIC ROCKS
EARLY PROTEROZOIC	INTRUSIVE ROCKS
	ARGILLITE AND GRAYWACKE (Thomson Formation and metasedimentary rocks)

Figure 3.--Bedrock geology of the study area (modified from Sims and Morey, 1972, pl. 1)



Base from U. S. Geological Survey
State base map, 1965

EXPLANATION

SURFICIAL DEPOSITS

QUATERNARY

- OUTWASH (Sand-plain aquifer)
- SUPERIOR LOBE TILL (Red drift)
- GRANTSBERG SUBLOBE TILL (Gray drift)

Figure 4.--Surficial geology of the study area (modified from Sims and Morey, 1972)

Extensive sand-plain aquifers in northern Carlton County, northern and southern Pine County, and southern Kanabec County are connected by elongate outwash-filled valleys eroded in the till.

Test drilling indicated that sand-plain aquifers overlie the sandstone aquifers in several areas (fig. 1). In almost every location, however, the aquifers are separated by a confining layer of till. In small 1- or 2-square-mile areas between Finlayson and Hinckley in Pine County and near Quamba in Kanabec County (pl. 1), test drilling indicates that no confining layer separates the aquifers. Outwash also may be in direct contact with sandstone aquifers near outcrops of the sandstone.

Aquifer Characteristics

The saturated thickness of the sand-plain aquifers was calculated by subtracting the altitude of the bottom of the aquifer (top of confining layer) from the altitude of the water table at each of the 67 observation wells and 750 test holes (lithologic logs for the test holes and observation wells are available for inspection in the files of the U.S. Geological Survey, St. Paul, Minn.). Saturated thickness in the three-county area averaged about 30 ft and ranged from 0 to 90 ft (pl. 1).

Hydraulic conductivity is a measure of the volume of water that will move in unit time under a unit hydraulic gradient through a unit area of an aquifer measured at right angles to the direction of flow. Hydraulic conductivity of the sand-plain aquifers was determined by aquifer tests and comparison of augered material with known grain-size analyses. Sieve analyses of representative samples from 38 test holes were made in the laboratory to determine particle-size distribution. Aquifer material in the study area ranges in size from clay and silt to coarse gravel (fig. 5). The bulk of the sand ranges in size from fine to very coarse. About 50 percent of the sand samples analyzed are medium sand. Larson (1976) established a relationship between relative grain size (based on the Wentworth scale) and estimated hydraulic conductivity (table 1). These values are similar to ones used by Helgesen and others (1977), Lindholm (1980), Miller (1982), and Myette (1983). Hydraulic conductivities also are affected by the degree of sorting of aquifer material. Lower hydraulic conductivities were assigned to poorly sorted materials and higher values to well-sorted materials. Estimated hydraulic conductivity values were assigned to each lithologic unit at each test-hole and observation-well site.

Transmissivity of the sand-plain aquifers was calculated at each test hole and observation well by summing the products of the saturated thickness of each lithologic unit below the water table and the hydraulic conductivity of the unit. Plate 2 shows the distribution of transmissivity. Transmissivity values in the sand and gravel areas generally range from less than 1,000 to 10,000 ft^2/d; however, about 15 percent of the area has transmissivities between 10,000 and 25,000 ft^2/d. The aquifer in these areas is most suitable for development of high-capacity wells for irrigation or industrial supplies.

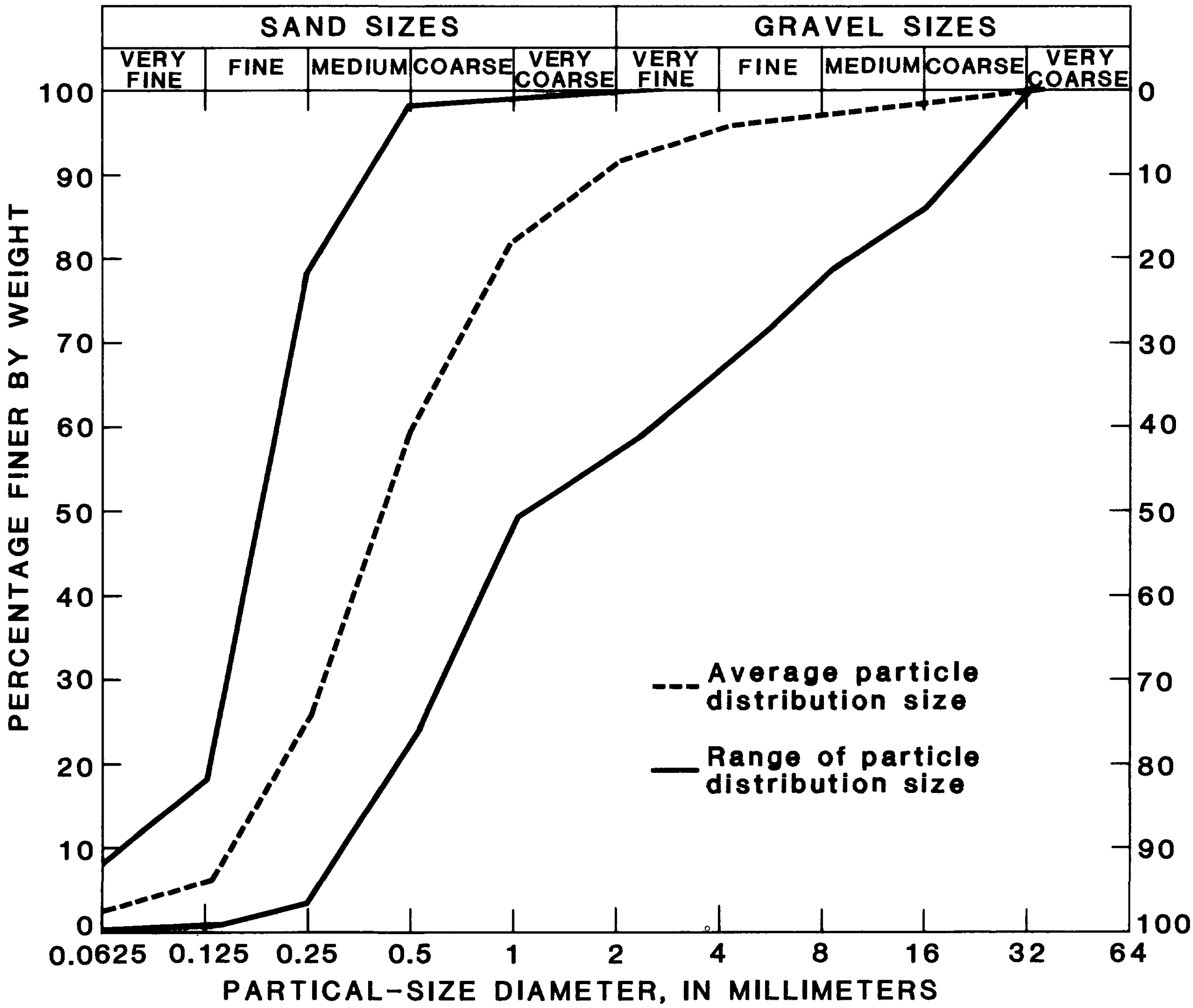


Figure 5.--Particle-size distribution of representative samples from 38 test holes in Carlton, Kanabec, and Pine Counties

Table 1.--Hydraulic conductivity of sand-plain aquifer materials (from Larson, 1976)

[mm, millimeters; ft/d, feet per day; >, greater than]

Predominant grain size (Wentworth scale)	Estimated hydraulic conductivity (ft/d)
Sand, very fine (0.0625-0.125 mm)	10-50
Sand, fine (0.125-0.250 mm)	50-100
Sand, medium (0.250-0.5 mm)	100-300
Sand, medium with gravel (0.250-72.0 mm)	200-400
Sand, coarse to very coarse (0.5-2.0 mm)	300-500
Sand, coarse to very coarse with gravel (0.5-72.0 mm)	400-600
Gravel (>2.0 mm)	500-700

Six aquifer tests in the three-county area, three in the sand-plain aquifer and three in the sandstone, provided data from which transmissivity and storage coefficient, specific yield, or specific storage were calculated. The storage coefficient of an unconfined aquifer is virtually equal to the specific yield of a well. The tests varied in duration from 24 to 48 hours. Transmissivities and storage coefficients of the unconfined sand-plain aquifers ranged from 8,300 to 12,000 ft^2/d and $1.3x10^{-1}$ to $3.3x10^{-1}$, respectively. Transmissivities and storage coefficients of the confined sandstone aquifer ranged from 1,850 to 2,200 ft^2/d and 2.2 to $6.4x10^{-3}$, respectively. Methods used to calculate the transmissivity and storage-coefficient values for the aquifers are described by Boulton (1963), Stallman (1965), and Lohman (1972). Aquifer-test results are site specific and represent values only at the test locations. They may, however, be used to approximate hydraulic properties in areas where the lithology is similar to the test site. Table 2 provides the results of the aquifer tests.

For the three tests of the sandstone aquifer, observation wells also were installed in the overlying sand-plain aquifer. At two of the three sites, the aquifers were separated by a thin (1 to 3 ft) confining layer of silty sand with clay lenses. At the Hinckley and Finlayson sites, at the end of the 48-hour test, there were no noticeable effects on the hydraulic head in the overlying unconfined sand-plain aquifer. However, increased pumping rates and duration of the test may result in leakage through the confining bed. At the third site near Quamba (Kanabec County), the aquifers are separated by a thin (1 ft)

Table 2.—Results of aquifer tests in the study area

[gal/min, gallons per minute; ft^2/d, feet squared per day; ft/d, feet per day; gal/min/ft, gallons per minute per foot]

					Aquifer characteristics					
Location	Length of test (hours)	Pumping rate (gal/min)	Lithology	Saturated thickness (feet)	Transmissivity (ft^2/d)	Hydraulic conductivity (ft/d)	Storage coefficient	Specific yield or specific storage (feet)	Specific capacity (gal/min/ft of drawdown)	Drawdown (feet)
UNCONFINED SAND-PLAIN AQUIFER										
045N20W25BCB	24	215	Sand, fine to very coarse; and gravel	59	12,000	200	$1.3x10^{-1}$	0.13(SY)	12	18
048N16W06CCB	46	150	Sand, coarse; and gravel	24	8,300	350	$1.7x10^{-1}$	0.17(SY)	15	10
049N17W17ADD	48	70	Sand, very coarse; and gravel	24	9,700	400	$3.3x10^{-1}$	0.33(SY)	35	2
CONFINED SANDSTONE AQUIFER										
040N23W23ABB	48	75	Sandstone, medium grained; loosely cemented	>89	2,200	25	$2.2x10^{-3}$	$2.5x10^{-5}$(SS)	12	6
041N21W24CDA	48	290	Sandstone, medium grained; loosely cemented	>430	1,900	4.6	$4.3x10^{-3}$	$1.0x10^{-5}$(SS)	8	36
043N20W18DCC	48	210	Sandstone, medium	>155	1,850	12	$6.4x10^{-3}$	$4.1x10^{-5}$(SS)	9	23

slightly silty sand lens. Drawdowns in well nests screened in the sand-plain aquifer and sandstone equidistant from the pumped well were approximately equal, suggesting that the aquifers are hydraulically connected. Additionally, prepumping heads were slightly lower in wells completed in the sandstone (vertical downward gradient of 0.004 ft/ft), which indicates vertical movement of water from the sand-plain aquifer to the sandstone aquifer.

Transmissivity values at each of the sandstone-aquifer-test sites are fairly similar; however, hydraulic conductivity values differ considerably. Variability within the sandstone aquifers probably is due largely to secondary permeability characteristics such as degree of cementation, weathering, and amount of fracturing. Each of these characteristics is site specific and highly variable regionally. (See plate 1 for location of aquifer tests.)

Ground-Water Flow and Water-Level Changes

Ground water moves from recharge areas of high hydraulic head to discharge areas of low head along flow lines generally perpendicular to the water-table contours. The configuration of the water table for the sand-plain aquifers (pl. 3) was based on water levels measured in augered test holes and in observation wells during September 1981. The September levels probably are fairly representative of average aquifer conditions because precipitation for the year was near normal and the cumulative departure from normal was very small. Regional ground-water flow in northern Carlton County generally is west to east; discharge is to the St. Louis River. Water-table elevations range from about 1,300 ft in the west to about 1,100 ft at the St. Louis River. In southern Carlton County, ground-water flow is predominantly north to south with discharge to the Moose and Moose Horn Rivers.

In northern Pine County, ground-water flow is north to south, and drainage is to the Grindstone, Kettle, and Moose Rivers. In southern Pine County, ground-water flow is north to south with drainage to the St. Croix River. Along the Snake River, flow is west to east and discharge is to the Snake River. Water-table elevations range from 1,100 ft in the north to about 800 ft in the south along the St. Croix River.

Ground-water flow in Kanabec County is predominantly north to south, draining to the Ann, Groundhouse, Knife, and Snake Rivers. In the southern part of the county, flow is generally west to east following the Groundhouse and Snake River valleys. Water-table elevations range from about 1,100 ft in western Kanabec County to 950 ft in the east along the Snake River.

In areas where sand-plain aquifers overlie sandstone aquifers, water-level data generally indicate higher hydraulic heads in the outwash than in the sandstone, suggesting downward movement of water and recharge to the underlying sandstone aquifers.

To document fluctuations of ground-water levels in the sand-plain aquifers, periodic measurements were made in 67 observation wells during 1980-81. Since 1981, water levels have been measured periodically in 13 representative wells by the U.S. Geological Survey as part of the statewide ground-water observation-well network.

Water levels in the sand-plain aquifers reflect a dynamic ground-water system that is influenced by recharge to and discharge from the aquifers. Water-level fluctuations depend on changes in hydrologic stress. The magnitude of water-level fluctuations is not uniform areally because of local differences in precipitation, evapotranspiration, soil type, aquifer characteristics, and hydraulic connection to lakes and streams. During 1981, for example, the range in fluctuation of water levels was less than 1 ft in well 039N24W20DDD (Kanabec County) to greater than 5 ft in well 046N19W10DDA (Pine County). Average water-level fluctuations during 1981 were about 2 ft as shown on figure 6. Because of seasonal and annual variations in climatic conditions, water-level fluctuations in other years probably will differ. Most recharge peaks occur during spring and late fall when precipitation is greatest and evapotranspiration lowest. The amount of fluctuation, because of specific yield, generally is greatest in uniform fine-grained material and least in uniform coarse-grained material. Water-level data for each of the observation wells can be obtained from the files of the U.S. Geological Survey, St. Paul, Minnesota.

Depth to water in the sand-plain aquifers varies with location because of changes in altitude of land surfaces, depth to the confining layer, and seasonal recharge. Most water levels in the study area are less than 20 ft below land surface, but they range from 0 to 50 ft. Depth to water usually is greater in areas of higher altitude, and water levels are at or near land surface in most of the stream valleys.

Aquifer Recharge

Infiltration of precipitation and snowmelt is the primary source of recharge to the sand-plain aquifers. The amount of recharge depends on several factors that include soil type, vegetative cover, antecedent soil moisture, and seasonal temperature variation; consequently, ground-water recharge often does not correlate well with the amount of precipitation and is difficult to predict on the basis of precipitation alone. Figure 7 illustrates the relationship between precipitation and ground-water levels at a representative site near Cloquet. At this location, ground-water levels and cumulative departure from average precipitation correlate reasonably well; a relationship that, although not perfect, provides insight into long-term aquifer recharge. Unfortunately, the observation well at the site was destroyed, making it impossible to extend the graph past 1974.

Recharge can be estimated from the change in ground-water level by multiplying that change by the specific yield of the aquifer at that point. Figure 8 illustrates the method (Lindholm, 1970) used to determine net effective recharge and annual residual change in storage in the aquifer in 1981 at well 038N23W06ABB (Kanabec County). Specific yield in the study area ranged from 0.13 to 0.33. For observation-well locations at which specific-yield data are not available, specific yields were estimated based on predominant grain size of the aquifer material at that point. Figure 9 shows the relationship of specific yield to grain size used by Todd (1959, p. 24). Average annual recharge to the sand-plain aquifers, based on 56 hydrographs developed for 1981, was 5.9 in. Average recharge, based on wells with at least 10 years of record at Willow

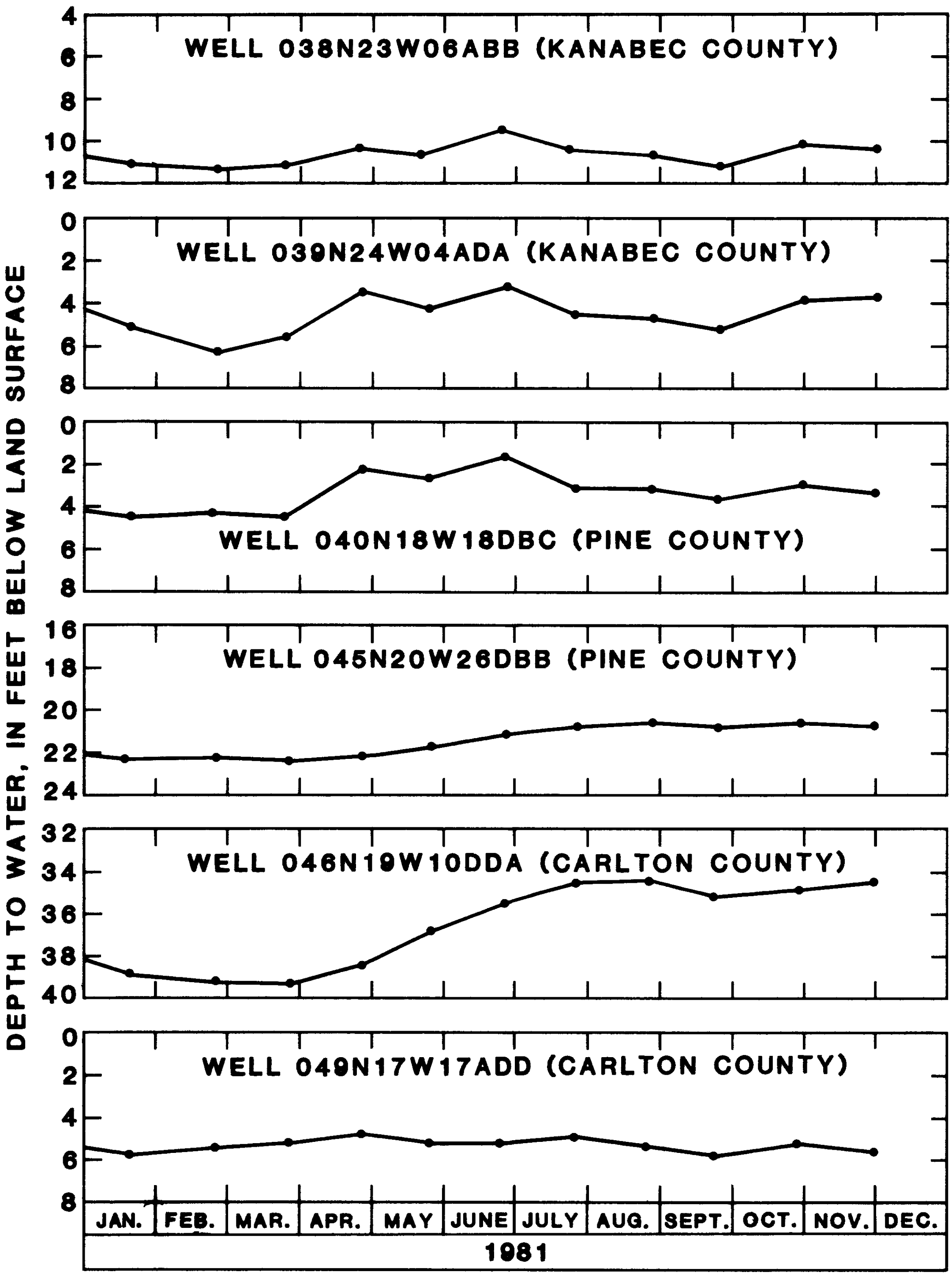


Figure 6.--Water levels in representative observation wells

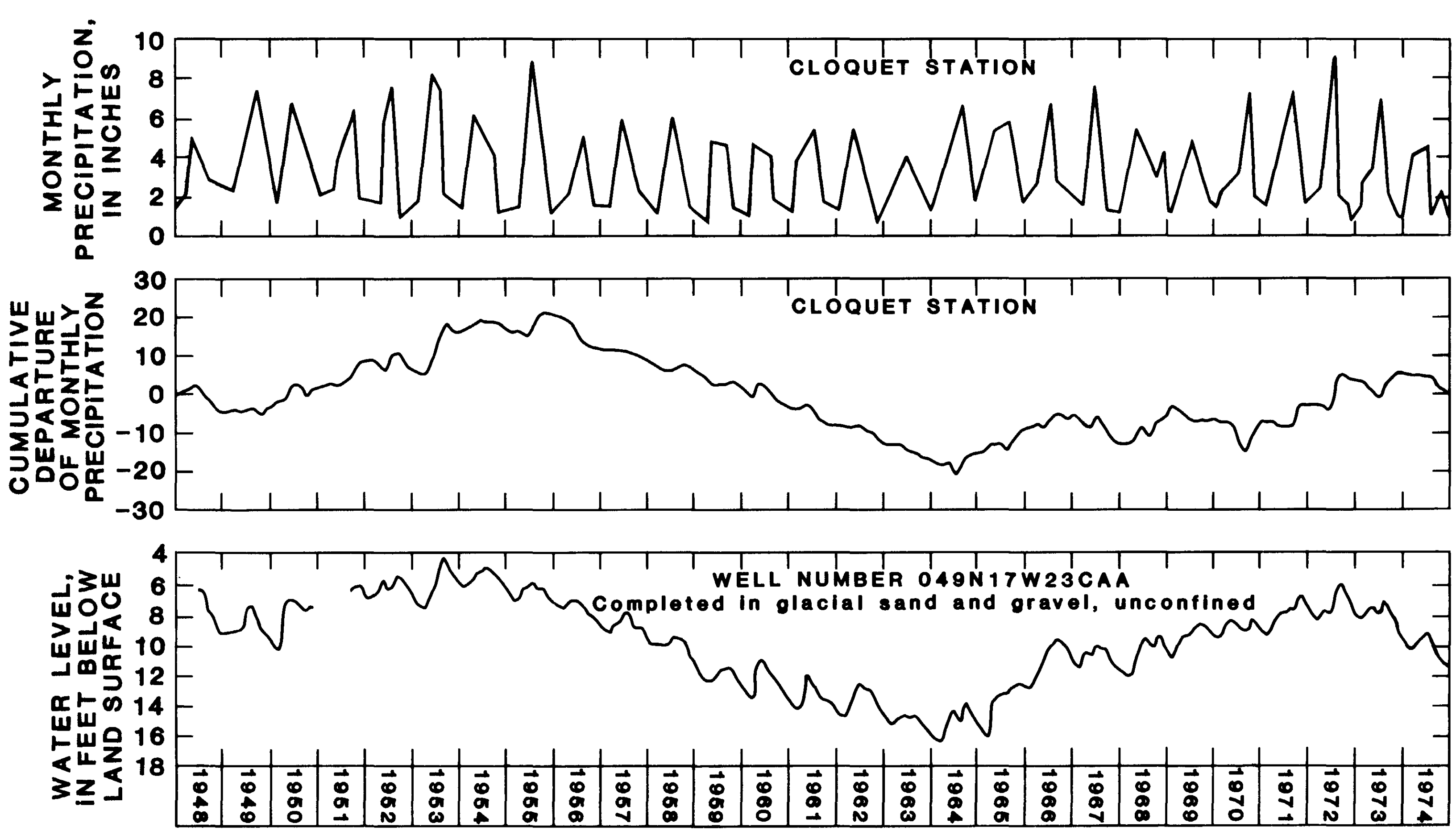


Figure 7.--Relationship of precipitation and ground-water levels near Cloquet, 1948-74 (modified from Lindholm and others, 1979, sheet 1)

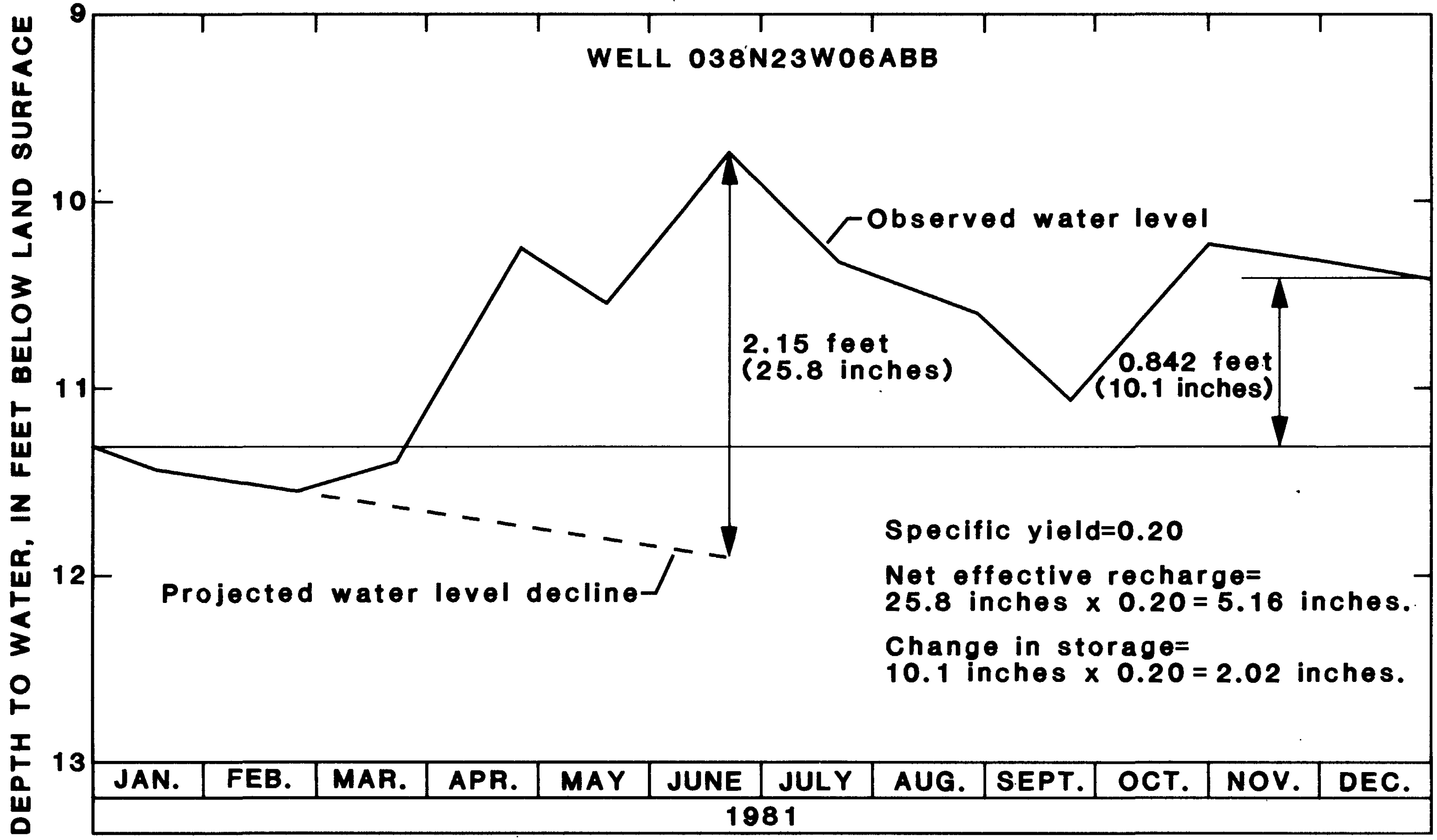


Figure 8.--Representative hydrograph illustrating method used to determine net effective recharge and change in amount of water in storage in the sand-plain aquifer during 1981

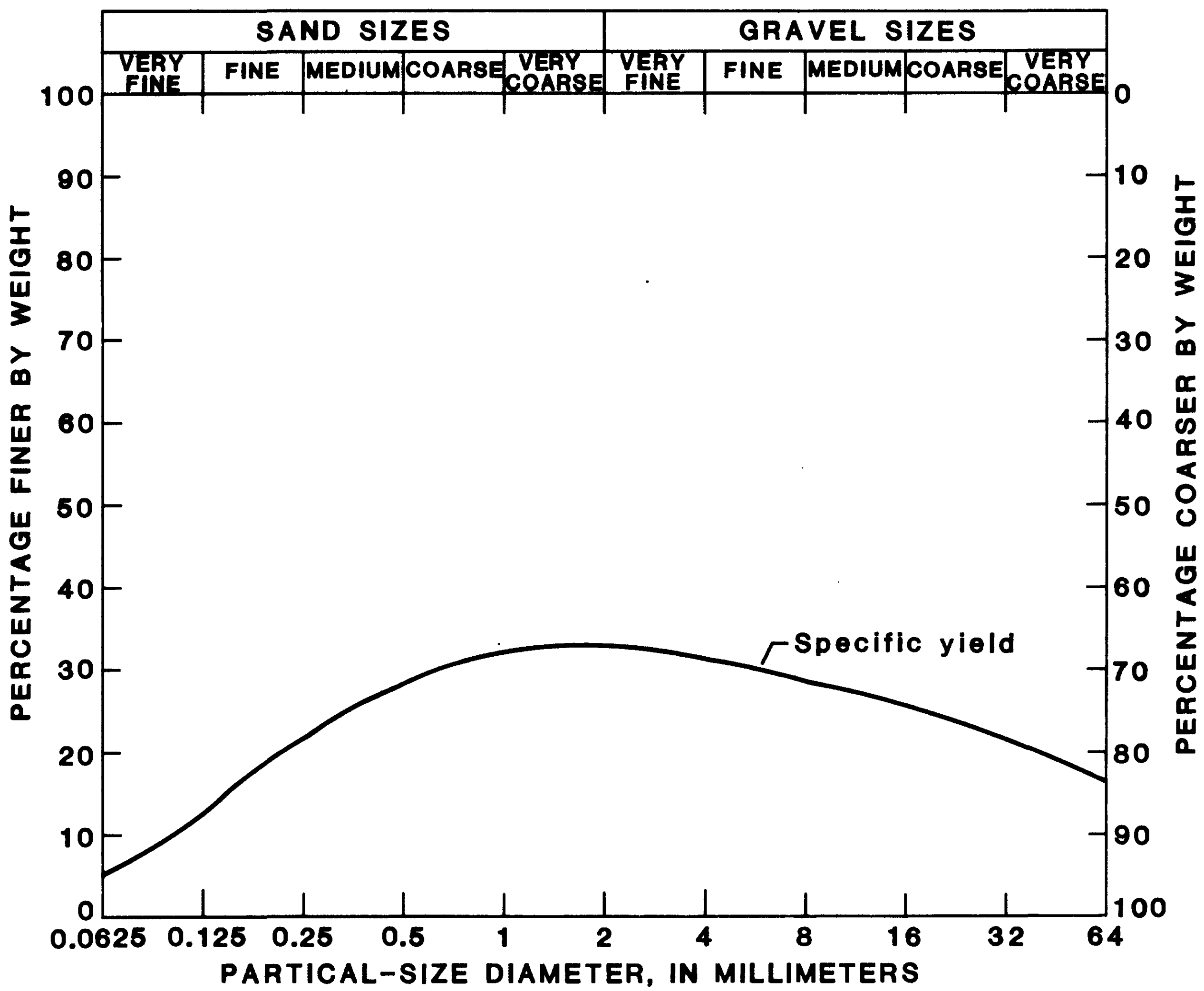


Figure 9.--Specific-yield variations with grain size (modified from Todd, 1959, p.24)

River in Pine County and at Cloquet in Carlton County, was 4.5 and 12.7 in., respectively. Estimates of recharge also were made based on base flow of the Kettle River from Sturgeon Lake to Sandstone and of the Blackhoof River near Holyoke. In these areas, net base-flow gains were both 0.54 ft^3/sec.mi or the equivalent of 7.3 in./yr. These recharge rates compare favorably with estimates of recharge in areas of similar geology obtained by Larson (1976), Helgesen and others (1977), Lindholm (1980), and Myette (1983).

The water-table configuration (pl. 3) indicates locally that some water may be recharging the sand-plain aquifers from the adjacent till. However, because the saturated thickness and the hydraulic conductivity of the till (10^{-5} to 10^{-1} ft/d; Siegel and Ericson, 1980, p. 7) is very low in comparison to the sand and gravel aquifer (10 to 250 ft/d), leakage across the boundary is not a significant percentage of the total amount of recharge to the aquifer.

Additionally, as much as 10 to 15 percent of the water applied for irrigation returns to the aquifer through infiltration (G. F. Lindholm, U.S. Geological Survey, oral commun., 1982). The quantity of water returned depends on the rates of application and evapotranspiration at time of application. Presently, because the amount of water used for irrigation is insignificant, the return flow is not significant.

Aquifer Discharge

Ground-water discharges from the sand-plain aquifers primarily through evapotranspiration, leakage to streams, and pumpage. The potential evapotranspiration rates for the study area were calculated by Helgesen and others (1973) and Lindholm and others (1974, 1979) using the method of Thornthwaite and Mather (1957). Potential evapotranspiration ranges from 17.8 in. annually in the northern part of the study area (Lindholm and others, 1979) to 20.4 in. annually in the southern part (Lindholm and others, 1974). Potential evapotranspiration is equivalent to about 65 or 70 percent of the average annual precipitation in the respective areas, thus reducing the potential for ground-water recharge. Evapotranspiration occurs largely in areas where ground-water levels are less than 5 ft below land surface; it may be a significant percentage of ground-water discharge in areas of lakes and swamps.

Ground water also discharges as leakage to streams. Flow-duration curves of representative streams within the study area (fig. 10) indicate the significance of base flow. The curves were prepared by the total-period method based on average daily discharge. Searcy (1959) suggests that a steeply sloping duration curve denotes highly variable flow derived largely from surface runoff, while a flatter slope denotes fairly constant flow derived largely from surface- or ground-water storage. Curves for rivers throughout the study area generally have moderate slopes with flattened tails that do not drop off to zero, which indicates that leakage from the aquifer storage sustains flow during dry periods. The amount of leakage to or from the stream depends on the difference in heads and the hydraulic connection between the aquifer and stream and, therefore, will vary locally. Aquifer discharge to streams equals about 2 to 3 in. annually and is a relatively small part of the total hydrologic budget. It is, however, equivalent to about 30 to 35 percent of ground water that discharges from the aquifer. Most of the remainder discharges by

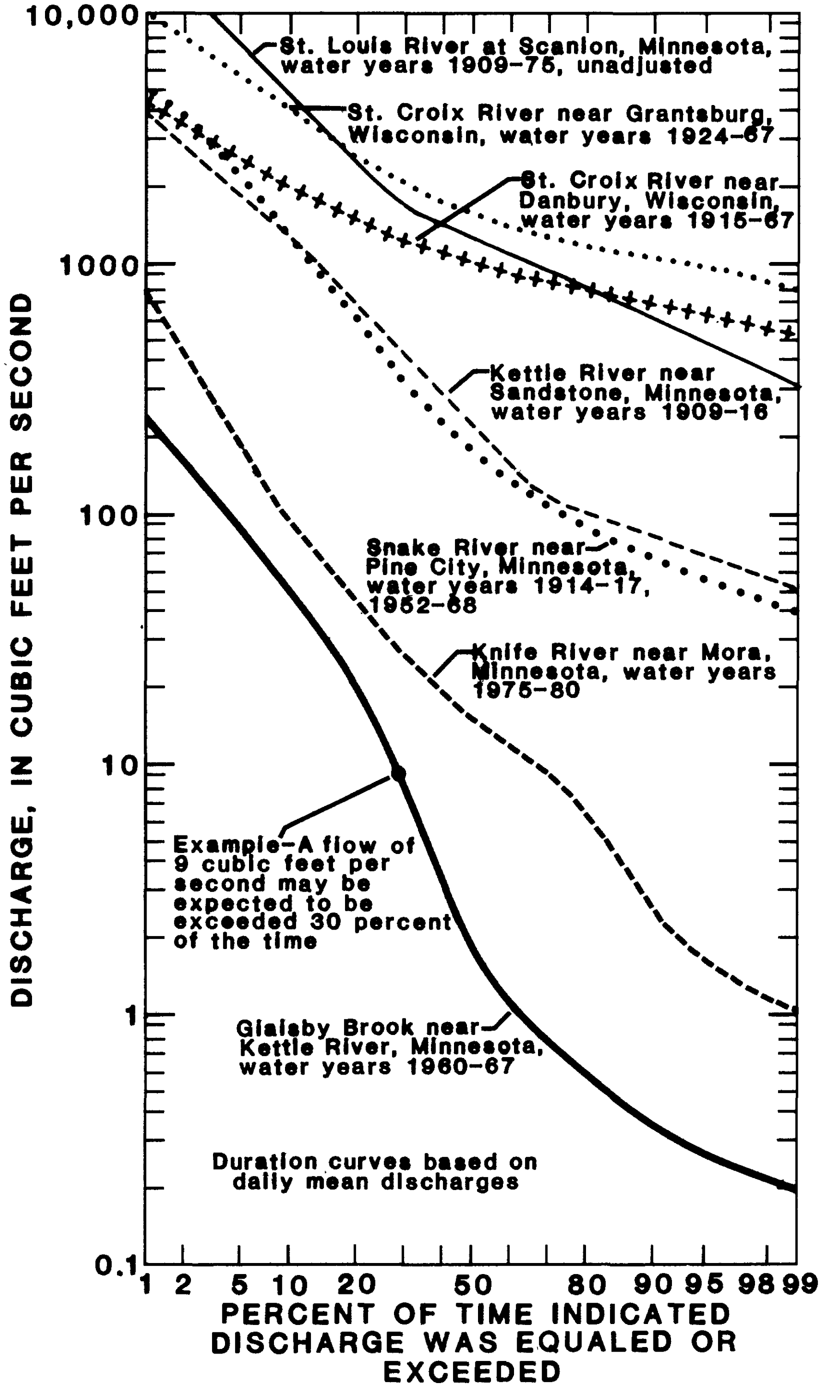


Figure 10.--Flow-duration curves for representative streams within the study area (modified from Helgesen and others, 1973; Lindholm and others, 1974, 1979; Olcott and others, 1978)

evapotranspiration. Drainage basins underlain by outwash (sand-plain aquifers) yield more ground-water discharge per square mile than basins underlain by till or fine-grained lake deposits (Helgesen and others, 1973).

Reported pumpage of wells completed in sand-plain aquifers during 1980 was about 70 Mgal/yr in Carlton County, about 70 Mgal/yr in northern Pine, and 26 Mgal/yr in southern Pine County. No pumpage was reported in Kanabec County (Bibbs, T., Department of Natural Resources, St. Paul, written commun., 1982). This pumpage is equivalent to only 0.7 ft^3/s within the three-county area and is only locally significant. Water-use records obtained from the Minnesota Department of Natural Resources (1980, most current data) show that there are fewer than 10 large-capacity water users pumping from the sand-plain aquifers within the study area. Actual water use for these three counties, however, probably is considerably greater than reported pumpage because most of the municipalities use water from either buried sand and gravel or bedrock aquifers, which is not included in these figures.

In localized areas, the sand-plain aquifer discharges to the sandstone aquifer by vertical leakage. Test drilling and observation-well data show that direct hydraulic connection between the aquifers is limited to small areas about 1 to 2 mi^2 in size. In addition, slight differences in hydraulic head (vertical gradient of 0.004 ft/ft) are observed in those areas. Consequently, leakage from the sand-plain aquifer to the sandstone aquifer is a small part of the total hydrologic budget of the sand-plain aquifer.

POTENTIAL YIELD OF WELLS

Potential yields of wells in the sand-plain aquifers can be estimated from transmissivity and saturated-thickness data. The method for calculation of potential yield is based on the Theis (1935) equation as modified by Jacob (1944), which accounts for dewatering and consequent reduction of transmissivity of an unconfined aquifer near a pumping well. Figure 11 illustrates the analytical technique used to estimate potential yield in the three-county area. Estimates of potential yield are subject to the following assumptions:

1. Wells tapping the aquifer are open to the full saturated thickness, are 100 percent efficient, and are at least 12 in. in diameter;

2. Drawdown after 30 days of pumping is equal to two thirds the original saturated thickness;

3. Interference from other pumping wells and effects of hydrologic boundaries are negligible;

4. Specific yield of the aquifer is 0.20.

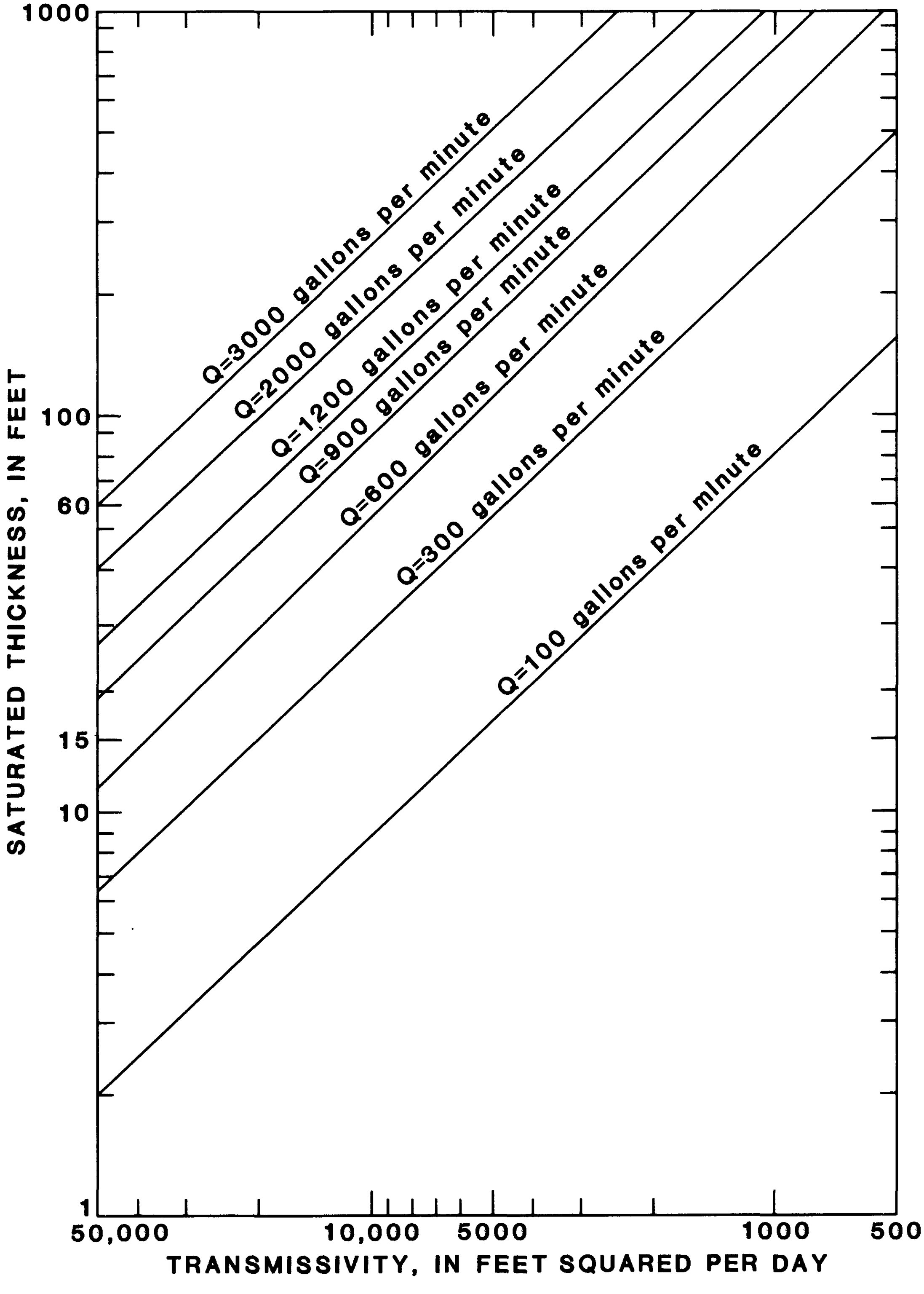


Figure 11.--Estimated potential yield of wells completed in sand-plain aquifers based on saturated thickness and transmissivity (modified from Miller, 1982, p.13)

Plate 4 shows areas in which estimated potential yields to wells completed in sand-plain aquifers are in excess of 100 gal/min. In some localized areas, properly constructed wells can yield 2,000 gal/min, but well yields greater than 100 gal/min are available from only about 20 percent of the aquifer area.

Actual yields to individual wells may differ from the estimated values shown on plate 4 because of proximity to pumping wells, hydrologic boundaries, and wells located in areas where there is substantial variation in hydraulic conductivity. Withdrawals in areas of marginal potential may be increased by use of infiltration ponds or by connecting several wells together to supply one system.

Well Interference

Withdrawal of water from a well causes drawdown of water levels around the well creating a cone of influence. The size of the cone depends on the volume and rate at which the well is pumped and on the hydraulic properties of the aquifer. When a pumping well is in close proximity to another pumping well or a hydrologic boundary, the cones of influence overlap or the boundary is intercepted, which affects drawdowns.

Well interference is a normal consequence of aquifer development and should be expected as ground-water pumpage increases. Figure 12 shows three possible effects that hydrologic boundaries and other pumping wells can have on a cone of influence. The effects of a well pumping near an impermeable till boundary is illustrated on the left of figure 12. Drawdown is greater between the well and boundary because of lack of ground-water flow from the boundary. The effect of a stream or lake boundary is illustrated in the middle of the figure. Drawdowns are less between the well and the boundary because additional water is being induced from the stream or lake to the aquifer. A stream or lake boundary, however, can act as a recharge source only as long as induction to the aquifer is less than stream or lake storage, or rate of replenishment. The effect of nearby pumping wells is illustrated on the right of figure 12. Drawdown is greater between the two pumping wells and is approximately equal to the sum of the drawdowns that would result at that point if each well was pumped singly.

The method used to determine the cone of influence (drawdown) is an analytical technique based on the Theis (1935) nonequilibrium equation. Figure 13 illustrates the theoretical relationship of drawdown to various distances from a pumped well and for various values of aquifer transmissivity. The curves were developed using a pumping rate of 300 gal/min, however, the graph can be used with other pumping rates because the drawdown is essentially directly proportional to the pumping rate. For example, if drawdown for a well pumping 600 gal/min were to be calculated, it would be approximately twice that shown in figure 13.

Under the water-table conditions present in the sand-plain aquifers, the curves in figure 13 cannot be applied directly. In addition, one must account for dewatering of the aquifer in the vicinity of the well (fig. 14; Jacob, 1944).

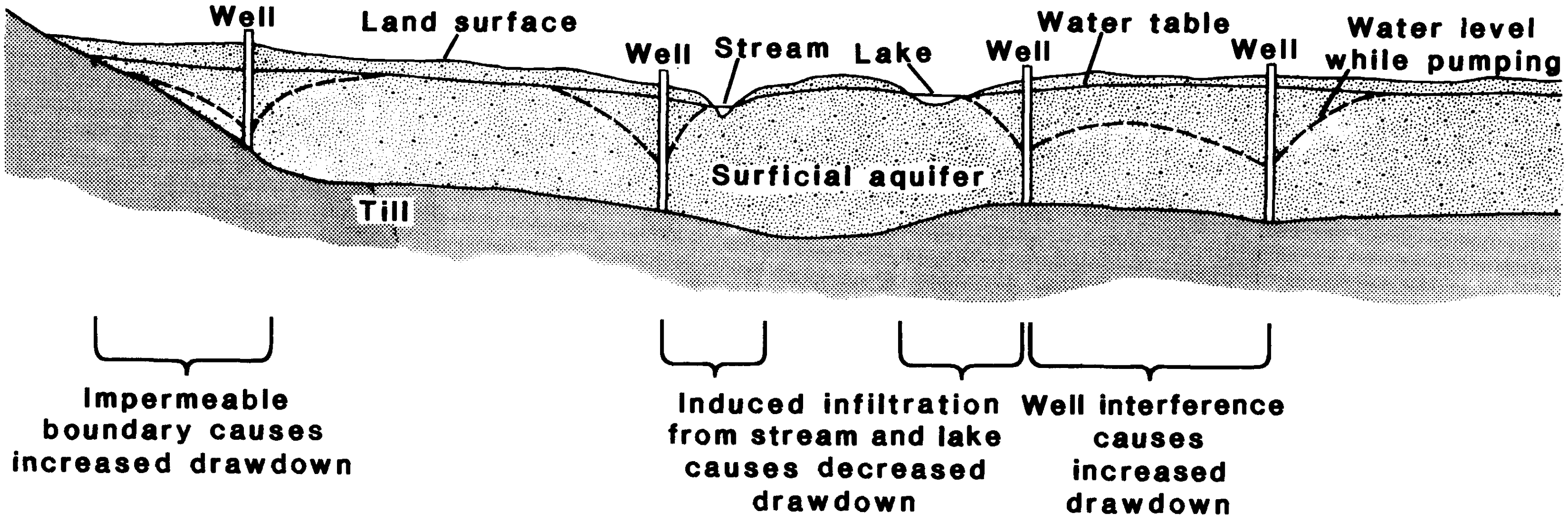


Figure 12.--Schematic hydrologic section illustrating effects of hydrogeologic boundaries and nearby pumping wells on cones of influence (from Larson, 1976. Scale varied)

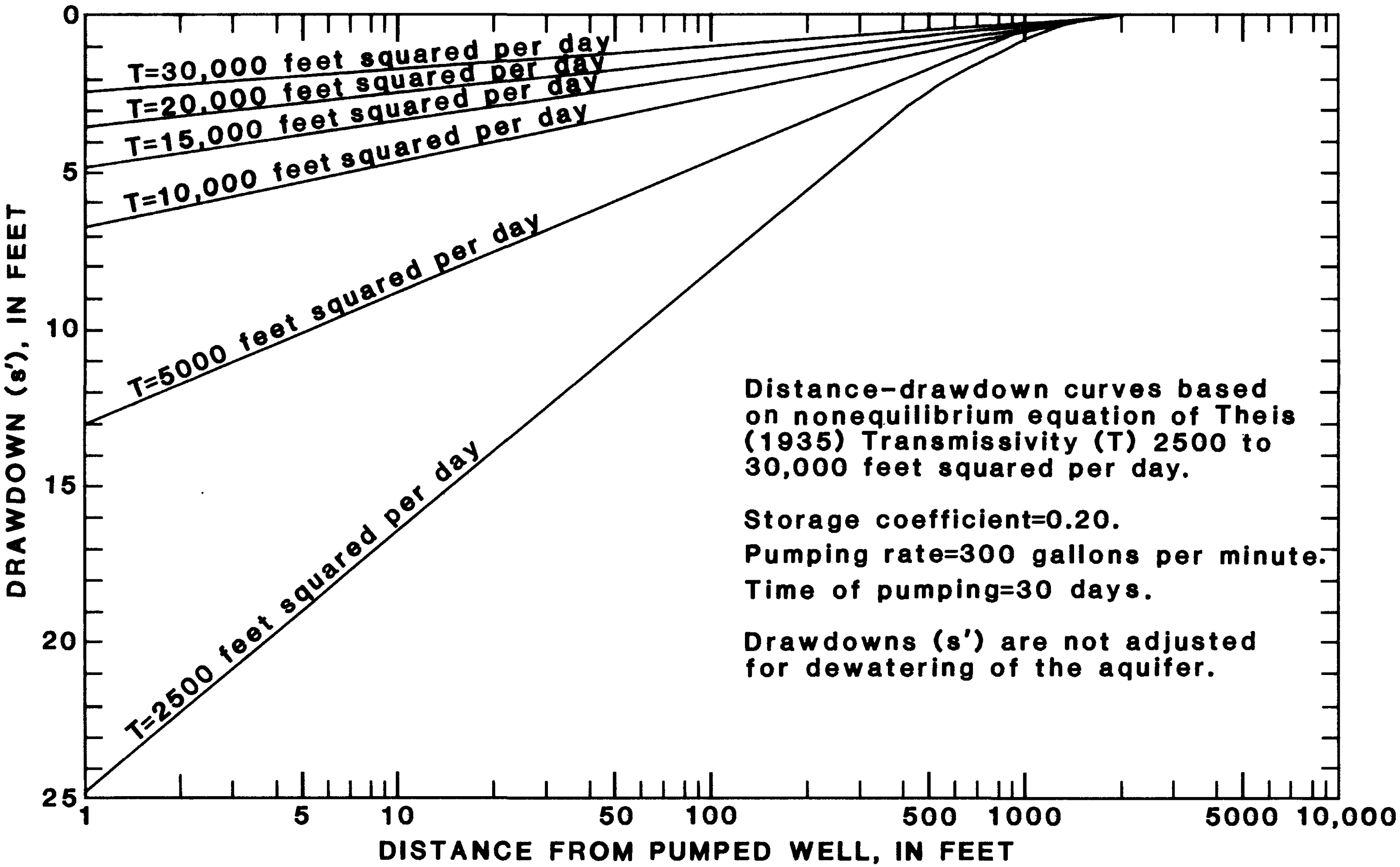


Figure 13.--Theoretical relationship of drawdown to transmissivity of an aquifer and distance from a pumped well (modified from Reeder, 1972, p. 29)

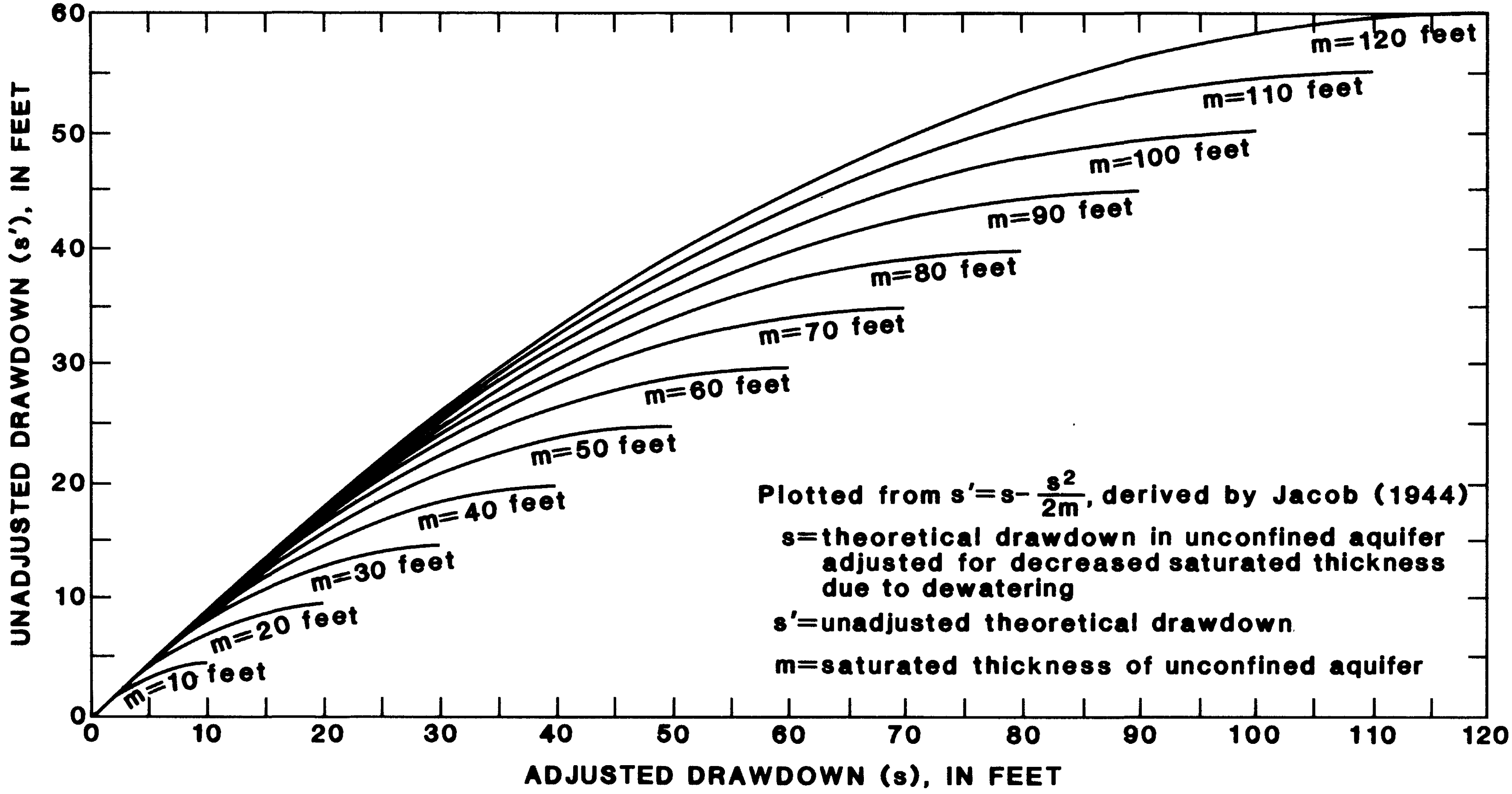


Figure 14.--Theoretical curves for adjustment of drawdown computed using the Theis equation as modified by Jacob (modified from Reeder, 1972, p. 30)

If drawdown between two pumping wells is to be calculated, drawdowns must be calculated for each well using figure 13 and the resultant summed. If water-table conditions exist after the drawdowns for each well are summed, the combined drawdown must be adjusted for dewatering (fig. 14).

The analytical techniques for calculating drawdowns are approximations and should not be used when drawdowns due to interference exceed 25 percent of the original saturated thickness. Actual drawdowns also will differ if they are affected by hydrologic boundaries.

QUALITY OF GROUND WATER

The chemical composition of ground water depends both upon the chemical composition of the water recharging the aquifer and the aquifer material through which it moves. Residence time, rate of flow, physical and chemical composition of the aquifer material, and some chemical reactions due to oxidation, pH, and temperature determine the degree of influence of the aquifer material on the quality of ground water.

Intended use often determines if the quality of water is acceptable. In Minnesota, for example, the most stringent water-quality standards are applied to water used for domestic consumption or food processing. Standards have also been established for other uses such as fisheries and recreation, industrial and agricultural, and wildlife. A complete set of water-quality standards are available from the MPCA (Minnesota Pollution Control Agency, 1978).

Water samples were taken from each of the 67 observation wells in the study area to establish baseline water quality. Most of the wells sampled (65) are completed in the sand-plain aquifers. Water from 34 of the wells was analyzed for field values of temperature, pH, and specific conductance; in addition to field values, water from the other 33 wells was analyzed for common major inorganic constituents and nutrients. Well locations were chosen to provide representative areal distribution. All wells were developed several weeks prior to the date of the sampling. Each well also was pumped prior to sampling until field values of pH, specific conductance, and temperature stabilized. Water samples were collected and analyzed following techniques outlined by Skougstad and others (1979). All samples were filtered and preserved as appropriate and shipped to the U.S. Geological Survey Central Laboratory in Atlanta, Ga., for analysis. Table 3 lists the laboratory results for the 33 water samples with most complete analyses. The field values determined for water from the additional 34 wells are not included in this report but were within the range of values measured for water from the 33 wells. Locations of wells sampled for chemical analyses are shown on plate 3. Table 4 is a statistical summary of results for common major constituents in samples collected during 1981 from the representative wells in Carlton, Kanabec, and Pine Counties.

The water is a calcium bicarbonate type and generally is moderately hard. Hardness (as $CaCO_3$) ranges from 5 to 420 mg/L (very hard).

Table 3.--Chemical analyses for common major constituents in water samples collected during 1981 from representative wells in Carlton, Kanabec, and Pine Counties

[mg/L, milligrams per liter; µg/L, micrograms per liter, µS/cm, microsiemens per centimeter; pCi/L, picocurie per liter]

Station number	Date of sample	Lat-i-tude	Long-i-tude	Se-quence num-ber	Local identifier	Time	Sam-pling depth (feet)	Specific con-ductance (µS/cm at 25°C)	pH
CARLTON COUNTY									
462614092305801	81-07-14	46 26 14	092 30 58	01	046N17W29DBD GROTH NR NI	1200	22.4	145	6.9
463130092322901	81-07-23	46 31 30	092 32 29	01	047N17W30CDD TRIANGLE CO	1525	15.4	200	6.6
463203092442401	81-07-16	46 32 03	092 44 24	01	047N19W22CCC C05 CORNER	1355	11.2	245	6.8
463228092404201	81-06-29	46 32 28	092 40 42	01	047N19W24ADD C03	1402	9.00	260	7.3
463437092313300	81-07-17	46 34 37	092 31 33	01	047N17W07AAB OLSON 3 FIE	0840	14.4	280	6.7
463635092345501	81-06-29	46 36 35	092 34 55	01	048N18W26DAD C01	1305	9.00	100	7.7
463715092413801	81-07-16	46 37 15	092 41 38	01	048N19W25BAA C04 DAIRY	1220	3.56	120	7.8
463949092281801	81-06-29	46 39 46	092 28 18	01	048N17W02CCD C06	1125	25.0	740	7.3
464006092420601	81-07-13	46 40 06	092 42 06	01	048N18W01CBC C010 HIPPIE	1540	17.5	295	7.4
464020092405401	81-07-16	46 40 20	092 40 54	01	048N18W06BCC C027 PERCH	0930	11.3	235	6.4
464036092380001	81-07-13	46 40 36	092 38 00	01	048N18W04BAC C07 SAWYER	1400	8.80	245	7.4
464217092312501	81-07-13	46 42 17	092 31 25	01	049N17W29BAD CLOQUET EXP	1230	22.0	265	6.4
464312092354201	81-07-15	46 43 12	092 35 42	01	049N18W23BBB C008 CHURCH	1545	10.4	220	6.2
464348092304801	81-06-29	46 43 48	092 30 48	01	049N17W17ADD CLOQUET #7	0945	9.00	300	8.2

Table 3.--Chemical analyses for common major constituents in water samples collected during 1981 from representative wells in Carlton, Kanabec, and Pine Counties--Continued

Station number	Date of sample	Temperature (°C)	Hardness (mg/L as $CaCO_3$)	Hardness, noncarbonate (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Percent sodium	Sodium adsorption ratio	Potassium, dissolved (mg/L as K)	Alkalinity, lab (mg/L as $CaCO_3$)
CARLTON COUNTY--Continued											
463130092322901	81-07-23	10.0	65	13	15	6.8	6.2	17	0.3	0.9	52
463203092442401	81-07-16	7.0	98	---	24	9.3	3.6	7	.2	.7	98
463228092404201	81-06-29	10.0	92	8.0	23	8.3	2.8	6	.1	.7	84
463437092313300	81-07-17	8.0	120	50	31	9.5	3.6	6	.1	.7	67
463635092345501	81-06-29	10.0	35	4.0	5.9	4.8	1.8	10	.1	.5	31
463715092413801	81-07-16	12.0	46	7.0	12	3.9	2.9	12	.2	.7	39
463949092281801	81-06-29	12.0	240	31	65	19	12	10	.3	1.7	210
464006092420601	81-07-13	9.0	73	6.0	22	4.5	2.6	7	.1	.4	67
464020092405401	81-07-16	10.0	93	15	27	6.2	2.8	6	.1	.7	78
464036092380001	81-07-13	13.0	100	11	33	4.5	2.6	5	.1	.5	90
464217092312501	81-07-13	10.0	76	10	21	5.6	16	31	.8	1.0	66
464312092354201	81-07-15	11.0	70	28	18	6.1	4.6	12	.2	.8	42
464348092304801	81-06-29	10.0	130	---	28	15	6.6	10	.3	.9	150

Table 3.--Chemical analyses for common major constituents in water samples collected during 1981 from representative wells in Carlton, Kanabec, and Pine Counties--Continued

Station number	Date of sample	Sulfate, dis- solved (mg/L as SO_4)	Chlo- ride, dis- solved (mg/L as Cl)	Fluo- ride, dis- solved (mg/L as F)	Silica, dis- solved (mg/L as SiO_2)	Solids, residue at 180°C dis- solved (mg/L)	Solids, sum of consti- tuents, dis- solved (mg/L)	Nitro- gen, NO_2+NO_3, dis- solved (mg/L as N)	Phos- phorus, dis- solved (mg/L as P)	Boron, dis- solved (µg/L as B)	Iron, dis- solved (µg/L as Fe)
					CARLTON COUNTY--Continued						
463130092322901	81-07-23	11	11	<.1*	10	117	99	.04	<.010	10	6000
463203092442401	81-07-16	7.3	4.1	.2	22	145	137	1.6	<.010	10	190
463228092404201	81-06-29	9.4	.9	.1	23	115	120	.02	<.010	30	960
463437092313300	81-07-17	9.0	13	<.1	21	186	163	7.8	<.010	20	180
463635092345501	81-06-29	5.8	.5	<.1	18	61	58	.02	<.010	20	1400
463715092413801	81-07-16	8.5	.9	<.1	.5	62	57	.07	<.010	30	3500
463949092281801	81-06-29	1.5	63	<.1	40	372	344	.01	.020	30	6900
464006092420601	81-07-13	11	.8	.1	23	96	105	.02	<.010	20	170
464020092405401	81-07-16	11	3.1	<.1	16	124	124	2.1	<.010	10	80
464036092380001	81-07-13	10	1.3	<.1	22	136	135	1.4	<.010	10	640
464217092312501	81-07-13	13	13	<.1	16	132	137	2.6	<.010	30	110
464312092354201	81-07-15	14	7.7	<.1	25	125	124	3.7	<.010	10	5900
464348092304801	81-06-29	.9	1.9	.3	16	159	161	.02	.060	30	920

* <.1 = below laboratory detection levels

Table 3.--Chemical analyses for common major constituents in water samples collected during 1981 from representative wells in Carlton, Kanabec, and Pine Counties--Continued

Station number	Date of sample	Manganese, dissolved (µg/L as Mn)	RA-226, dissolved, planchet count (pCi/L)	Radon 222, dissolved (pCi/L)
CARLTON COUNTY--Continued				
463130092322901	81-07-23	150	--	--
463203092442401	81-07-16	20	--	--
463228092404201	81-06-29	20	<.1	340
463437092313300	81-07-17	20	--	--
463635092345501	81-06-29	120	<.1	430
463715092413801	81-07-16	190	--	--
463949092281801	81-06-29	8200	.1	10
464006092420601	81-07-13	50	--	--
464020092405401	81-07-16	450	--	--
464036092380001	81-07-13	540	--	--
464217092312501	81-07-13	9	--	--
464312092354201	81-07-15	100	--	--
464348092304801	81-06-29	200	<.1	180

Table 3.--Chemical analyses for common major constituents in water samples collected during 1981 from representative wells in Carlton, Kanabec, and Pine Counties--Continued

Station number	Date of sample	Lat-i-tude	Long-i-tude	Se-quence num-ber	Local identifier	Time	Sam-pling depth (feet)	Specific con-ductance (µS/cm at 25°C)	pH
KANABEC COUNTY									
454909093152001	81-05-21	45 49 09	093 15 20	01	038N23W06ABB K01	0830	14.0	265	7.2
455045093210001	81-05-20	45 50 45	093 21 00	01	039N24W20DDD K03	1130	8.00	840	6.3
	81-06-29					1825	8.00	1050	6.4
455145093270901	81-05-20	45 51 45	093 27 09	01	039N25W15CCC K05	1500	15.0	140	6.6
455400093155101	81-05-20	45 54 00	093 15 51	01	039N23W06BCB K02	1000	22.0	235	8.2
455400093194401	81-05-21	45 54 00	093 19 44	01	039N24W04ADA CASHMAN	1230	5.00	390	7.3
455600093103001	81-11-04	45 56 00	093 10 03	01	040N23W23ABB OESTREICK(SS)*	1200	10.0	410	7.7
455600093103002	81-11-04	45 56 00	093 10 30	02	040N23W23ABB OESTREICK	1230	5.00	650	8.3

* (SS) Sandstone Formation.

Table 3.--Chemical analyses for common major constituents in water samples collected during 1981 from representative wells in Carlton, Kanabec, and Pine Counties--Continued

Station number	Date of sample	Temperature (°C)	Hardness (mg/L as $CaCO_3$)	Hardness, noncarbonate (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Percent sodium	Sodium adsorption ratio	Potassium, dissolved (mg/L as K)	Alkalinity, lab (mg/L as $CaCO_3$)
KANABEC COUNTY--Continued											
454909093152001	81-05-21	7.0	110	25	26	12	6.7	11	0.3	0.5	89
455045093210001	81-05-20	8.0	420	63	130	24	12	6	.3	1.6	360
	81-06-29	11.0	--	--	--	--	--	--	--	--	--
455145093270901	81-05-20	8.0	60	4.0	15	5.4	4.9	15	.3	.8	56
455400093155101	81-05-20	8.0	100	24	26	8.6	3.3	7	.1	1.3	76
455400093194401	81-05-21	7.0	120	.00	28	13	7.7	12	.3	.9	130
455600093103001	81-11-04	8.0	220	.00	57	20	5.4	5	.2	1.2	240
455600093103002	81-11-04	12.0	310	67	72	31	11	7	.3	1.3	240

Table 3.--Chemical analyses for common major constituents in water samples collected during 1981 from representative wells in Carlton, Kanabec, and Pine Counties--Continued

Station number	Date of sample	Sulfate, dis-solved (mg/L as SO_4)	Chlo-ride, dis-solved (mg/L as Cl)	Fluo-ride, dis-solved (mg/L as F)	Silica, dis-solved (mg/L as SiO_2)	Solids, residue at 180°C dis-solved (mg/L)	Solids, sum of consti-tuents, dis-solved (mg/L)	Nitro-gen, NO_2+NO_3, dis-solved (mg/L as N)	Phos-phorus, dis-solved (mg/L as P)	Boron, dis-solved (mg/L as B)	Iron, dis-solved (mg/L as Fe)
KANABEC COUNTY--Continued											
454909093152001	81-05-21	11	9.2	0.2	37	178	178	4.9	.010	10	70
455045093210001	81-05-20	2.3	62	.1	49	609	543	.02	1.80	20	44,000
	81-06-29	--	--	--	--	--	--	--	--	--	--
455145093270901	81-05-20	4.2	4.7	<.1	26	105	103	1.8	<.010	10	560
455400093155101	81-05-20	4.7	7.9	<.1	25	153	143	4.7	.080	10	60
455400093194401	81-05-21	6.8	16	.2	19	172	173	.07	<.010	10	2,100
455600093103001	81-11-04	2.0	2.9	.2	27	253	264	.03	.020	20	4,100
455600093103002	81-11-04	37	46	.3	11	360	368	3.2	<.010	60	230

Table 3.--Chemical analyses for common major constituents in water samples collected during 1981 from representative wells in Carlton, Kanabec, and Pine Counties--Continued

Station number	Date of sample	Manganese, dissolved (mg/L as Mn)	RA-226, dissolved, planchet count (pCi/L)	Radon 222, dissolved (pCi/L)
KANABEC COUNTY--Continued				
454909093152001	81-05-21	40	--	--
455045093210001	81-05-20	1200	--	--
	81-06-29	--	0.3	570
455145093270901	81-05-20	40	--	--
455400093155101	81-05-20	50	--	--
455400093194401	81-05-21	710	--	--
455600093103001	81-11-04	180	--	--
455600093103002	81-11-04	130	--	--

Table 3.--Chemical analyses for common major constituents in water samples collected during 1981 from representative wells in Carlton, Kanabec, and Pine Counties--Continued

Station number	Date of sample	Lat-i-tude	Long-i-tude	Se-quence num-ber	Local identifier	Time	Sam-pling depth (feet)	Specific con-ductance (µS/cm at 25°C)	pH
					PINE COUNTY				
455139092524401	81-07-21	45 51 39	092 52 44	01	039N20W18DDD LINDAHL	1120	1.27	140	6.7
455636092362501	81-07-22	45 56 36	092 36 25	01	040N18W21BBD HEADQUATER	0925	3.60	60	6.3
455833092440801	81-07-21	45 58 33	092 44 08	01	040N19W08AAA PO-9	0955	15.5	115	6.0
455939092365801	81-07-23	45 59 39	092 36 58	01	041N18W33AAD ST CROIX	1115	--	--	--
455947092542301	81-07-21	45 59 47	092 54 23	01	041N20W32BBB SIKKINK	1505	22.8	185	7.9
460007092395801	81-07-21	46 00 07	092 39 58	01	041N18W30ABB PO-11	0910	11.2	500	6.4
460512092194801	81-07-14	46 05 12	092 19 48	01	042N16W26BDD MARKSVILLE	1415	9.14	250	6.3
460945093000401	81-07-21	46 09 45	093 00 04	01	043N21W33CAD PO-8	1615	12.2	105	6.2
461215092550301	81-09-24	46 12 15	092 55 03	01	043N20W18DCC FINIAYSON T(SS)*	1200	170	170	6.3
461536092521501	81-07-23	46 15 36	092 52 15	01	044N20W28DCD PO-1	0745	16.9	175	6.7
461809092481201	81-06-29	46 18 09	092 48 12	01	044N20W13AAA P05	1650	8.00	105	6.4
462348092483601	81-06-29	46 23 48	092 48 36	01	045N20W12ACD PO2	1550	49.0	190	8.4

* (SS) Means Sandstone Formation.

Table 3.--Chemical analyses for common major constituents in water samples collected during 1981 from representative wells in Carlton, Kanabec, and Pine Counties--Continued

Station number	Date of sample	Temperature (°C)	Hardness (mg/L as $CaCO_3$)	Hardness, noncarbonate (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Percent sodium	Sodium adsorption ratio	Potassium, dissolved (mg/L as K)	Alkalinity, lab (mg/L as $CaCO_3$)
PINE COUNTY--Continued											
455139092524401	81-07-21	13.0	36	.00	8.2	3.8	4.7	21	0.3	2.0	38
455636092362501	81-07-22	9.0	16	.00	3.9	1.4	1.6	18	.2	.4	19
455833092440801	81-07-21	11.0	35	6.0	9.3	2.8	1.6	9	.1	.5	29
455939092365801	81-07-23	--	54	.00	14	4.6	2.8	10	.2	1.1	55
455947092542301	81-07-21	10.0	72	.00	16	7.9	3.9	10	.2	.9	76
460007092395801	81-07-21	13.0	130	28	23	17	18	21	.7	15	99
460512092194801	81-07-14	15.0	31	.00	10	1.5	30	64	2.3	3.9	50
460945093000401	81-07-21	11.0	5	.00	1.0	.7	1.3	30	.2	.9	7.0
461215092550301	81-09-24	8.0	52	7.0	13	4.8	4.0	14	.2	1.3	45
461536092521501	81-07-23	9.0	42	--	10	4.1	1.8	8	.1	1.6	--
461809092481201	81-06-29	11.0	23	.00	5.8	2.0	1.7	14	.2	.7	26
462348092483601	81-06-29	12.0	60	7.0	16	4.8	2.0	7	.1	.7	53
462614092305801	81-07-14	13.0	30	10	7.3	2.8	2.7	16	.2	.6	20

Table 3.--Chemical analyses for common major constituents in water samples collected during 1981 from representative wells in Carlton, Kanabec, and Pine Counties--Continued

Station number	Date of sample	Sulfate, dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Solids, residue at 180°C dissolved (mg/L)	Solids, sum of constituents, dissolved (mg/L)	Nitrogen, NO_2+NO_3, dissolved (mg/L as N)	Phosphorus, dissolved (mg/L as P)	Boron, dissolved (mg/L as B)	Iron, dissolved (mg/L as Fe)
PINE COUNTY--Continued											
455139092524401	81-07-21	0.1	8.2	<.1	0.5	56	51	.01	<.010	10	720
455636092362501	81-07-22	5.6	1.1	<.1	12	39	40	.17	<.010	10	10
455833092440801	81-07-21	7.6	3.1	<.1	13	64	63	1.0	<.010	0	3,100
455939092365801	81-07-23	18	7.2	.3	10	76	95	.01	<.010	10	3,800
455947092542301	81-07-21	8.3	4.7	.1	.9	95	90	.10	<.010	10	710
460007092395801	81-07-21	49	30	<.1	1.1	249	223	1.8	<.010	50	2,300
460512092194801	81-07-14	11	19	<.1	18	134	135	2.2	<.010	30	1,900
460945093000401	81-07-21	5.6	1.2	<.1	16	49	43	.01	.060	0	12,000
461215092550301	81-09-24	8.0	7.0	.1	17	96	96	1.1	<.010	110	7,800
461536092521501	81-07-23	--	--	--	1.1	--	--	.04	<.010	30	7,400
461809092481201	81-06-29	3.8	1.7	<.1	25	60	66	.24	.010	9	7,000
462348092483601	81-06-29	7.1	3.1	<.1	15	100	84	.02	<.010	20	50
462614092305801	81-07-14	9.1	13	<.1	<.1	33	35	.11	<.010	10	1,200

Table 3.--Chemical analyses for common major constituents in water samples collected during 1981 from representative wells in Carlton, Kanabec, and Pine Counties--Continued

Station number	Date of sample	Manganese, dissolved (mg/L as Mn)	RA-226, dissolved, planchet count (pCi/L)	Radon 222, dissolved (pCi/L)
PINE COUNTY--Continued				
455139092524401	81-07-21	200	--	--
455636092362501	81-07-22	80	--	--
455833092440801	81-07-21	60	--	--
455939092365801	81-07-23	120	--	--
455947092542301	81-07-21	70	--	--
460007092395801	81-07-21	190	--	--
460512092194801	81-07-14	110	--	--
460945093000401	81-07-21	70	--	--
461215092550301	81-09-24	470	--	--
461536092521501	81-07-23	410	--	--
461809092481201	81-06-29	1100	<.1	610
462348092483601	81-06-29	160	<.1	4.0
462614092305801	81-07-14	170	--	--

Table 4.--Statistical summary of results of water-quality analyses of samples from selected wells in Carlton, Kanabec, and Pine Counties

[mg/L, milligrams per liter; µg/L, micrograms per liter; pCi/L, picocuries per liter; pCi, picocuries; µS/cm, microsiemens per centimeter]

Constituent or property	Recommended limit	Number of samples	Median	Range
Depth (ft)	---	32	11.2	1.3 to 170
Specific conductance (uS/cm at 25°C)	[a]1,000	32	200	60 to 1,050
pH	[a]6.0-8.5	32	6.6	6.2 to 8.4
Temperature (°C)	---	32	10	7 to 15
Hardness as $CaCo_3$ (mg/L)	---	32	73	5 to 420
Hardness, noncarbonate (mg/L.	---	31	6	0.00 to 67
Calcium (mg/L)	---	32	18	1.0 to 130
Magnesium (mg/L)	---	32	6.1	0.7 to 31
Sodium (mg/L)	---	32	3.9	1.3 to 30
Sodium adsorption ratio.	---	32	0.2	0.1 to 2.3
Potassium (mg/L)	---	32	0.9	0.4 to 15
Alkalinity (laboratory) (mg/L)	---	31	67	7.0 to 360
Sulfate (mg/L)	[b]50	31	8.0	0.1 to 49
Chloride (mg/L)	[b]250	31	7.0	0.9 to 63
Fluoride (mg/L)	[b]1.5	31	<0.1	<0.1 to 0.3
Silica (mg/L)	---	31	18	<0.1 to 49
Solids, residue at 180 degrees Celsius (mg/L)	[b]500	31	117	33 to 609
Solids, sum of constituents (mg/L)	---	31	124	40 to 543
Nitrogen, NO_2 + NO_3 (mg/L)	[c]10	32	0.11	0.1 to 7.8
Phosphorous (mg/L)	---	32	<0.01	<0.01 to 0.06
Boron (µg/L)	[a]500	32	20	0 to 110
Iron (µg/L)	[b]300	32	1,200	10 to 44,000
Manganese (µg/L)	[b]50	32	120	9 to 8,200
RA-226 pCi/L	[c]0.5/pCi/day	7	<0.1	<0.1 to 0.3
Radon 222 pCi/L	---	7	340	4.0 to 610

[a] Minnesota Pollution Control Agency, 1978 (agriculture).
[b] Minnesota Pollution Control Agency, 1978 (domestic consumption).
[c] National Academy of Science, 1973 (domestic consumption).

Dissolved-solids concentrations (listed as solids, residue at 180 °C dissolved) consist primarily of calcium, magnesium, and bicarbonate. Concentrations ranged from 33 to 610 mg/L. Only one sample, which was from a well immediately downgradient from a landfill area near Mora, Kanabec County, exceeded MPCA recommended limits of 500 mg/L.

Salinity is a measure of total dissolved solids in water. The effect of salinity on crops varies considerably with soil type and crop tolerance. The U.S. Salinity Laboratory (1954) developed a technique for classifying the water salinity hazard for irrigation based on the specific conductance. Salinity hazards within the sand and gravel aquifer ranged from low to high (fig. 15). The U.S. Salinity Laboratory (1954) also developed a technique for classifying water for suitability for irrigation based on the sodium and sodium adsorption ratio (SAR), which is the computed ratio of sodium to calcium and magnesium. Using this technique, the sodium hazard of ground water in the study area is low.

Regionally, dissolved iron concentrations in ground water generally are above MPCA recommended limits of 300 µg/L. Concentrations ranged from 10 to 44,000 µg/L with mean and median concentrations of 3,820 and 1,200 µg/L, respectively. The large difference between the mean and median values reflects the statistical influence of several analyses of samples with uncommonly high concentrations. The source of high iron concentrations in ground water probably is due to hydrolization of oxide coatings on outwash sand grains (Wilke and Coffin, 1973) but may also, to a limited degree, be from dissolution of the black steel well casings which were used in this study (Hem, 1973, p. 124).

Dissolved manganese concentrations in ground water regionally were also generally above MPCA recommended limits of 50 µg/L. Concentrations of manganese ranged from 9 to 8,200 µg/L with mean and median concentrations of 475 and 120 µg/L, respectively. Data also indicate that several high values have skewed the mean value. Probable explanations for high manganese concentrations in ground water are the same as those for high concentrations of iron. In general, wells that produce water with high concentrations of iron also produce water that has high concentrations of manganese.

Nitrogen concentrations (expressed as NO_2+NO_3 as N) were within recommended limits. Nitrogen concentrations ranged from 0.01 to 7.8 mg/L with mean and median concentrations of 1.2 and 0.11 mg/L, respectively. Concentrations generally are quite low; however, water from well 047N17W07AAB near irrigated agricultural land in Carlton County contained 7.8 mg/L of NO_2+NO_3 as N, which is approaching the recommended limit of 10 mg/L.

Water samples were collected from two wells completed in sandstone aquifers. Concentrations of chemical constituents analyzed in water from the sandstone aquifers at these locations are similar and statistically indistinguishable from concentrations in water from the sand-plain aquifers. At site 040N23W23ABB, in Kanabec County, water from both a sandstone and a sand and gravel well was sampled. Concentrations of all the constituents analyzed were slightly higher in water from the sand and gravel well than in water from the sandstone well. Concentrations of iron and manganese were higher in water from the sandstone aquifer, and are probably due to lower dissolved-oxygen

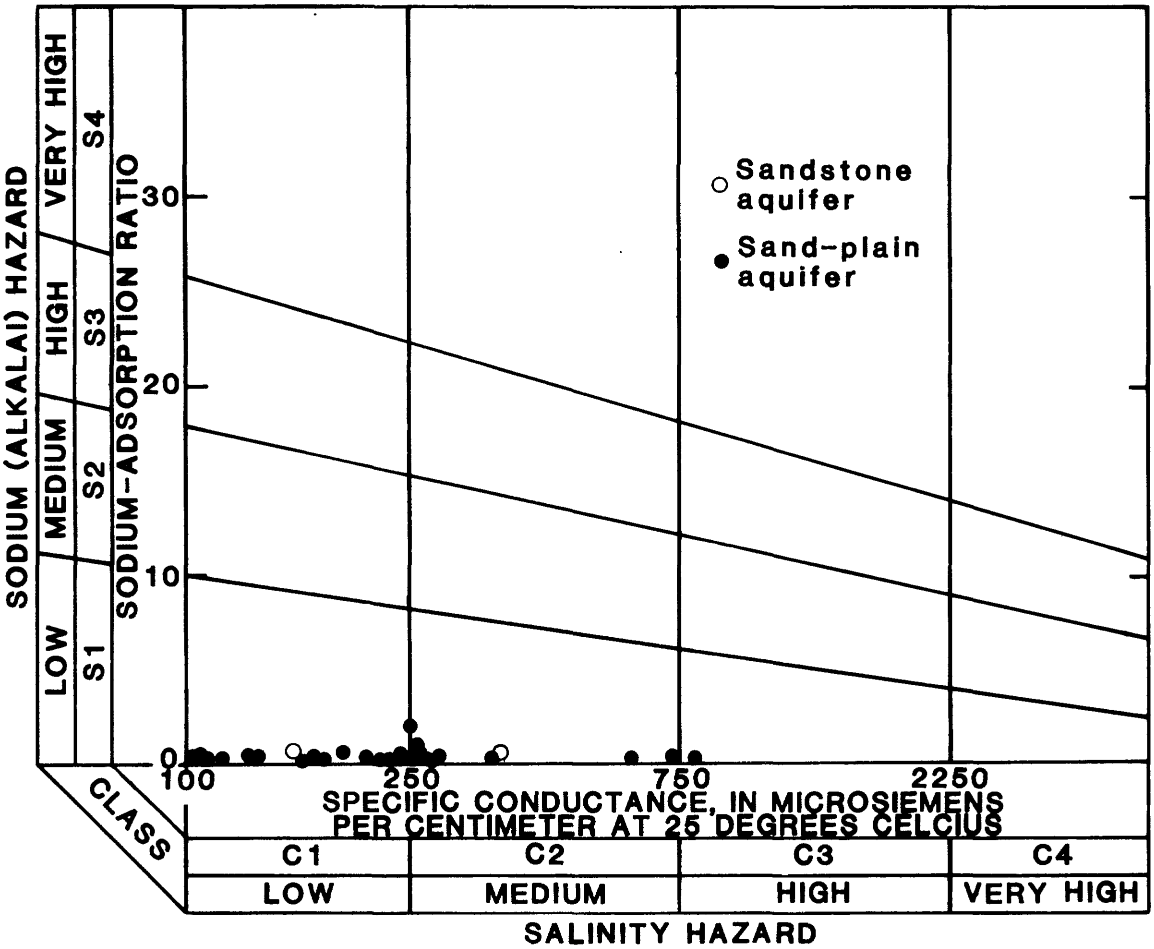


Figure 15.--Suitability of ground water for irrigation in terms of sodium-adsorption ratio and specific conductance (U.S. Salinity Laboratory, 1954)

concentrations in the deeper aquifer. The higher concentrations of chloride, dissolved solids, nitrate, and sulfate in the sand-plain aquifer probably are a result of contamination by effluent from a nearby septic-system leachfield.

Exploration for uranium in the study area has caused local residents to become concerned about possible contamination of water supplies by these deposits. Water samples from several sand and gravel wells were collected in areas of uranium exploration (Minnesota Department of Natural Resources records, preliminary map, 1981) and analyzed for radium 226 and its decayed form, radon 222. The samples were collected in special glass containers to prevent release of gas following techniques for collection and preservation of samples described by Thatcher and others (1977).

Results of the analyses indicate that all samples were below the recommended limits for radium 226. Five of the samples were below the laboratory detection limits. Radon 222, however, was detected in each of the samples. Water with the highest level of radium 226 and radon 222 is from a well in Kanabec County, a few hundred feet southeast and downgradient of the landfill (pl. 1).

Ground-water in the sand-plain and sandstone aquifers generally is suitable for most domestic or agricultural uses. Locally, however, high concentrations of dissolved solids may cause well-screen incrustation. Additionally, in those areas where iron and manganese concentrations are high (greater than 300 µg/L), water may have to be treated to avoid staining or odor problems. Certain salt-sensitive crops may be damaged if irrigated in areas where salinity is high. Salt accumulation within the soil probably will not, however, become a problem because of the high leaching properties of the sandy soils. High nitrogen concentrations generally result from excessive amounts of fertilizers used on cropland and (or) barnyard and sewage effluents (Hem, 1973, p. 181). While this is not a problem at present, it may become a problem as land is developed. The concentrations of radium 226 and radon 222 generally are very low, with most concentrations below the detectable limit of 0.1 pCi/L.

SIMULATION OF THE SAND-PLAIN AQUIFER FLOW SYSTEMS

Because of the regional scope of the study, only areally extensive parts of the sand-plain aquifer with hydraulic properties sufficient to support large-scale withdrawals of water were simulated. High-yielding wells can be located in other areas; however, these areas are small and are not suitable for regional development of water supplies. Two areas that warranted regional simulations are in northern and southern Pine County. For reference herein, areas modeled will be referred to as the Northern Pine County and Southern Pine County models (pl. 1). For those areas not modeled, analytical techniques presented earlier in the text can be used for estimating local aquifer responses due to development.

The sand-plain aquifers were simulated using the finite-difference numerical model developed by Trescott and others (1976). The model simulates ground-water flow in the aquifer in two dimensions under equilibrium (steady-state) conditions and long-term, steady-state responses to changes in climate and aquifer development. The model, however, cannot simulate an aquifer in every detail. At best, it represents an approximation of the real system.

The models are regional in scope and are not intended to predict localized effects of site-specific development. The models are intended to demonstrate the aquifer's suitability for additional substantial development and the response to climatic stress; not for localized development schemes. Development schemes are presented to demonstrate regional hydrologic effects.

Description of the Model Program

The model program uses a digital-computer code and finite-difference methods to approximate the ground-water-flow equation in two dimensions, as given by the following partial differential equation:

$$\frac{\partial}{\partial x}(K_{xx} b \frac{\partial h}{x} + \frac{\partial}{\partial y}(K_{yy} b \frac{\partial h}{\partial y}) = S_Y \frac{\partial h}{\partial t} + W(x,y,t)$$

where:

$K_{xx}K_{yy}$ = the principal components of the hydraulic conductivity tensor (Lt^{-1}),
S_Y = the specific yield of the aquifer (dimensionless),
b = the saturated thickness of the aquifer (L),
h = the hydraulic head (L), and
$W(x,y,t)$ = the volumetric flux of input or withdrawal per unit surface area of the aquifer (Lt^{-1}).

The program assumes that the coordinate axes are aligned with the principal components of the hydraulic-conductivity tensor. The strongly implicit procedure (SIP) was used to solve the finite-difference equations simultaneously (Trescott and others, 1976).

A finite-difference grid was used to divide the modeled areas into discrete blocks. The models use a block-centered scheme which performs equation calculations at the center of each block (referred to as the node). Averaged aquifer properties and hydraulic stresses for the block area are specified at each node.

Data input to the model consists of (1) dimensions of each block, (2) altitude of land surface, (3) hydraulic head/water level, (4) altitude of the aquifer's base, (5) hydraulic conductivity, and (6) hydraulic stresses, such as rates of ground-water recharge and discharge by pumpage and evapotranspiration. Both models simulate unconfined aquifers; therefore, transmissivity is computed by the model as a product of hydraulic conductivity and saturated thickness. The model, in turn, calculates saturated thickness as the difference between the aquifer's base and the hydraulic head to account for changes in transmissivity as a result of aquifer dewatering or head buildup.

Hydrologic boundaries were specified by selecting one of the following boundary conditions: (1) constant hydraulic head at the boundary, (2) constant flux across the boundary, or (3) head-dependent flux across the boundary. At constant-head boundaries, the model maintains initial water levels at the boundary by allowing enough water to enter the model to satisfy imposed stresses. By contrast, a constant-flux boundary allows a predetermined amount of water across the boundary. That amount does not change in response to simulated stress. The constant flux may be set to zero to simulate an impermeable boundary or it may have a finite value to simulate leakage across the boundary. If it has a large finite value, it approximates a constant-head boundary. The head-dependent flux allows the model to determine the flux into or out of the aquifer on the basis of the transmissivity and the difference between a model-computed head in the aquifer and a specified fixed head on the other side of a leaky layer at the boundary.

Calibration of the Models

The models were calibrated to equilibrium (steady state) conditions. There was insufficient pumpage and historical water-level data in the modeled area to calibrate the models to transient conditions. The steady-state calibration was made by successively adjusting input variables within reasonable limits consistent with the conceptual model until model-calculated water levels were within plus or minus 5 ft of Septemer 1981 ground-water levels at nodes with observation wells. The solutions obtained by the models for any of the experiments are not unique; similar results may be obtained by running the model with other combinations of input parameters. Upon calibration of the models to current aquifer conditions, the models were used to simulate aquifer response to different stress conditions representing different schemes for aquifer development and future climatic conditions. The lack of historical data causes the models, as presently constructed, to be restricted to simulating steady-state conditions. Steady-state models, however, simulate long-term, worst-case drawdown effects and, therefore, provide a conservative long-term portrayal of aquifer development.

Model Experiments

Upon calibration of the models to current aquifer conditions, the models were used to simulate long-term average aquifer response to different conditions representing schemes for aquifer development and climatic conditions.

Two schemes of development and climatic stresses were used for each of the steady-state models. The first scheme is based on development of the aquifer with average recharge rates. The development and placement of the pumping centers was based on potential yield estimates of the aquifers (pl. 4) and suitability of the land for irrigation and crops. Pumpage rates were set to approximate an application of 8 in. of water annually to irrigated areas.

The second scheme utilized the same development scenario and pumpage rates but recharge was reduced to simulate drought conditions. For this scheme, the average annual recharge rate is reduced to one half of the average annual recharge used for calibration of the respective model.

Northern Pine County Model

Location and Description of Model

The Northern Pine County model simulates regional ground-water flow in the major sand-plain aquifers in the northern half of Pine County. Figure 16 shows the areal extent of the modeled area. Natural hydrogeologic boundaries, such as the contact between till and outwash deposits, streams, and small stringers of outwash, determined the extent of the modeled area.

The Northern Pine County model consists of an 864-block (16 x 54) grid with a uniform spacing of 2,640 ft on a side (fig. 16). Each block represents 160 acres. The long axis of the model grid is approximately parallel or perpendicular to the primary direction of ground-water flow.

Simulation of Model Boundaries and Streams

Hydrologic boundaries in the Northern Pine County model were simulated using constant-head, constant-flux, no-flow, and head-dependent boundary types (fig. 16). Constant heads were assigned to blocks representing areas where water enters or leaves the system as streamflow or ground-water flow. Constant-flux boundaries with zero flux were used to simulate "no flow" conditions at till-outwash contact areas where flow from the till to the outwash, because of the relatively low values of hydraulic conductivity of the till, is an insignificant part of the hydrologic budget. Other constant-flux boundaries were assigned values based on leakage calculated by the model at equilibrium conditions. Areas simulated in this manner are connected stringers of outwash, which are a continuation of the aquifer. These stringers are a source of significant ground-water flow across the boundary. Head-dependent flux boundaries were used to simulate flow between lakes or streams and the aquifer.

Calibration of the Northern Pine County Model

The Northern Pine County model was calibrated with the following variables: (1) evapotranspiration, (2) pumpage, (3) recharge, (4) hydraulic conductivity of the aquifer, and (5) streambed-leakage coefficients.

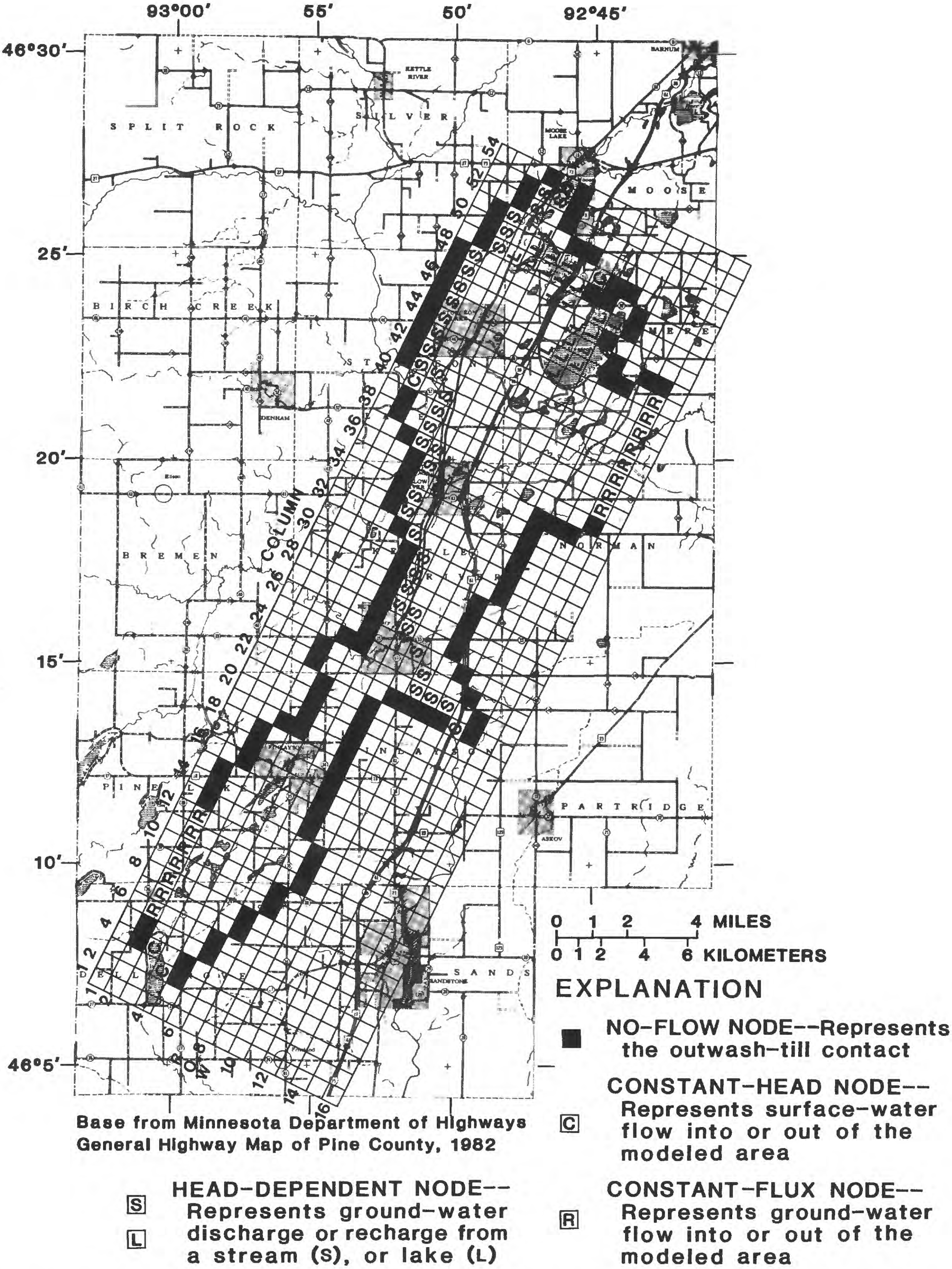


Figure 16.--Areal extent, finite-difference grid, and boundary conditions for the Northern Pine County model

Evapotranspiration was 18.4 in. annually as calculated by Helgeson and others (1973) using the method developed by Thornthwaite and Mather (1957). Evapotranspiration was assumed to be at the full potential rate where water levels are at land surface and decrease linearly to zero where ground-water levels are at a depth greater than 5 ft below land surface.

Pumpage, based on 1980 water records of the Minnesota Department of Natural Resources, was estimated to be 70 Mgal/yr (0.3 ft^3/s) in Pine County. In general, the pumping systems in use, with the exception of irrigation wells at the General C. C. Andrews Nursery in Willow River, are of small scale with low discharge rates and pressures. Location of the pumping centers is shown in figure 17.

A recharge rate of 5.3 in./yr was estimated for the modeled area by analyzing hydrographs of 12 wells for 1981. Based on 13 years of record, the average rate of recharge at a well near Willow River was 5.0 in./yr. There was an acceptable match between computed and observed water levels at observation wells throughout the modeled area when a recharge rate of 5.0 in./yr was applied uniformly over the whole model area.

The model was only slightly sensitive to regional changes of hydraulic conductivity of the aquifer. Reducing the hydraulic conductivity of the modeled area by one half generally lowered heads regionally by less than 5 ft. In a localized area near Finlayson where the aquifer narrows, however, it was necessary to increase hydraulic conductivities by about 20 percent from an estimated 250 ft/d to 300 ft/d in order to lower heads locally by about 10 ft to simulate observed levels.

Ground-water leakage to streams was determined by changing the leakage coefficient of the streambed and comparing resultant calculated heads to field observations of streamflow and head. A leakage coefficient of 3.1×10^{-7} ft/s was used for each of the representative streamflow nodes. Use of this rate provided necessary leakage to adequately match heads and to make discharge to streams similar to observed base-flow records. The value also provided enough restriction of flow to allow heads in nodes adjacent to stream nodes to fluctuate in response to stress. A similar value for streambed leakage was used successfully by Larson (1976), Miller (1982), and Myette (1983) in areas of similar geologic setting.

A comparison of water levels computed by the model to those measured at observation-well locations indicate a good calibration (table 5). The approximate hydrologic budget for the calibrated Northern Pine County model is shown in table 6.

Northern Pine County Model Experiments

The first experiment simulates the development of 77 pumping centers (fig. 17) pumped at a rate equivalent to applying 8 in. of water annually uniformly over the whole node. Total pumpage in this scenario was increased from 70 Mgal/yr (0.3 ft^3/s) to 2.6 Bgal/yr (11 ft^3/s). Recharge was maintained at 5 in./yr. Computed results indicate that regional water-level declines as much

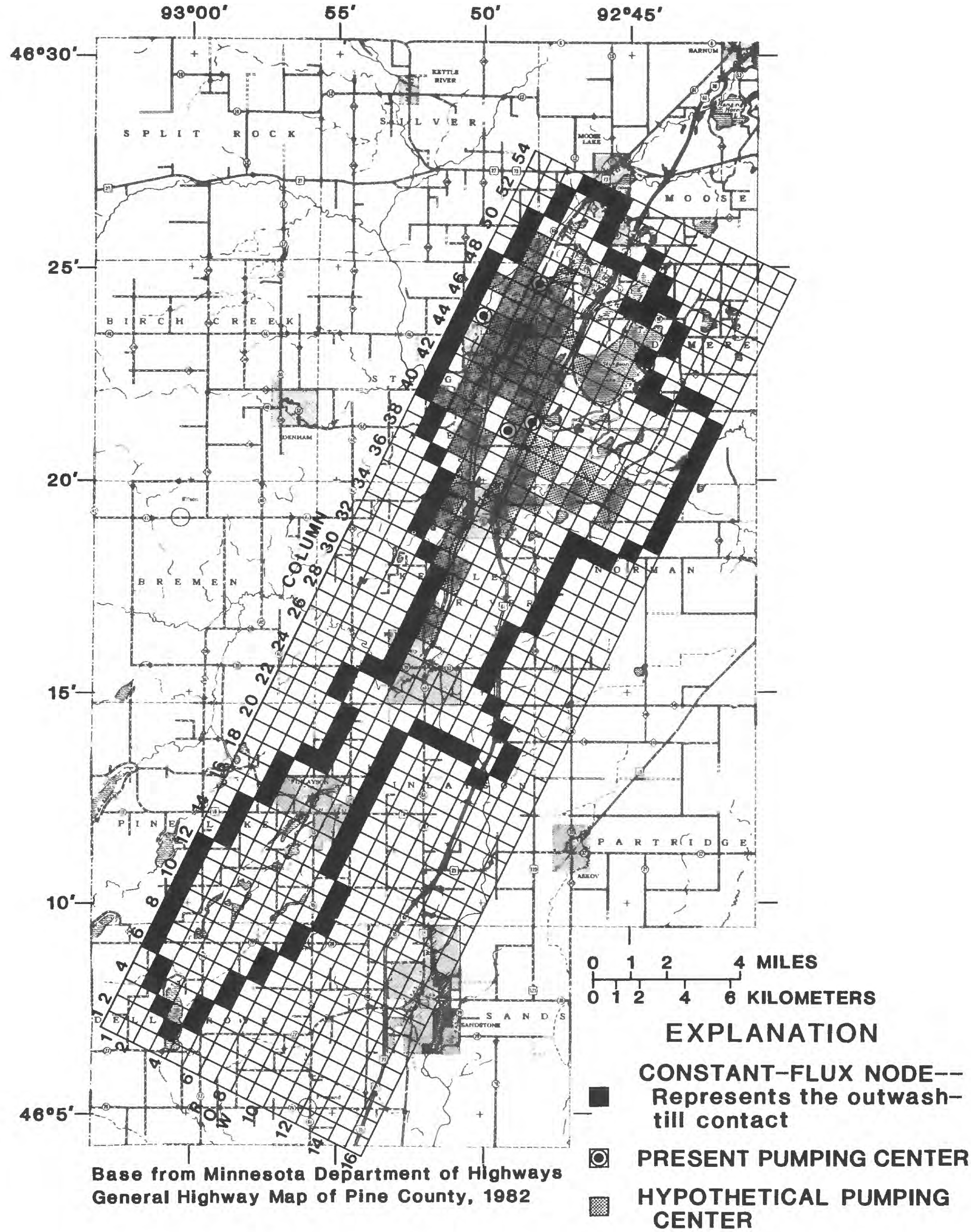


Figure 17.--Location of present and hypothetical pumping centers for the Northern Pine County model

Table 5.--Comparison of water levels computed by the model and measured at wells for the calibrated steady-state Northern Pine County model

Block number (row, column)	Computed water level (altitude above sea level, in feet)	Measured water level, September 1981 (altitude above sea level, in feet)	Difference (computed minus measured, in feet)
2, 8	1,120.5	1,121.0	-0.5
3, 39	1,027.6	1,028.0	-.4
4, 46	1,047.9	1,047.0	+.9
4, 49	1,058.7	1,060.0	-1.3
4, 51	1,053.6	1,050.0	+3.6
5, 40	1,032.9	1,031.0	+1.9
5, 46	1,045.3	1,045.0	+.3
7, 17	1,104.2	1,104.0	+.2
7, 26	1,023.4	1,022.0	+1.4
9, 43	1,065.1	1,065.0	+.1
11, 35	1,048.1	1,052.0	-3.9
11, 38	1,055.2	1,055.0	+.2
15, 39	1,089.0	1,090.0	-1.0

Table 6.--Approximate hydrologic budget for the calibrated steady-state Northern Pine County model

	Cubic feet per second
Inflow	
Recharge from precipitation	31.4
Leakage from streams and lakes	1.2
Leakage to aquifer	2.7
Total	35.3
Outflow	
Leakage from aquifer	3.0
Leakage to streams and lakes	11.2
Pumpage	.3
Evapotranspiration	20.8
Total	35.3

as 6 ft may occur near Willow River and discharge to Kettle and Moose Rivers may be reduced by as much as 22 percent. Figure 18 shows approximate areas and amount of decline computed by the model for this experiment.

The second experiment simulates system response to drought by use of the same 77 hypothetical pumping centers and pumpage rates as in the first experiment, but with recharge of 2.5 in./yr (one-half average annual). Computed results indicate that regional water-level declines as much as 12 ft may occur near Willow River and discharge to the Kettle and Moose Rivers may be reduced by as much as 42 percent. Figure 19 shows approximate areas and relative amounts of decline computed by the model for this experiment. Areas of least decline occur near large bodies of water such as Sturgeon Lake and the Kettle River where additional water would be induced through leakage to the aquifer from surface-water storage.

Southern Pine County Model

Location and Description of Model

The Southern Pine County model simulated ground-water flow in the sand-plain aquifer in southern Pine County. The extent of the modeled area was determined by natural hydrogeologic boundaries such as till-outwash contacts, streams, and small stringers of outwash (fig. 20).

The model consists of a 1,080-block (20x54) grid with uniform spacing of 2,640 ft on a side (fig. 20). Each block represents 160 acres. The long axis of the model grid is oriented approximately parallel or perpendicular to the primary directon of ground-water flow.

Simulation of Model Boundaries and Streams

Hydrologic boundaries in the Southern Pine County model were simulated using constant-head, head-dependent, and no-flow boundary types (fig. 20). Constant heads were assigned to blocks representing areas where water enters or leaves the system as streamflow or ground-water flow. Constant-flux boundaries with zero flux were used to simulate "no-flow" conditions at till-outwash contact areas where flow from the till to the outwash, because of the relatively low hydraulic conductivity of the till, is an insignificant part of the hydrologic budget. Head-dependent flux boundaries were used to simulate flow between streams or lakes and the aquifer.

Calibration of the Southern Pine County Model

The Southern Pine County model was calibrated with the following variables: (1) evapotranspiration, (2) pumpage, (3) recharge, (4) hydraulic conductivity of the aquifer, and (5) streambed-leakage coefficients.

Evapotranspiration was 18.4 in. annually as calculated by Helgesen and others (1973) using the method developed by Thornthwaite and Mather (1957). Evapotranspiration was assumed to be at the full potential rate where water levels are at land surface and to decrease linearly to zero below 5 ft.

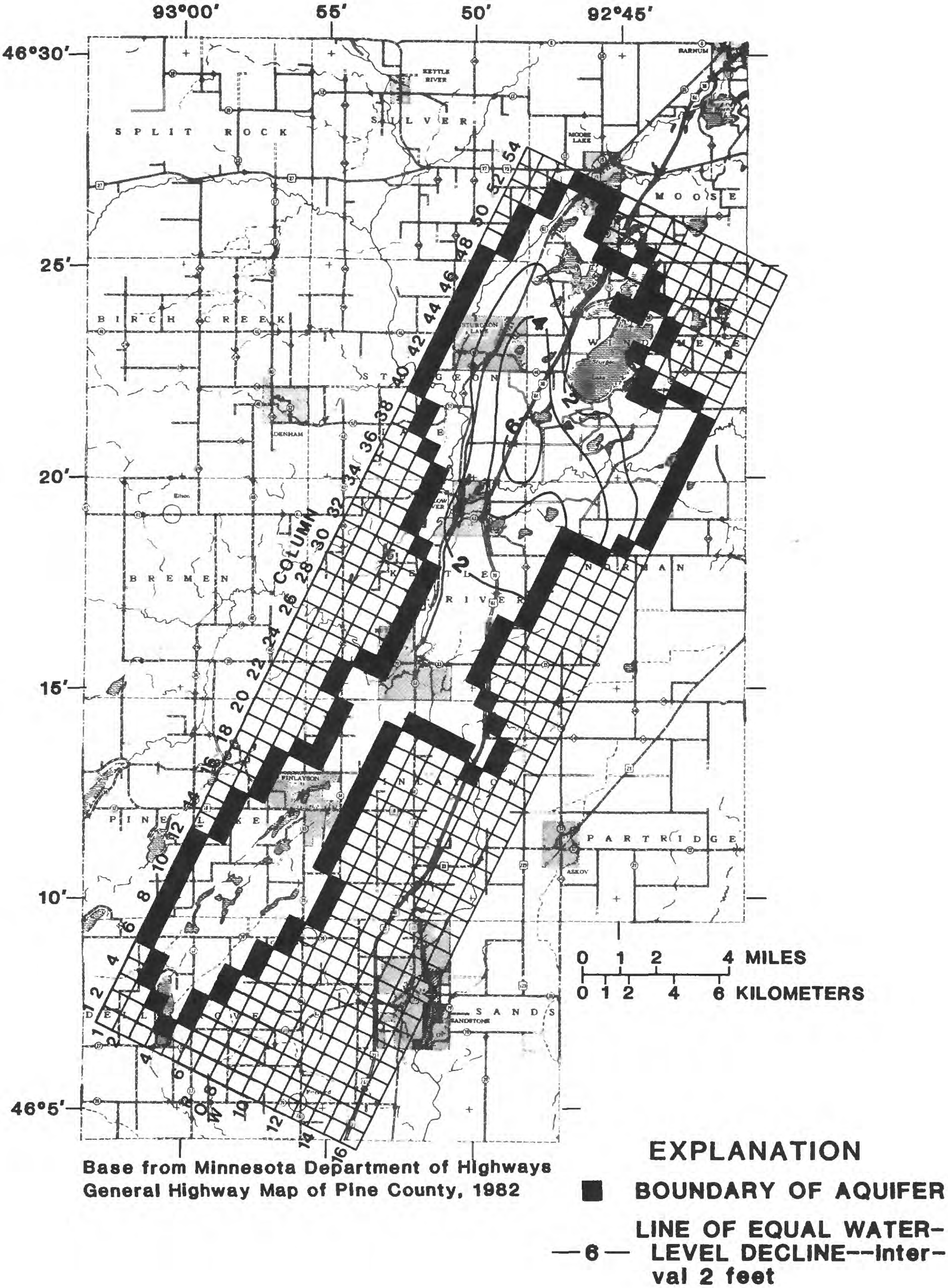
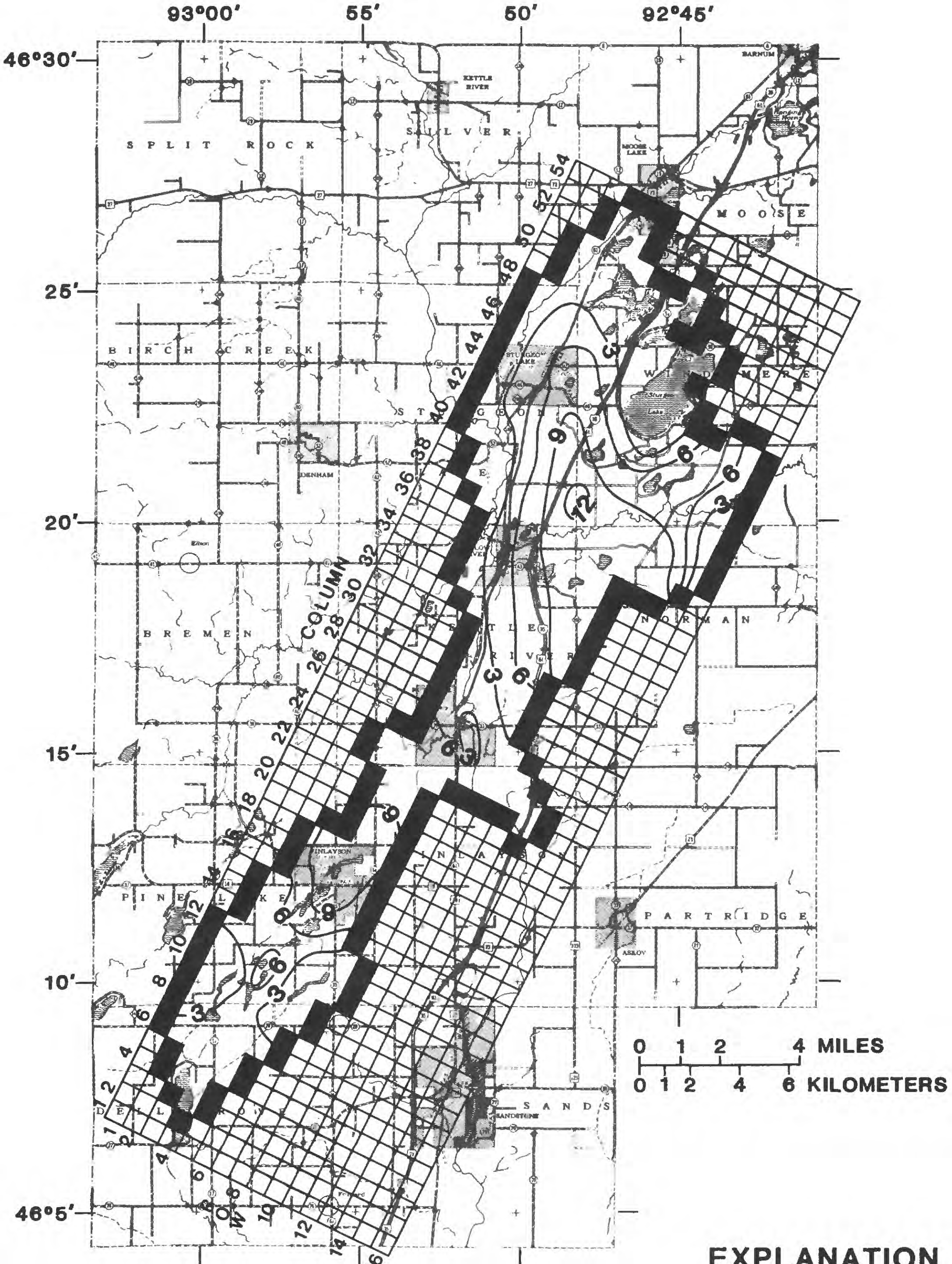


Figure 18.--Computed water-level decline under hypothetical development and normal recharge conditions for the Northern Pine County model



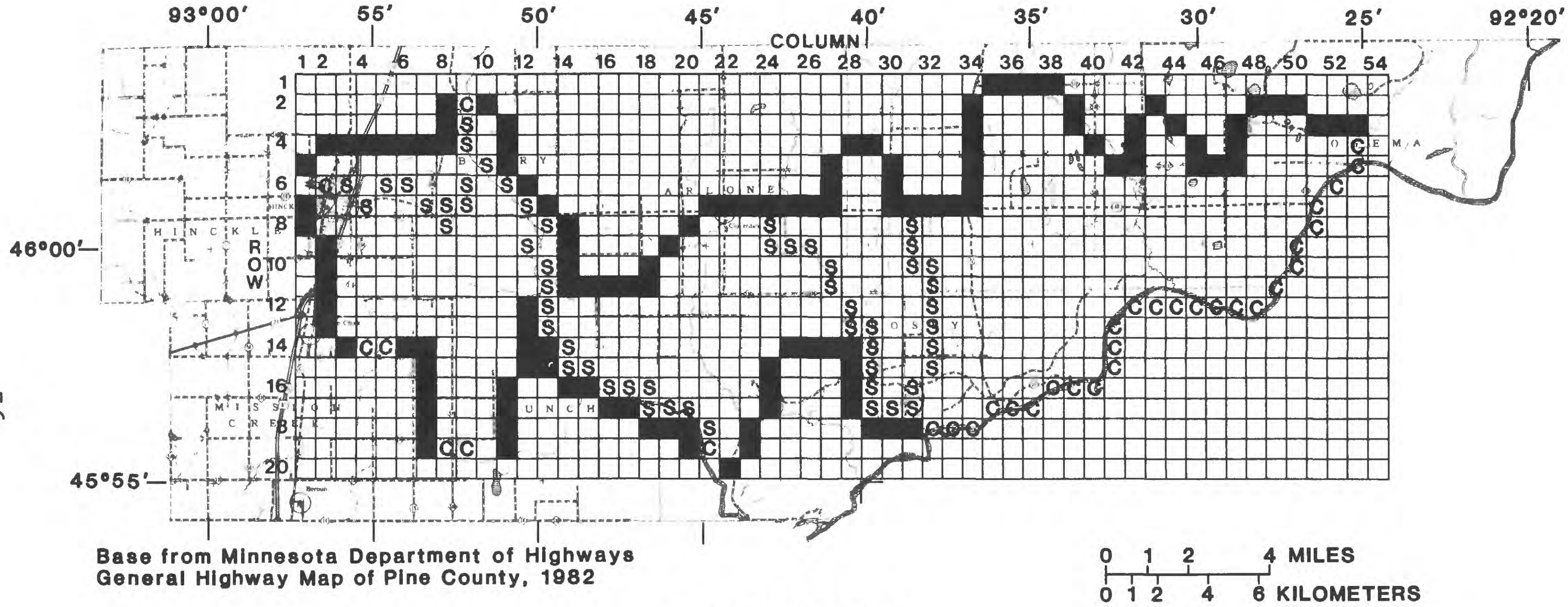
Base from Minnesota Department of Highways
General Highway Map of Pine County, 1982

EXPLANATION

■ BOUNDARY OF AQUIFER

—9— LINE OF EQUAL WATER-LEVEL DECLINE--Interval 3 feet

Figure 19.--Computed water-level decline under hypothetical development and one-half normal recharge conditions for the Northern Pine County model



Base from Minnesota Department of Highways
General Highway Map of Pine County, 1982

EXPLANATION

■ NO-FLOW NODE--Represents the outwash-till contact

C CONSTANT-HEAD NODE--Represents surface-water flow into or out of the modeled area

S HEAD-DEPENDENT NODE--Represents ground-water discharge or recharge from a stream

Figure 20.--Areal extent, finite-difference grid, and boundary conditions for the Southern Pine County model

Pumpage, from records of the Minnesota Department of Natural Resources (1980) was estimated to be 26 Mgal/yr (0.1 ft^3/s) from five pumping centers, all of which were irrigation pits (fig. 21).

Recharge was estimated to be 5.5 in./yr from analysis of 12 observation-well hydrographs for 1981. A uniform rate of 6 in., however, provided a closer match between model-computed and field-measured water levels.

The model was relatively insensitive to regional variation of hydraulic conductivity. Reducing hydraulic conductivity by one half resulted in regional lowering of water levels by only a few feet. However, in two localized areas within the St. Croix State Park, where ground-water gradients are steep and data are limited, it was necessary to reduce estimated hydraulic conductivities by 50 percent. These changes caused water levels to rise by 10 to 15 ft in the local areas, which better simulated observed water levels.

Ground-water leakage to streams was determined by changing the leakage coefficient of the streambed and comparing resultant calculated heads to match observed heads and streamflows in the Southern Pine County area. A leakage coefficient of 3.1×10^{-7} ft/s was used for each representative stream node.

Comparisons of computed and observed water levels at observation-well locations are shown in table 7. The approximate hydrologic budget for the Southern Pine County model is shown in table 8.

Southern Pine County Model Experiments

The first experiment simulates the development of 30 pumping centers (fig. 21), 20 of which were pumped at a discharge rate equivalent to 8 in./yr. However, to prevent simulating dewatering of nodes 9,21, and 9,22, it was necessary to use a pumpage rate equivalent to 6 in./yr for pumping wells near those nodes. Total pumpage in this scenario was increased from 26 Mgal/yr (0.1 ft^3/s) to 950 Mgal/yr (4.0 ft^3/s). Recharge was set to a rate equivalent to 6 in./yr. Computed results indicate that ground-water level declines as much as 20 ft may occur near St. Croix State Park and discharge to streams may be reduced by as much as 17 percent (fig. 22). The greatest drawdowns occur in areas of relatively thin finer-grained material where irrigation from pits is the primary technique of withdrawal.

The second experiment simulates system response to drought. The location and number of pumping centers and pumping rates remained the same as in the first experiment. However, average annual recharge was changed to 3.0 in./yr. Computed results indicate that ground-water level declines as much as 25 ft may occur near St. Croix State Park and that discharge to streams may be reduced by as much as 65 percent (fig. 23). Greatest water-level declines would be in areas of finer-grained aquifer materials. Areas of least decline are near the larger rivers such as the Kettle and Grindstone where water would be induced from the river.

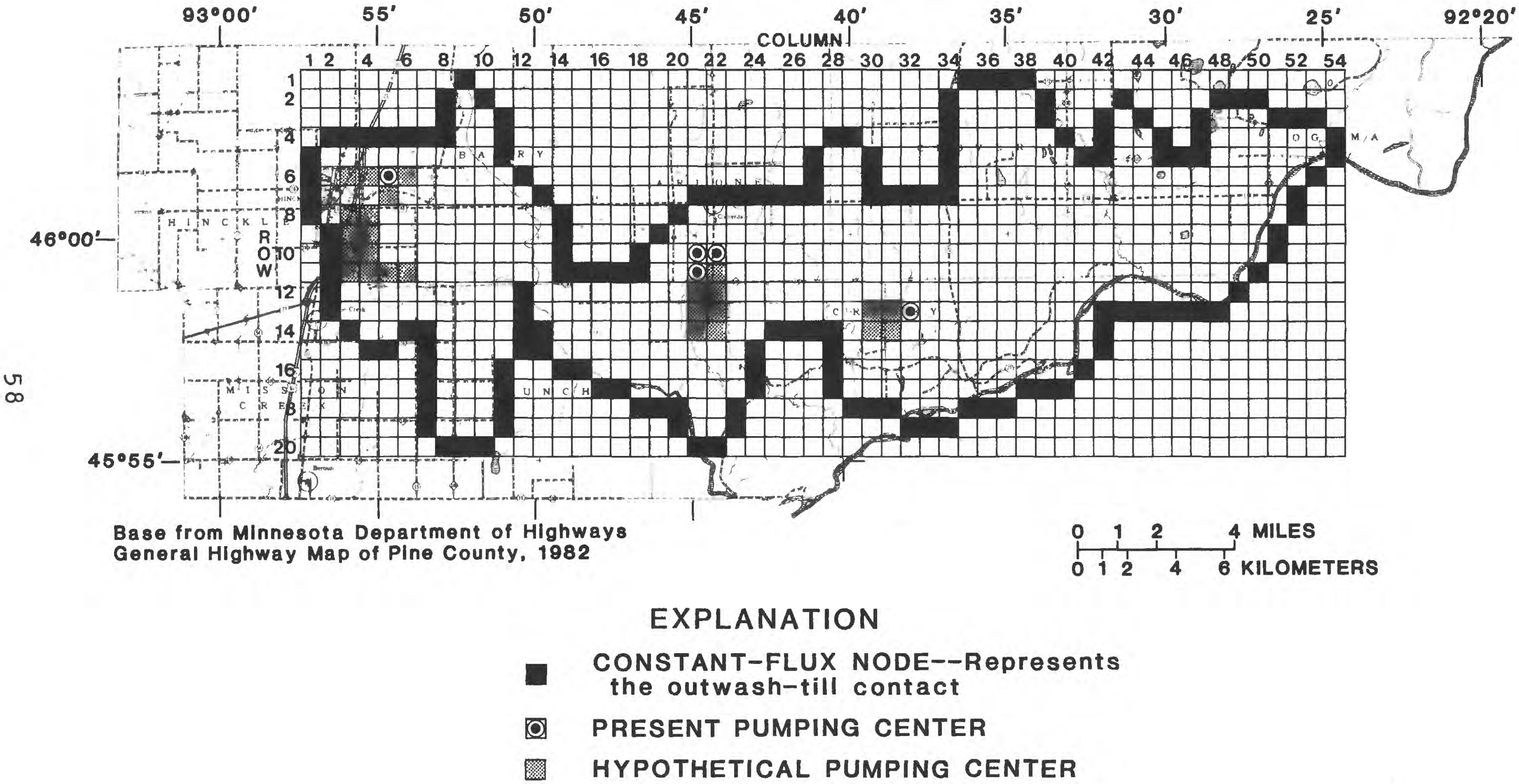


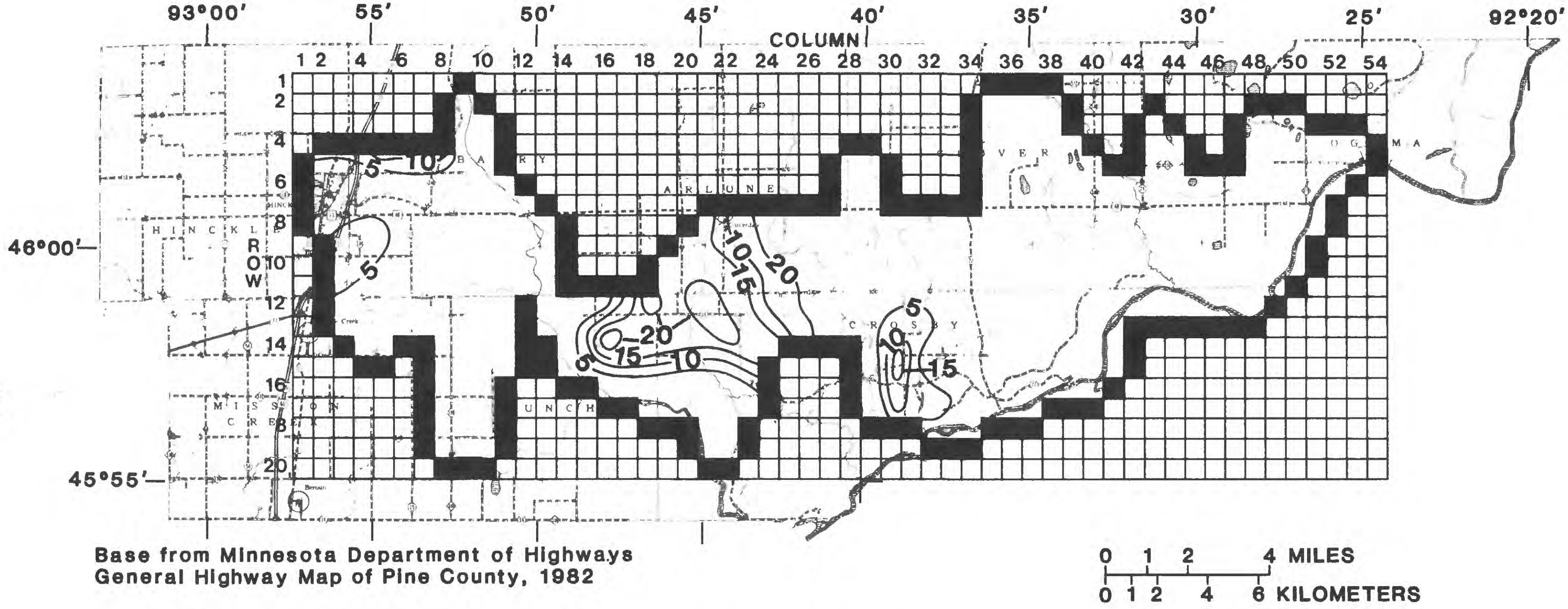
Figure 21.--Location of present and hypothetical pumping centers for the Southern Pine County model

Table 7.--Comparison of water levels computed by the model and measured at wells for the calibrated steady-state Southern Pine County model

Block number (row, column)	Computed water level (altitude above sea level, in feet)	Measured water level, September 1981 (altitude above sea level, in feet)	Difference (computed minus measured in feet)
7, 29	958.5	960.0	-1.5
8, 47	960.5	960.0	+.5
9, 5	989.6	993.0	-3.4
9, 46	954.5	950.0	+4.5
10, 34	945.2	948.0	-2.8
11, 20	963.7	965.0	-1.3
12, 22	959.6	955.0	+4.6
12, 39	898.4	900.0	-1.6
14, 81	893.7	891.0	+2.7
16, 32	887.1	892.0	-4.9
18, 8	957.3	955.0	+2.3

Table 8.--Approximate hydrologic budget for the calibrated steady-state Southern Pine County model

	Cubic feet per second
Inflow	
Recharge from precipitation	47.9
Leakage from streams	.9
Total	48.8
Outflow	
Constant head	7.2
Leakage to streams	15.2
Pumpage	.1
Evapotranspiration	26.3
Total	48.8



EXPLANATION

■ BOUNDARY OF AQUIFER

—10— LINE OF EQUAL WATER-LEVEL DECLINE--Interval 5 feet

Figure 22.--Computed water-level decline under hypothetical development and normal recharge conditions for the Southern Pine County model

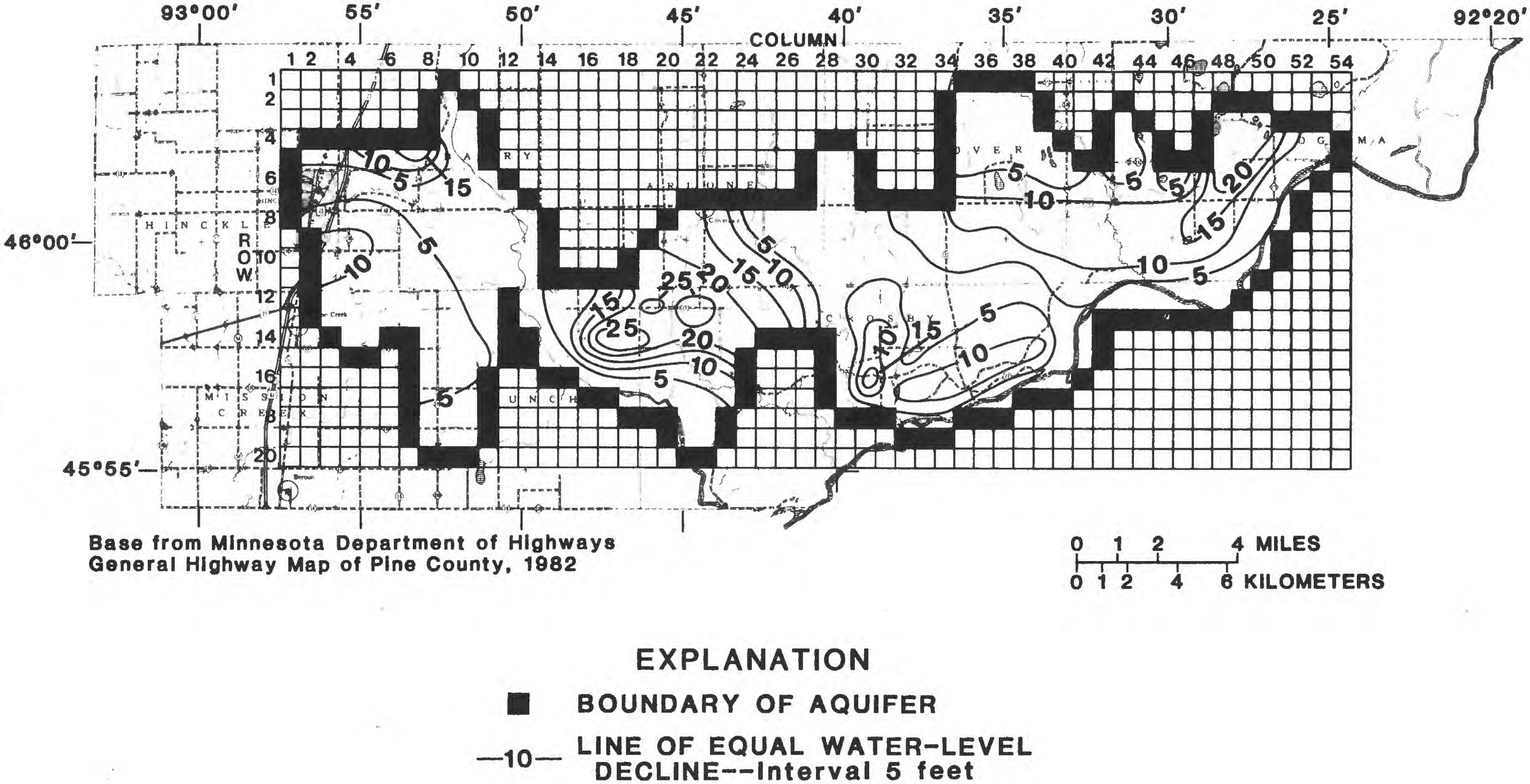


Figure 23--Computed water-level decline under hypothetical development and one-half normal recharge conditions for the Southern Pine County model

SUMMARY

Sand-plain aquifers consisting of glacial outwash deposits in Carlton, Kanabec, and Pine Counties cover approximately 500 mi^2. The largest deposits are found near Cloquet in Carlton County, between Moose Lake and Willow River in Pine County, and near Ogilvie and Mora in Kanabec County. The outwash is predominantly fine to medium sand, but locally it consists of very coarse sand with gravel. The outwash ranges in thickness from less than 1 ft near lateral boundaries to more than 110 ft in outwash-filled valleys. Depth to the water table in the sand-plain aquifers generally is less than 20 ft below land surface. Saturated thicknesses range from less than 1 ft to more than 90 ft. Transmissivity estimates range from less than 100 to more than 25,000 ft^2/d. In localized areas, theoretical yields to wells may exceed 2,000 gal/min.

Hydraulic data from three aquifer tests indicate that transmissivity of the sandstone aquifers ranges from 1,850 to 2,200 ft^2/d; specific capacities range from 9 to 12 (gal/min)/ft of drawdown. Aquifer testing and test-hole information indicate that there is poor hydraulic connection between the sand-plain and sandstone aquifers, even where the sand-plain aquifers overlie the sandstone.

Mean annual precipitation ranges from 27.5 in. near Cloquet to 28.9 in. near Mora. Annual precipitation during 1981 for Cloquet and for Mora was 29.4 and 29.7 in., respectively. The average annual recharge to the sand-plain aquifers, obtained by analysis of 56 hydrographs for 1981, was 5.8 in. The average annual recharge based on two wells with more than 10 years of record was 5.0 and 7.7 in.

Analyses of water samples indicate that ground water is a calcium carbonate type and generally is medium hard to hard; concentrations of dissolved solids range from 30 to 610 mg/L. Except for locally high concentrations of iron and manganese, the quality of water meets State drinking-water standards and is suitable for most uses. There is no major difference between the quality of water from the sand-plain and sandstone aquifers.

Simulation of sand-plain aquifers indicates that expanded ground-water development and drought conditions in northern Pine County could regionally lower ground-water levels in sand-plain aquifers as much as 12 ft and reduce discharge to streams as much as 42 percent. Simulation indicates that expanded development and drought conditions in southern Pine County could regionally lower ground-water levels in the sand-plain aquifers as much as 25 ft and reduce discharge to streams as much as 65 percent. The model simulations demonstrate that each area will support substantial additional withdrawals of ground water without dewatering the sand-plain aquifer. Lowering ground-water levels, however, probably will lead also to lower lake levels and decreased streamflow. In addition, partial dewatering of the aquifer in some areas will decrease individual well yields. Future development of ground-water supplies can be guided by additional simulations of the ground-water system accompanied by periodic monitoring of ground-water levels and water quality.

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