APPRAISAL OF WATER FROM SURFICIAL-OUTWASH AQUIFERS IN TODD COUNTY AND PARTS OF CASS AND MORRISON COUNTIES, CENTRAL MINNESOTA

By C. F. Myette

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CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS

TABLES

CONVERSION FACTORS

For readers who prefer to use metric units, conversion factors for terms used in this report are listed below:

Multiply inch-pound unit	By	To obtain SI unit
acre	0.4047	hectare (ha)
foot (ft)	0.3048	meter (m)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (Mgal/d)	0.04382	cubic meter per second (m^3/s)
inch (in)	25.4	millimeter (mm)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.59	square kilometer (km^2)

APPRAISAL OF WATER FROM SURFICIAL-OUTWASH AQUIFERS IN TODD COUNTY AND PARTS OF CASS AND MORRISON COUNTIES, CENTRAL MINNESOTA

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ABSTRACT

Outwash deposits consisting of medium to very coarse sand constitute a major aquifer in Todd County and in parts of Cass and Morrison Counties. The outwash ranges in thickness from 0 to 150 feet. Depth to water is generally less than 15 feet, and annual water-level fluctuations are less than 5 feet. Aquifer-test results indicate that transmissivities range from 4,600 to 18,500 feet squared per day and storage coefficients range from 0.10 to 0.25. Yields of more than 2,000 gallons per minute can be obtained locally from properly constructed wells.

Average annual precipitation is 25.93 inches, and average annual recharge to the aquifer is estimated to be 8 inches. Base-flow measurements of the Long Prairie River between Long Prairie and Motley during October 1978 and October 1979 indicate average net gains of 0.85 and 1.3 cubic feet per second per river mile.

The water is a calcium bicarbonate type and is generally suitable for most uses. However, elevated concentrations of selected chemicals in local areas may require treatment of the water for specialized uses. The water is hard to very hard with dissolved-solids concentrations ranging from about 200 to 400 milligrams per liter. Locally, nitrate concentrations are as much as 6.4 milligrams per liter. Residuals of pesticides are present but do not exceed recommended limits as established by the U.S. Environmental Protection Agency for domestic consumption.

Results from numerical modeling experiments indicate that, with proper development, the ground-water system can accommodate additional withdrawals. One experiment indicated that reduction in recharge from 8 to 4 inches annually over 4 years, and anticipated increases in pumping from 2.1 million gallons per day (1978 pumpage) to 7.7 million gallons per day, would cause water levels to decline regionally only about 9 feet and ground-water discharge to streams to decline only about 20 percent.

INTRODUCTION

Irrigated acreage in Minnesota increased from 4,400 acres in 1970 to almost 400,000 acres in 1977 (University of Minnesota, 1978). During the same period, irrigated acreage in the study area increased from 2,500 acres to more than 8,000 acres. After the drought of 1976, irrigated acreage increased to more than 11,000 acres by 1978.

Because of the projected increase in demand for ground water, the U.S. Geological Survey, in cooperation with the Minnesota Department of Natural Resources and the Todd, Cass, and Morrison Counties Steering Committee, studied the surficial aquifers in Todd County and parts of Cass and Morrison Counties from July 1977 to June 1980.

Purpose and Scope

The purpose of this study was to provide geohydrologic data on the major surficial aquifers in Todd and parts of Morrison and Cass Counties. Specifically, the objectives of the study were to (1) map the areal extent of the aquifer, (2) determine its hydraulic properties, (3) estimate annual recharge to the aquifer, (4) develop a digital computer model of parts of the aquifer to simulate its response to various levels of large-scale pumping, (5) determine the quality of ground water and its suitability for various uses, and (6) install wells for observing changes in water levels and water quality.

This report presents the results of this study and addresses each of the study objectives. This report will provide managers with data to guide orderly development of ground-water resources for irrigation and for domestic, municipal, and industrial water supplies. Because of present ground-water development practices, the study is limited to an appraisal of the surficial-outwash aquifer system.

Location and Description of the Study Area

The study area is located in central Minnesota, approximately 25 miles west-southwest of Brainerd, the geographical center of the State (fig. 1). The area lies in the Crow Wing, Mississippi, and Sauk watersheds. Most of the area is drained by the Long Prairie River, which joins the Crow Wing River near Motley.

Outwash deposits cover approximately 250 mi^2 of Todd and parts of Cass and Morrison Counties. The major deposit, referred to as the Long Prairie sand plain, is long and narrow with its axis alined north-south (fig. 2). The Swanville spillway sand-plain area, 40 mi^2, also trends generally north-south. This area is nearly divided by the Todd-Morrison County line and is limited by the extent of its sandy soils (fig. 2).

Sand and gravel aquifers are known to be buried in the drift, but little is known about the areal distribution or hydraulic characteristics. Study of the buried outwash is beyond the scope of this investigation.

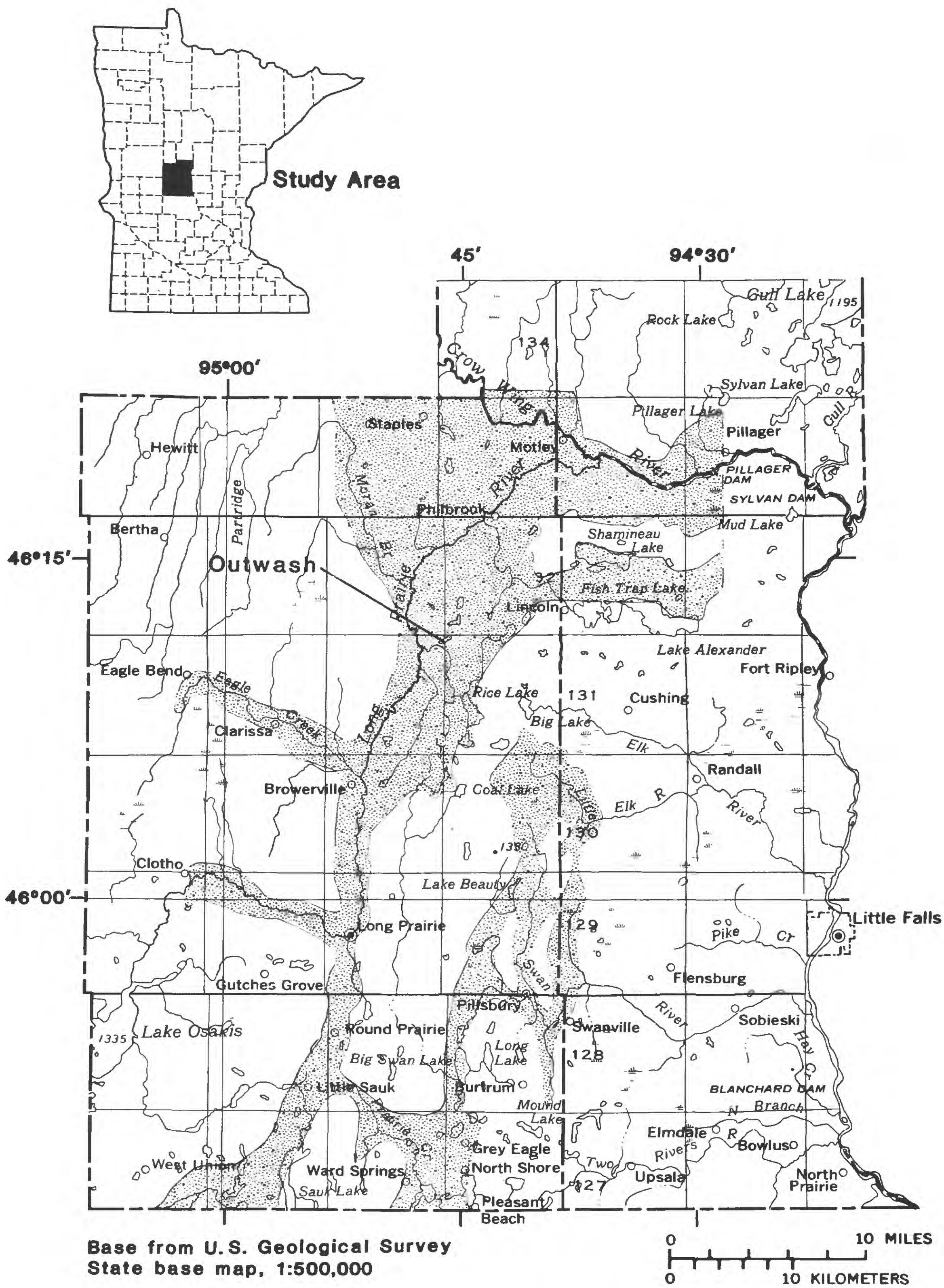


Figure 1.--Location of study area

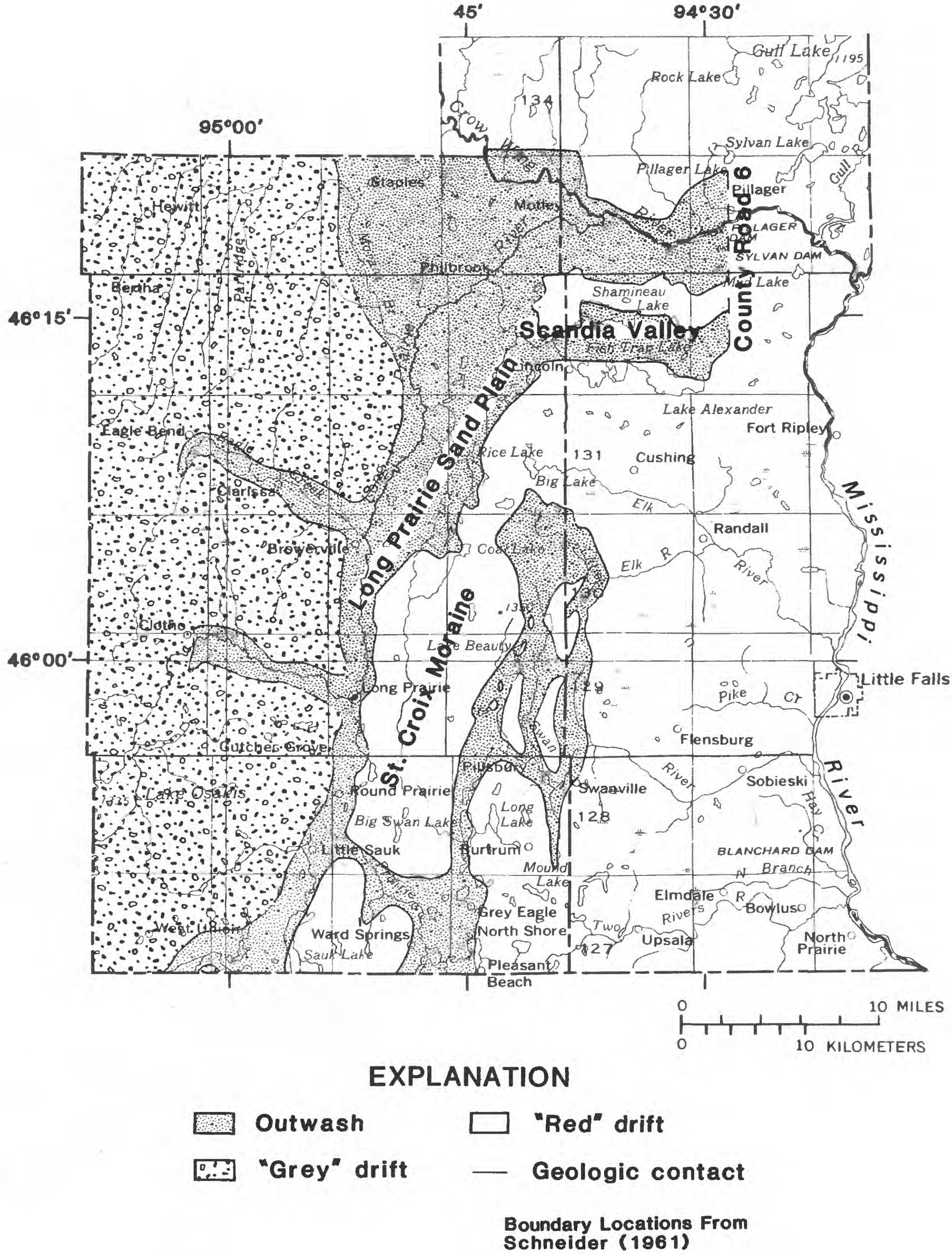


Figure 2.--Areal extent of surficial deposits

Previous Investigations

The earliest hydrogeologic investigation in the area was done by Winchell and Upham (1888) who described the surficial geology, hydrology, and vegetation. A more comprehensive study by Allison (1932) discusses the geology, water quality, and potential yields of wells in the surficial drift and bedrock. Studies of the glaciation were made by Leverett (1932), Schneider (1961), Wright (1962), Wright and Frey (1965), and Sims and Morey (1972).

Hydrologic atlases by Lindholm and others (1972) and Helgesen and others (1975) present geologic, hydrologic, and climatologic data, regional hydrologic budgets, general water-quality analyses, and estimated water use. Ground water was appraised in adjacent sand plains by Jones and others (1963), Lindholm (1970; 1980), Helgesen (1973; 1977), and McBride (1975).

At present (1982), the MPCA (Minnesota Pollution Control Agency) is sampling wells in Todd County that are part of a statewide network for observing ground-water quality (Hult, 1979).

Methods of Investigation

Data for this report were collected from July 1977 to June 1980. Geologic and hydrologic maps were prepared from local soil maps, drillers' logs, aerial photographs, and lithologic records from more than 500 augered test holes. Twenty-nine test holes were finished with steel casings and sandpoints for use as observation wells. Auger samples of several test-hole sites were sent to a private testing facility for grain-size analysis. Hydraulic conductivities were estimated for each test hole based on visual observations of grain size. Transmissivity and storage coefficient were calculated based on results of aquifer tests.

Water-table maps were constructed from water-level data from the augered holes, observation wells, and irrigation wells. Hydrographs were developed for each of the observation wells based on monthly measurements. The hydrographs were used to estimate annual ground-water recharge by analysis of water-level fluctuations.

Streamflow data were collected daily at three sites on the Long Prairie River. Stage was measured daily at two sites, whereas the other site was equipped with a continuous recording system. Discharges were measured every 5 weeks at all three sites. Base flow was measured twice at 35 sites along the Long Prairie River and its tributaries. Streamflow data were analyzed, and flow-duration curves were constructed.

Water samples were collected several times at sites selected to represent areal variations in water quality. The sampling provides data on seasonal and annual variations in water quality.

A model (Trescott and others, 1976) of the Long Prairie outwash aquifer was constructed to simulate the ground-water-flow system and provide estimates of water-level changes in response to variations in climatic and pumping conditions.

Test-Hole and Well-Numbering System

The system of numbering wells and test holes in Minnesota is based on the U.S. Bureau of Land Management's system of subdivision of public lands. The Todd County area is located in the fifth principal meridian and base-line system. The first segment of a well or test-hole number indicates the township north of the base line, the second indicates the range west of the principal meridian, and the third indicates the section in which the well or test hole is located. The uppercase letters, A, B, C, and D, following the section number, locate the well within the section. The first letter denotes the 160-acre tract; the second, the 40-acre tract; and the third, the 10-acre tract, as shown in figure 3. The letters are assigned in a counterclockwise direction, beginning with the northeast quarter. Within a given 10-acre tract successive well numbers beginning with 01 are added as suffixes. For example, the number 131N34W20ABD01 indicates the first well or test hole in the SE¼NW¼NE¼ sec. 20, T. 131 N., R. 34 W. Wells used in the study are plotted on plate 1.

Acknowledgments

The author would like to thank the personnel of the U.S. Soil Conservation Service for supplying data on land use and on the projected development of irrigable lands. Thanks are also extended to the local property owners and well drillers who provided information and especially to land owners and irrigators who allowed observation wells to be placed on their property and aquifer tests to be made with their equipment. Special thanks are also given to the Minnesota Department of Natural Resources, Division of Waters, for water-use information and support and to the Steering Committee of Todd, Cass, and Morrison Counties without whose support the project would not have been possible.

HYDROLOGY

Hydrogeology

The predominant geologic formations in the Todd County area are Precambrian crystalline rocks and metasedimentary rocks, remnants of Cretaceous sedimentary rocks, and Pleistocene drift.

Crystalline rocks generally occur from 100 to 300 feet below land surface. The upper 40 to 80 feet of the rocks is weathered to a soft, mostly white, kaolinitic clay, although shades of red, brown, and green have been observed (Allison, 1932). Two outcrops are known; a "granitic" knoll near Long Prairie and a "gabbro" near Philbrook (Allison, 1932). Precambrian metasedimentary rocks crop out in several areas of Todd County. Graywacke slate, with little surface weathering, crops out in several areas near Staples. Biotite and sericite schist with white-quartz veinlets were identified from well cuttings near Grey Eagle (Allison, 1932). See figure 1 for locations of the above-mentioned towns.

The bedrock generally is a poor aquifer because it is hard and dense. Yields to individual wells are greatest where the upper surface is weathered and fractured, but rarely exceed 10 gal/min.

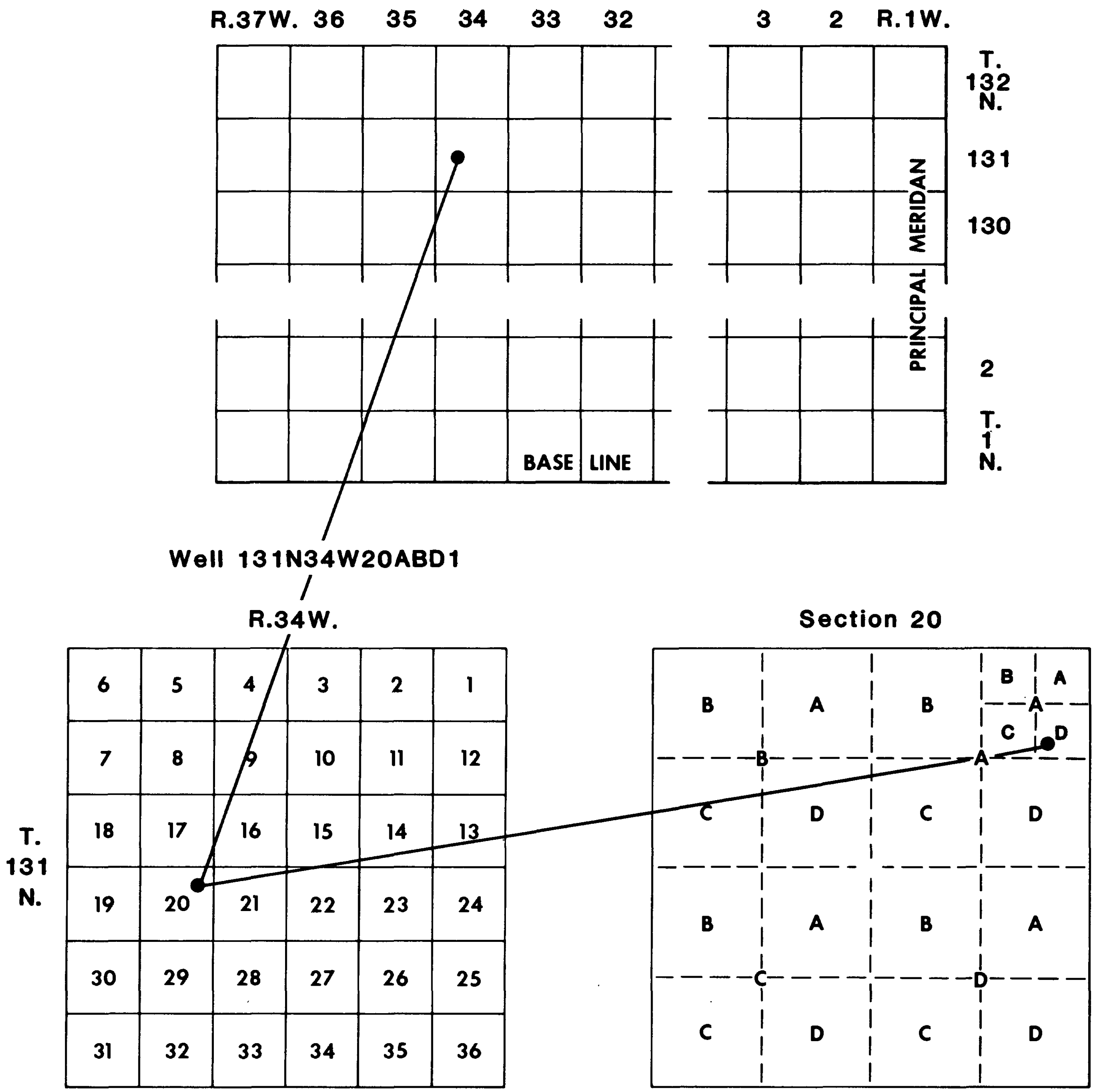


Figure 3.--Test-hole and well-numbering system

Allison (1932) suggests that sedimentary rocks of Cretaceous age underlie parts of western Todd County, but the rocks were not identified in the study area. Cretaceous rocks, where present, consist mostly of blue shale with traces of pyrite and lignite and are commonly thin and of low porosity. Well yields vary spatially, but large yields are uncommon.

Glacial deposits cover virtually the entire area (fig. 2). The deposits range in thickness from 100 to 300 feet, and consist mainly of till, stratified sand and gravel, outwash, and ice-contact deposits. The drift was deposited in a complex series of events. The western half of Todd County is covered by young "gray" drift deposited by the Wadena Lobe of Wisconsin age, which originated in southern Manitoba (Wright, 1962). The eastern part of the county is covered by young "red" drift deposited by the Superior Lobe. The north-south trending St. Croix Moraine, which nearly bisects Todd and Morrison Counties, separates the gray and red drifts. The glacial sequences have been described in detail by Schneider (1961).

The greatest potential for ground-water development is from outwash form ing the sand plains and stream valleys. The outwash in these areas generally has a high hydraulic conductivity and good hydraulic connection to major streams. Yields to wells range from 10 to more than 2,000 gal/min.

Aquifer Distribution

The best areas for ground-water development are generally in the surficial-outwash plains. The major outwash, the Long Prairie valley outwash aquifer, ranges in width from 1 mile near Long Prairie to 3 miles at Browerville to 6 miles near the confluence of the Long Prairie and Crow Wing Rivers. The thickest deposits are in a trough about 1-mile wide near the Long Prairie River. From Round Prairie to north of Browerville, the sand is as thick as 150 feet, and has an average thickness of 40 feet. The deposits thin to less than 40 feet near Motley. Other areas in which deposits of sand and gravel are thick include Scandia valley, Swanville, southwest of Grey Eagle, and west of Sauk Lake. See figure 1 for location of outwash area.

Aquifer Characteristics

Data from nearly 500 augered test holes, several hundred wells (domestic, irrigation, and industrial), 60 observation wells, and 3 aquifer tests were analyzed to determine hydraulic properties of the outwash. Its saturated thickness was determined by subtracting the altitude of the bottom of the aquifer from the altitude of the water table at each test hole and well location. Saturated thickness ranges from 0 to about 140 feet. Average saturated thickness is about 35 feet. Plate 1 shows the distribution of saturated thickness based on data collected from test holes and from irrigation and observation wells. Most of the data were collected during fall 1978 and spring 1979.

Hydraulic conductivity is 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. It can be expressed in gallons per day per square foot, but the units are usually reduced to feet per day. Hydraulic conductivity was determined by aquifer-test results, laboratory grain-size analyses, comparison of augered material with known grain-size analyses, and on degree of sorting. Table 1 shows the relation between grain size and estimated hydraulic conductivity. The relationship is one used by Helgesen (1977) and Lindholm (1980) in areas of outwash adjacent to Todd County. Lower hydraulic

Table 1.—Hydraulic conductivity of surficial-outwash materials

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 (0.250-0.5 mm, >2 mm)	200-400
Sand, coarse to very coarse (0.5-2.0 mm)	300-500
Sand, coarse to very coarse with gravel (0.5->2 mm)	400-600
Gravel (>2.0 mm)	500-700

conductivity was assigned to poorly sorted materials and higher to well-sorted material. Figure 4 shows particle-size distribution of sand samples at three aquifer-test sites. The grain sizes range from very fine sand to medium gravel with most of the material ranging from medium to very coarse sand.

Transmissivity of the outwash aquifer was calculated at each test hole and 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, which ranges from 0 to 20,000 ft^2/d. Transmissivity is generally between 5,000 and 10,000 ft^2/d. Most water supplies for irrigation are obtained in areas where transmissivity is greater than 10,000 ft^2/d.

Aquifer tests at three sites in Todd County (table 2) provided information from which transmissivity and storage coefficient (which is virtually equal to the specific yield of a well in an unconfined aquifer) were calculated. The tests varied in duration from 29 to 72 hours. Transmissivity and storage coefficient ranged from 4,600 to 18,500 ft^2/d and 0.10 to 0.25, respectively. Methods used to calculate transmissivity and storage coefficient are from Boulton (19 as described by Lohman (1972). The tests are site specific and

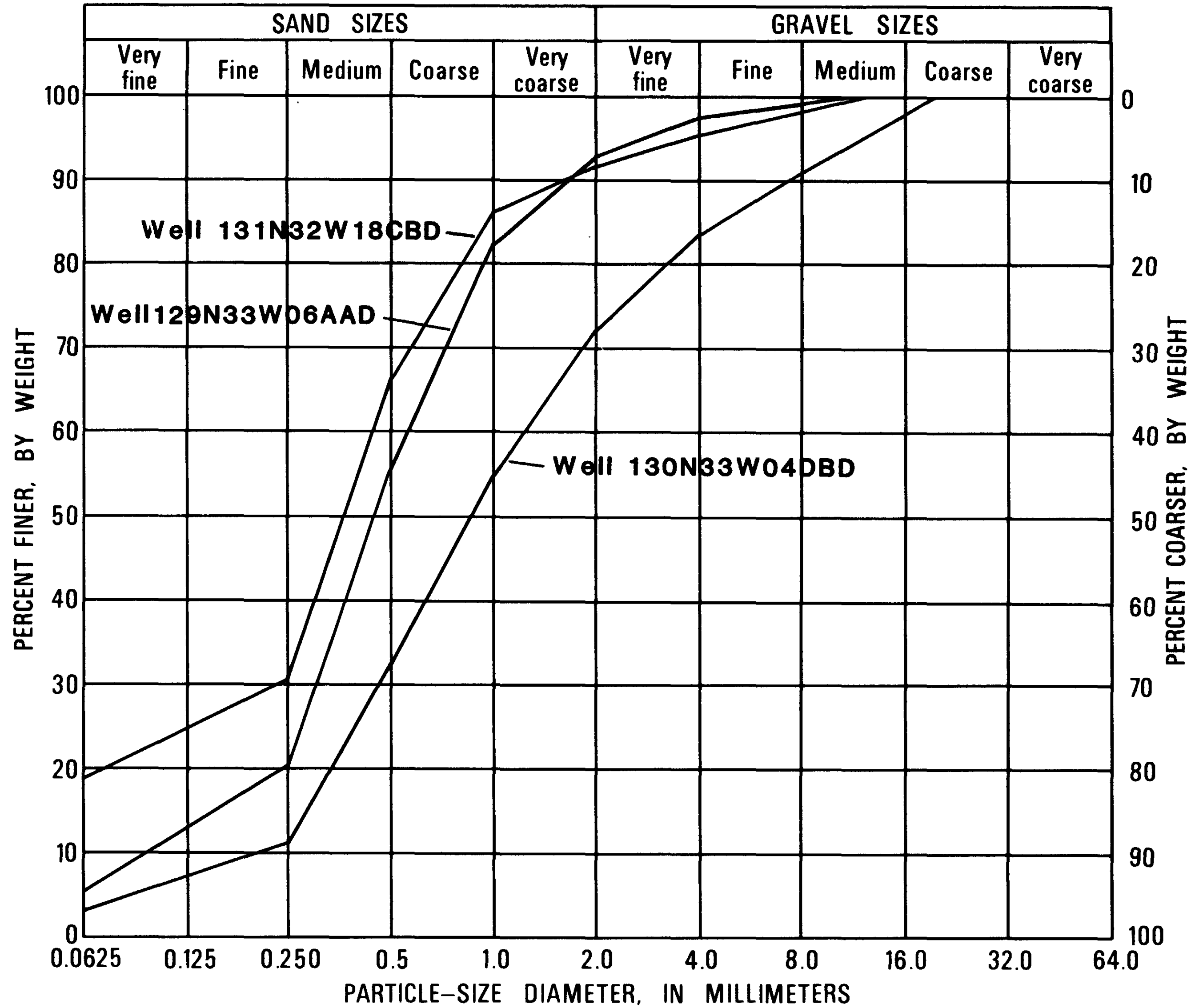


Figure 4.--Particle size distribution of outwash deposits at representative wells

Table 2.—Hydrologic properties of the surficial outwash determined by aquifer tests

Location	Lithology	Saturated thickness (feet)	Pumping rate (gal/min)	Length of test (hours)	Transmissivity (ft^2/d)	Average hydraulic conductivity (ft/d)	K_h/K_z*	Storage coefficient
129N33W06ADD	Sand, fine to very coarse; and gravel.	51	300	48	4600	90	10:1	0.10
130N33W04DBA	Sand, medium to very coarse; and clean gravel.	43	850	72	14,500	337	10:1	.21
131N32W18CBD	Sand, fine to very coarse; trace of gravel.	65	600	29	18,500	285	15:1	.25

* Ratio of horizontal to vertical hydraulic conductivity.

represent values at the test locations. At site 129N33W06ADD, for example, a nearby lateral boundary (sand-till interface) reduces the potential yield compared with that from a well in similar deposits farther away from such a boundary. However, the values can be used to estimate hydraulic properties in areas where the lithology is similar to that of the test site.

The ratio of horizontal to vertical hydraulic conductivity was also calculated at each test site based on curves showing nondimensional response to pumping a fully penetrating well in an unconfined aquifer (Lohman, 1972). The ratios (K_h/K_z) in table 2 indicate that ground-water flow is largely horizontal.

To document fluctuations of the water table, 29 wells were installed and observed monthly. On completion of the project, the network will be turned over to the Todd County Soil Conservation Service for continued observation of water levels and water quality.

Ground-Water Flow

The configuration of the water table, based on water-level data from observation wells, irrigation wells, and augered test holes is shown on plate 3. Ground water moves from areas of high head to areas of low head along lines perpendicular to the water-table contours. Regionally, in the Long Prairie valley, the direction of ground-water flow is much the same as regional streamflow. North of Little Sauk, flow is northeast toward the Crow Wing River. South of Little Sauk, flow is south toward the Sauk River.

Ground-water flow in the northern part of the Swanville Spillway outwash is toward the South Branch Little Elk River. Flow in the southern part of the outwash is toward the Swan River.

Water-Level Fluctuations

The water table fluctuates as part of a dynamic flow system in response to stresses of recharge to and discharge from the aquifer. Fluctuations are not uniform throughout the aquifer because of areal variations in precipitation, soil properties, aquifer properties, and proximity of lakes and streams.

Figure 5 shows water-level fluctuations in three representative observation wells in Todd County in 1979. Climatic records indicate that temperature was below normal in 1979 and precipitation was above normal in parts of the area in midsummer. The range of annual fluctuations for all the observation wells was generally less than 5 feet in 1979.

Aquifer Recharge

The primary source of recharge in the outwash is precipitation and snowmelt. Recharge does not always correlate well with precipitation and is, therefore, difficult to predict. Generally, when precipitation is above normal, recharge is greater than when it is below normal. The average annual

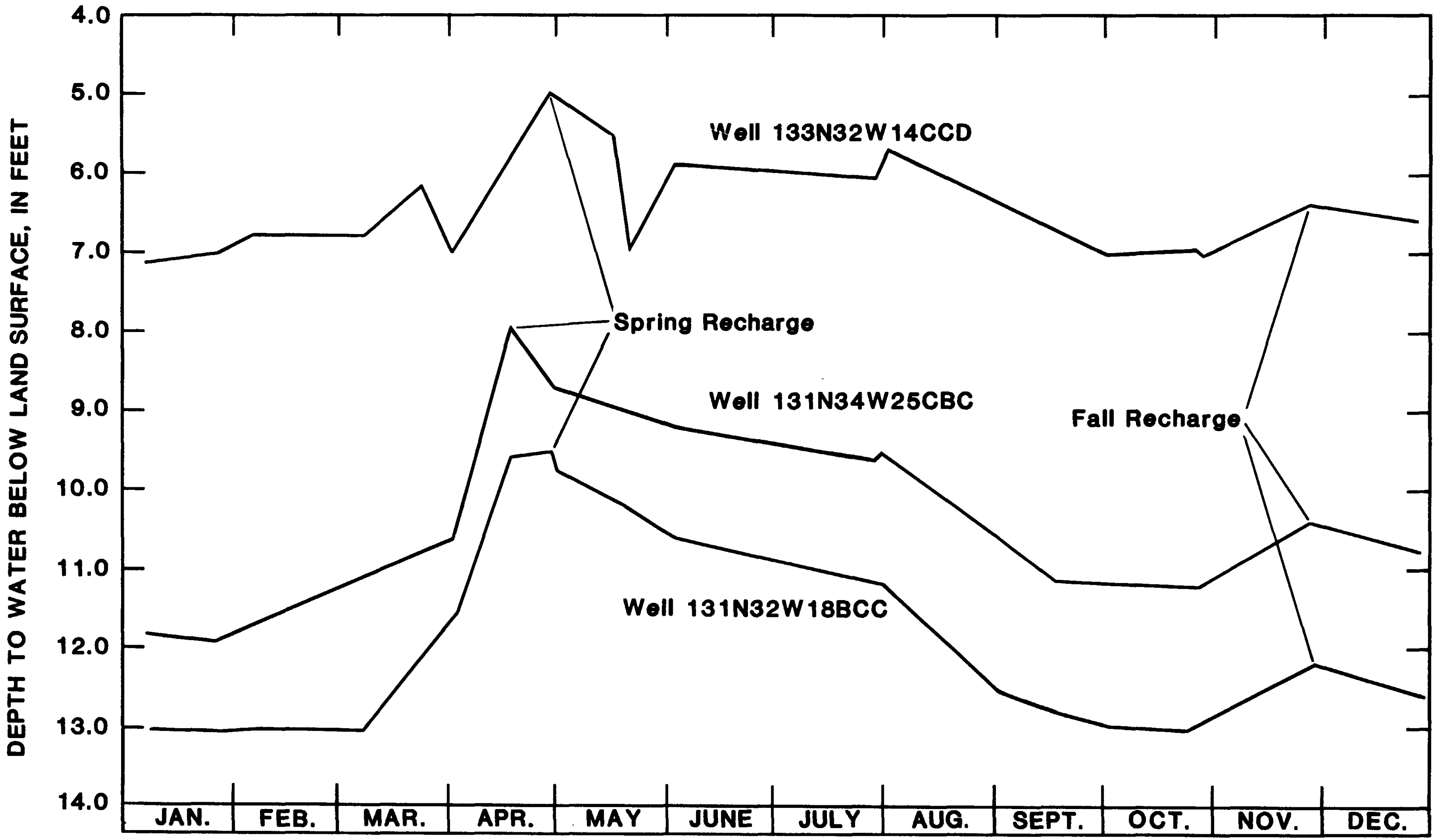


Figure 5.--Hydrographs of three representative observation wells in Todd County, 1979

precipitation at Long Prairie, based on 65 years of record at the U.S. Weather Bureau station, is 25.93 inches. Precipitation for 1978 and 1979 was 24.17 and 28.63 inches, respectively.

If the physical properties of the aquifer are known, the net recharge can be estimated. The volume of water associated with a rise or decline in water levels can be estimated by multiplying the change in water level by the specific yield. Figure 6 is a hydrograph illustrating the method used to estimate annual spring recharge and net change in amount of water in storage in the aquifer in 1979 at site 131N32W08BCC. The average recharge based on analyses of 20 hydrographs for 1979, a year of above normal precipitation, was 10.2 inches. Recharge estimates ranged from 5.9 to 13.3 inches. Average annual recharge is estimated at 8 inches, which compares favorably with estimates of recharge in adjacent areas (Lindholm, 1970; 1980; Helgesen, 1977).

The configuration of the water table (pl. 3) indicates that water from adjacent drift flows into the outwash along the margins of the aquifer. However, because the saturated thickness and hydraulic conductivity of material near the aquifer boundary are low, leakage across the boundary is not a significant percentage of the aquifer's water budget.

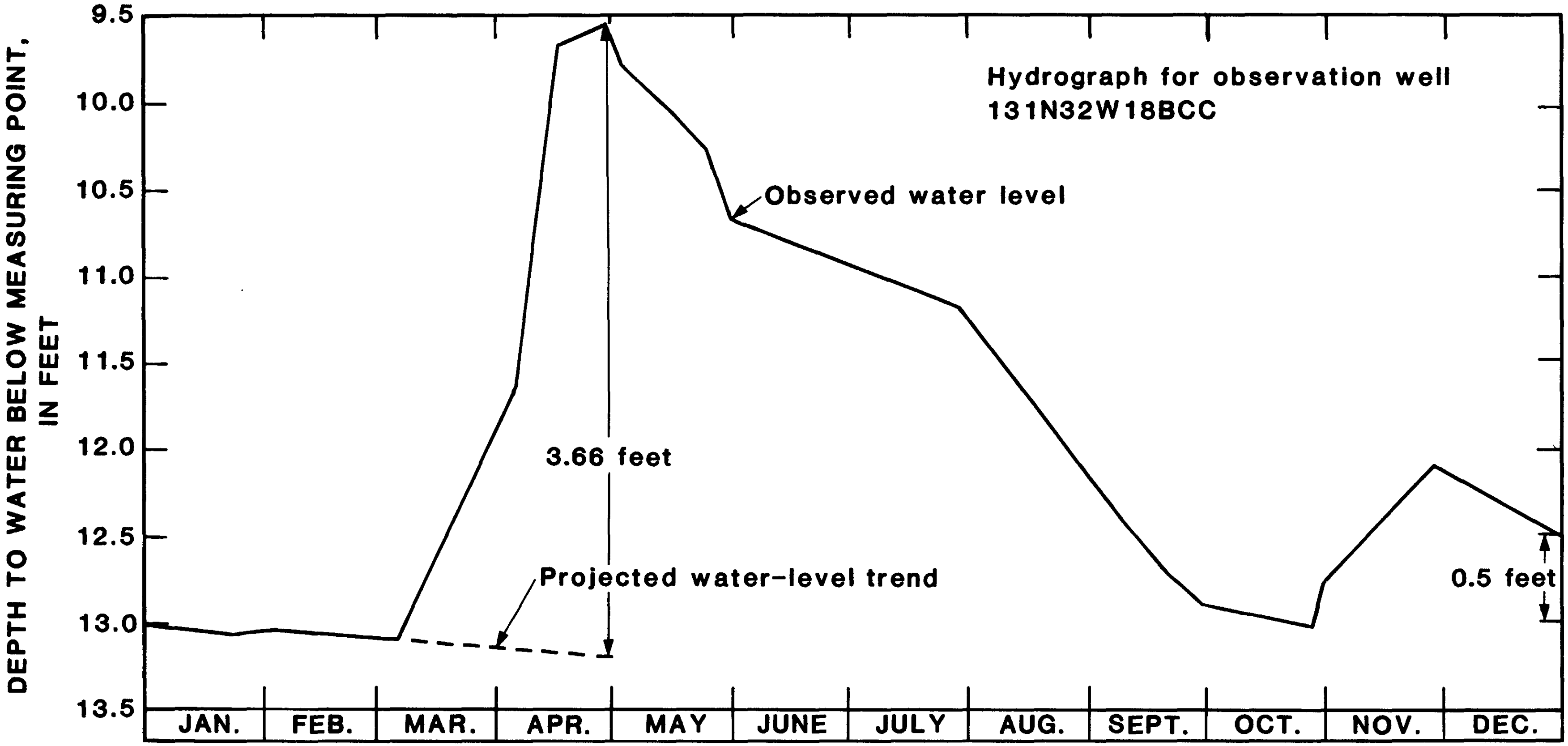
Some of the water applied for irrigation returns to the aquifer. The quantity depends on the rate of application and evapotranspiration at the time of application. However, the return flow is also probably not a significant part of the aquifer's water budget.

Ground-Water Discharge to Streams

The importance of ground-water discharge in sustaining base flow of streams can be shown by flow-duration curves, the shape and slope of which reflect the hydrogeologic characteristics of the drainage area. Figure 7 shows the flow-duration curve of the Long Prairie River based on records collected at Long Prairie from 1972 to 1979. The curve was prepared by the total-period method, a statistical method based on daily discharge (Searcy, 1959). The curve relates stream discharge to the percentage of time during which that discharge is equaled or exceeded; for example, discharge of the Long Prairie River at Long Prairie equals or exceeds 75 ft^3/s during 50 percent of the time.

Searcy (1959) suggests that a flow-duration curve with a steep slope denotes highly variable streamflow derived largely from direct runoff; whereas, a curve with a flat slope denotes fairly constant streamflow as a result of surface-water or ground-water storage. The curve shown in figure 7 of the Long Prairie River has a moderate slope, suggesting that streamflow is influenced by ground-water storage as well as by runoff from precipitation. The flat slope of the lower part of the curve indicates that water released from storage in the aquifer sustains streamflow during periods of dry weather.

Measurements of base flow were made to estimate ground-water discharge to the Long Prairie River. Thirty-five sites along the river and its tributaries from Long Prairie to the Crow Wing River at Motley (fig. 1) were measured during October 25-26, 1978, and October 29-30, 1979. For several days prior to



Recharge (largely from snowmelt and early spring rain) = (water-level rise) x (estimated specific yield)

= (43.92 inches) x (0.25)

= 10.98 inches

Figure 6.--Representative hydrograph illustrating method used to determine net effective areal ground water recharge and net change in amount of water in storage in the surficial-outwash aquifer during 1979 at indicated site

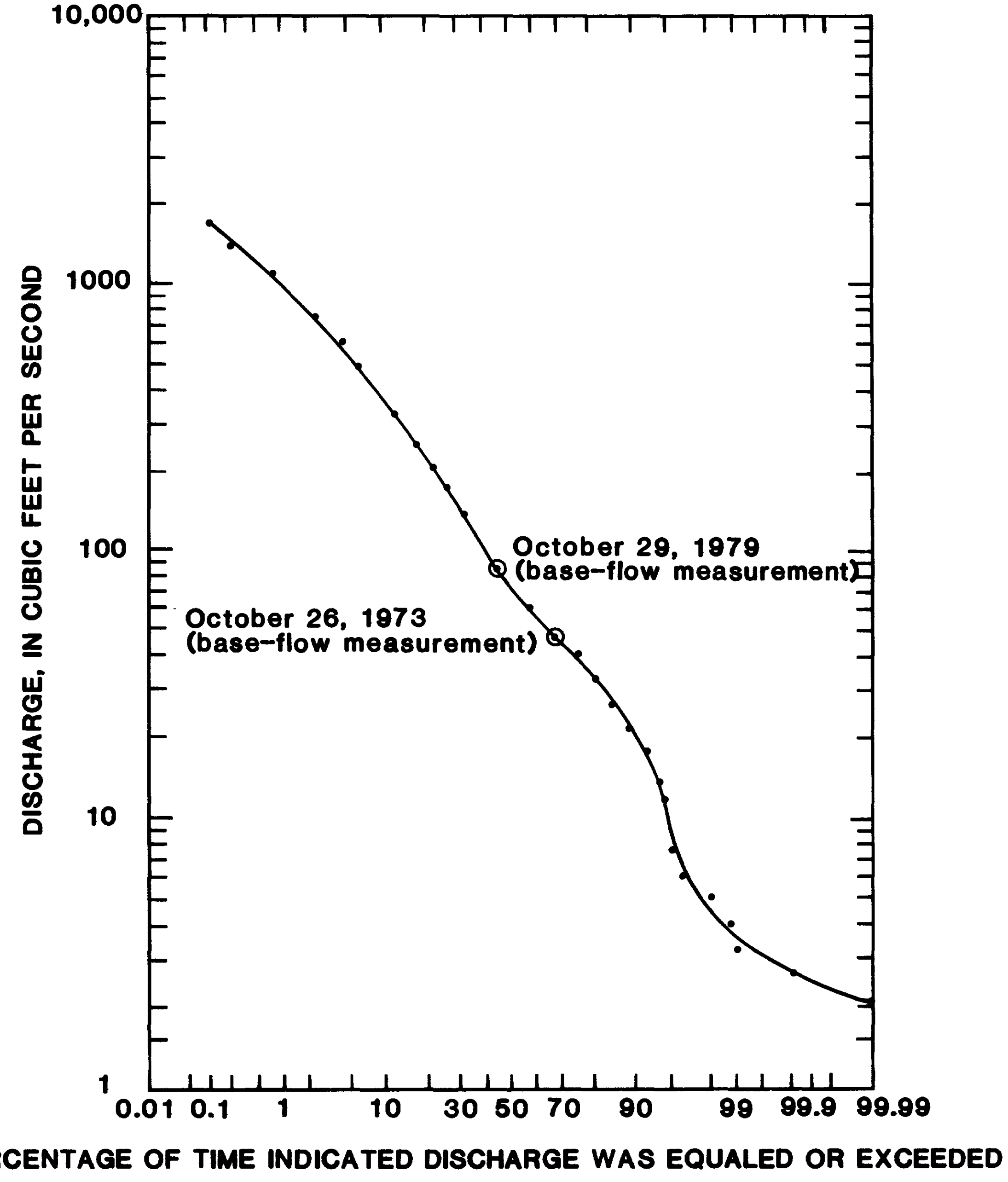


Figure 7.--Flow-duration curve for the Long Prairie River at Long Prairie (1972-79)

the collection of base-flow measurements, climatic conditions had been cool, dry, and above freezing, therefore, reducing direct streamflow losses by evaporation or as storage due to ice buildup and also reducing gains of streamflow because of direct precipitation and overland flow. Results of the base-flow measurements show net streamflow gains (total minus tributary gains), attributed to ground-water discharge, between Long Prairie and Motley of 38 and 65 ft^3/s in 1978 and 1979, respectively. Figure 7 shows dates and stream discharge at Long Prairie at the time that measurements were made. The gain in streamflow contributed by ground-water discharge represents a net gain of 0.85 and 1.3 ft^3/s per river mile in 1978 and 1979, respectively.

Evapotranspiration

Lindholm and others (1972) estimated that 85 percent of the precipitation in the Crow Wing River watershed evaporates or is transpired by plants. Evapotranspiration includes both direct evaporation from land surfaces and transpiration of water by plants. The rate of evapotranspiration from the ground-water system depends on length of root system and depth to water in the aquifer; it decreases with depth to the water table. In this study, the potential evapotranspiration rate is assumed to be a uniform 22.5 inches per year as calculated by Lindholm and others (1972) by the method of Thornthwaite and Mather (1957). Locally, evapotranspiration is assumed to be maximum (22.5 inches) when water levels are at land surface and to decrease with depth.

Depth to water in the outwash areas varies with location, altitude, and season. Water levels generally range from 0 to 30 feet below land surface, but most levels are less than 15 feet deep. Depth to water is greater in upland areas, whereas, the water table is at or near land surface in much of the valley areas.

Ground-Water Use

Data on ground-water use in 1978 were obtained from the Minnesota Department of Natural Resources. Reported pumpage was 770 million gallons. This total does not include pumpage by the cities of Browerville and Long Prairie that obtain water mostly from semiconfined sand and gravel aquifers.

POTENTIAL YIELD OF WELLS

Individual Wells

Potential yield to wells tapping the surficial-outwash aquifer was estimated from known aquifer characteristics (saturated thickness and transmissivity), assumed well characteristics, and pumping effects. In this analysis, the following assumptions were made:

1. Wells tapping the surficial-outwash aquifer are open to the full saturated thickness of the aquifer, are 100 percent efficient, and are of large diameter (16 inches);

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

3. interference from other wells and the effects of hydrologic boundaries are negligible;

4. storage coefficient of the aquifer is 0.20.

Plate 4 shows the estimated potential yield of wells completed in the surficial outwash. The yields were estimated from Theis' equation (1935), as described by Lohman (1972) and modified by Jacob (1944), to account for dewatering and reduction of transmissivity of an unconfined aquifer near the well in response to vertical-flow components. Although some of the assumptions may not be fully satisfied, the method produces a quantitative estimate of the aquifer's water-yielding potential. The potential yields shown on plate 4 are intended to be relative and should not be used to predict production for individual wells. Additional test holes need to be drilled for site-specific information. Locally, aquifers are capable of supplying more than 2,000 gal/min, but yields of 500 to 1,000 gal/min are more common. Wells in about half of the area underlain by the Long Prairie valley and Fawn Lake outwash are capable of yielding more than 100 gal/min. Outwash in most of the Scandia valley is capable of supplying about 100 gal/min, whereas only about 20 percent of the outwash in the Swanville area is capable of supplying more than 100 gal/min.

Individual well yields may also differ from estimates on plate 4 because of proximity to hydrogeologic boundaries such as the outwash-till contact or lakes and streams. Yields in marginal areas may be increased by use of infiltration ponds or by connecting several wells to supply one system.

Mutually Interfering Wells

Figure 8 is a generalized hydrogeologic section illustrating four possible effects on water levels of hydrologic boundaries and pumping of nearby wells. The amount of interference depends on the proximity of the boundary to the well and the rate of ground-water flow to the pumped well. The first scheme shows the effects of a well pumping near an impermeable boundary. Drawdown is greater between the well and the boundary because of a lack of ground-water flow toward the well. The second scheme illustrates the effects of a stream boundary. Drawdown is not as great because the stream supplies additional flow toward the well. The third scheme is similar to the second with water induced from a lake instead of a stream. A lake or stream, however, will act as a recharge boundary only as long as the withdrawals are less than the storage or rate of replenishment. The fourth scheme represents interference from another pumping well. Drawdown between the two wells is increased and is equal to the sum of the drawdowns that would result at that point caused by pumping each well. Well interference is a normal consequence of full development of an aquifer. Real drawdowns may be greater than those shown in figures 9 and 10 because wells are not 100 percent efficient, that is, drawdowns within wells are generally greater than drawdowns immediately adjacent to the wells because of inefficiencies of the wells. This condition can be caused by improper well design, improper well development, or screen-related problems such as clogging or corrosion.

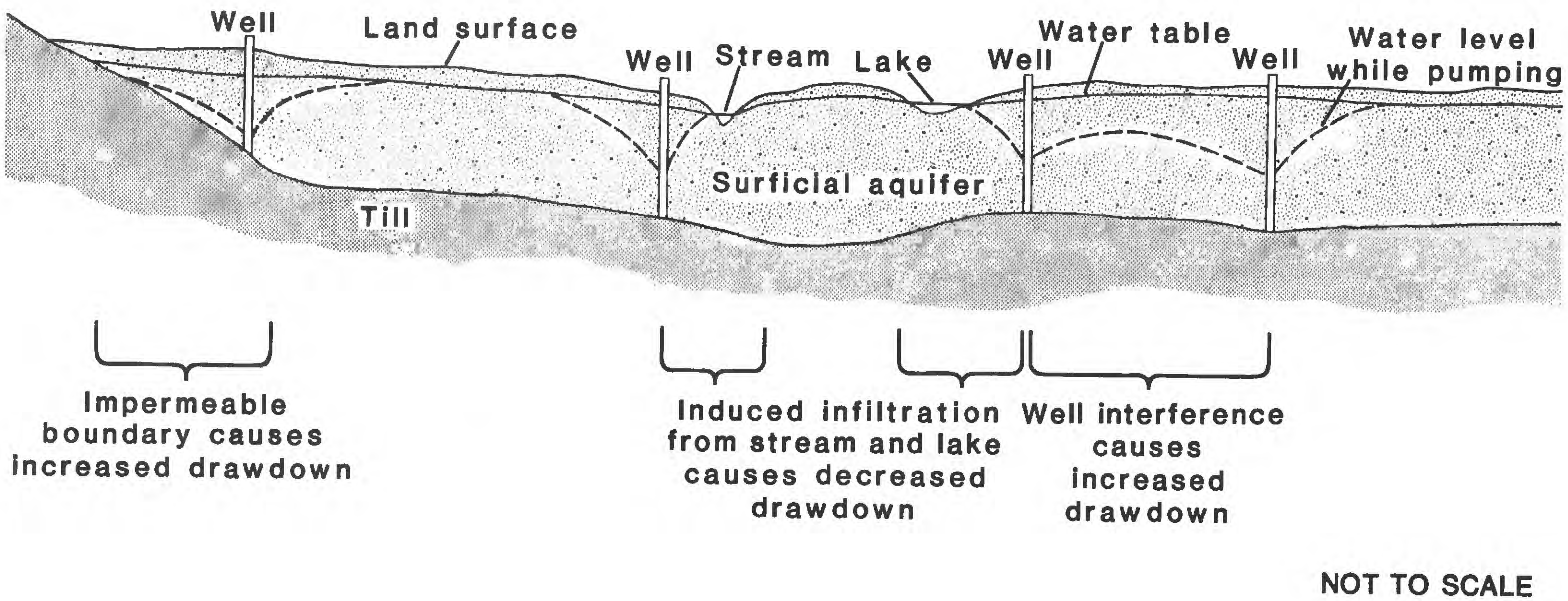


Figure 8.--Generalized hydrologic section illustrating effects of hydrogeologic boundaries and nearby wells on cones of influence

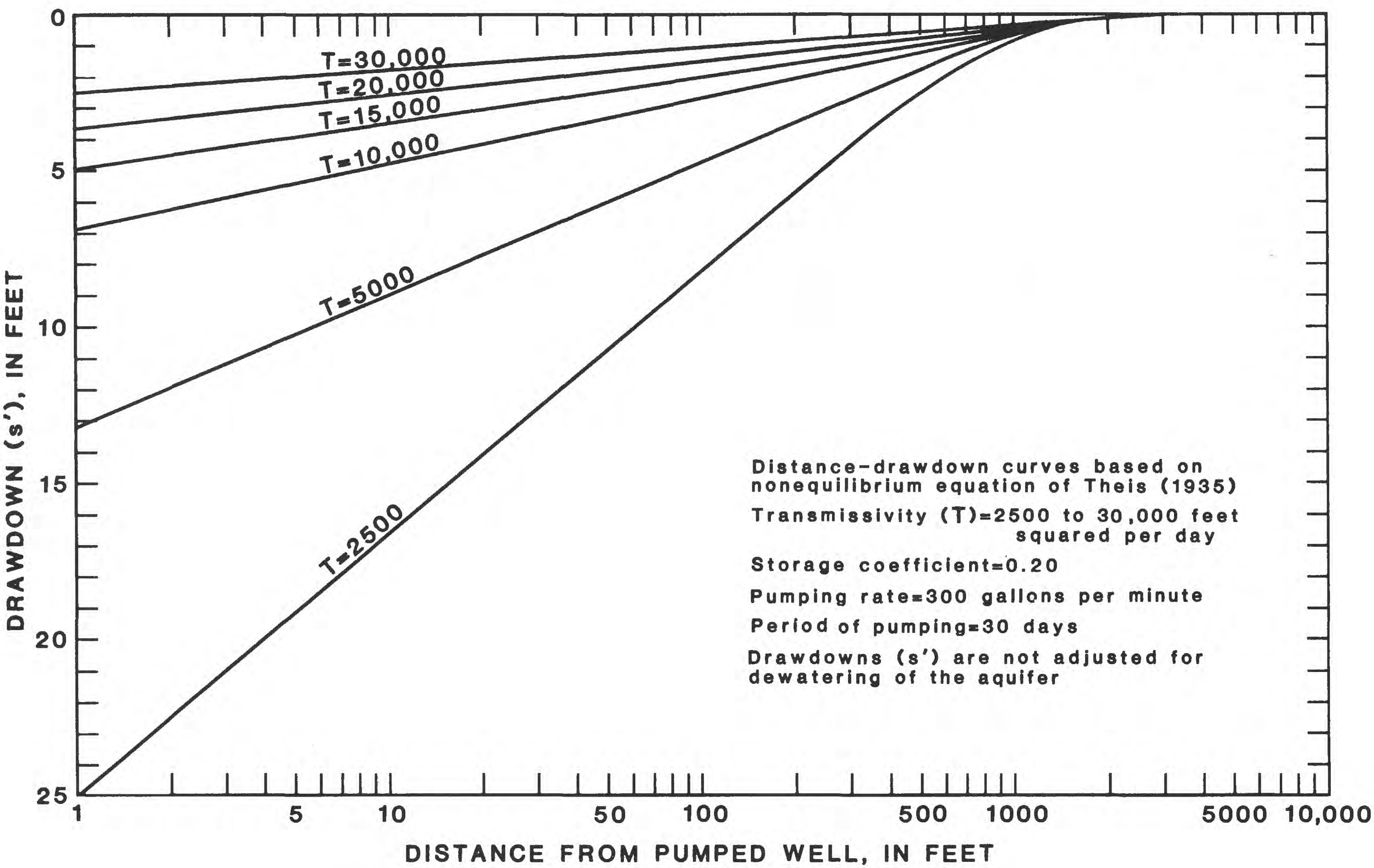


Figure 9.--Theoretical relationship of drawdown to distance from a pumped well

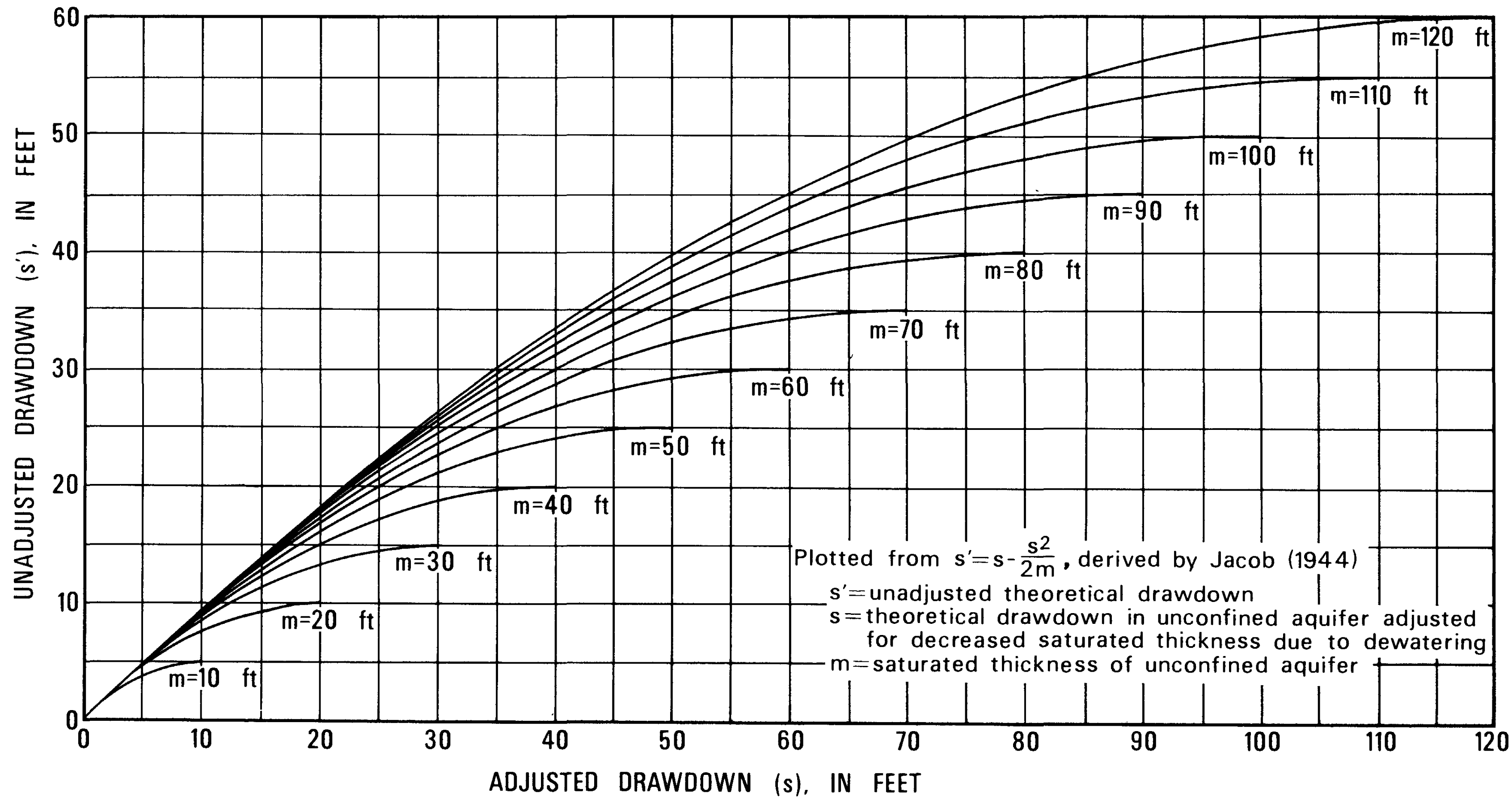


Figure 10.--Theoretical curves for adjustment of drawdown, computed by the Theis equation as modified by Jacob (1944)

Analytical methods for determining the cone of influence or drawdown in the vicinity of a pumping well are available for a variety of aquifer characteristics and boundary conditions. The method used in this report is the Theis nonequilibrium equation as outlined in Lohman (1972). Figure 9 shows theoretical relations of drawdown caused by vertical-flow components near the well (unadjusted for dewatering), to distance from a pumped well for various values of transmissivity. Drawdown can be calculated for distances from 1 to 10,000 feet from the pumping well. Although the pumping rate used to construct the graph is 300 gal/min, the curves are applicable to other rates because unadjusted drawdown is almost directly proportional to the pumping rate. For example, if the pumping rate is doubled to 600 gal/min, drawdowns at a given distance and time would be about twice those shown in figure 9. For unconfined aquifers, such as in this study, the Theis equation is not directly applicable because it does not account for dewatering of the aquifer. Therefore, drawdowns must be adjusted by using the Jacob equation (1944). This factor becomes especially important in the immediate vicinity of the pumped well. Figure 10 illustrates the theoretical curves for adjustment of drawdown for dewatering by Jacob's (1944) method. In this analysis, the same assumptions were made as for calculating potential yields of individual wells.

If drawdown due to interference between two pumping wells is to be calculated at a specific site, the drawdown at the site caused by pumping each of the wells must be calculated by use of figure 9; the results are then summed. If water-table conditions exist, the combined drawdowns must be adjusted for dewatering by using figure 10. This analytical method for calculating interference is an approximation of drawdown and should be used with caution when drawdowns exceed 25 percent of the original saturated thickness.

Hypothetical examples on the use of figures 9 and 10 are given below.

Example 1. A well is pumping 900 gal/min from an unconfined (water table) aquifer where the saturated thickness is 40 feet, the average hydraulic conductivity is 500 ft/d (based on table 1) and the storage coefficient is 0.2. The well is open to the full saturated thickness and is 100 percent efficient.

A. Find the drawdown 1 foot from the center of the well after 30 days of pumping.

1. Transmissivity is 20,000 ft^2/d (40 ft x 500 ft/d).

2. From figure 9, unadjusted drawdown for a well pumping 300 gal/min is about 3.6 feet, or 10.8 feet (3.6 ft x 3) when pumped at a rate of 900 gal/min.

3. From figure 10, an unadjusted drawdown of 10.8 feet in an aquifer having an initial saturated thickness of 40 feet gives an adjusted drawdown of about 12 feet.

Example 2. Two wells, 200 feet apart, are pumping 900 gal/min from an unconfined aquifer where the saturated thickness is 40 feet, the average hydraulic conductivity is 500 ft/d, and the storage coefficient is 0.2. The wells are open to the full saturated thickness and are 100 percent efficient.

A. Find the drawdown midway between the two wells after 30 days continuous pumping.

   1. Transmissivity is 20,000 ft^2/d (40 ft x 500 ft/d).

   2. From figure 9, unadjusted drawdown at the midpoint between the wells with only one well pumping 300 gal/min is 1.5 feet, or 4.5 feet when pumped at 900 gal/min.

   3. The unadjusted drawdown midway between the interfering wells with both wells pumping 900 gal/min would be equal to the sum of the drawdown at 100 feet from each well, or about 9.0 feet.

   4. From figure 10, adjusted drawdown for dewatering is about 10.2 feet.

B. Find the drawdown 1 foot from the center of each well after 30 days pumping.

   1. Transmissivity is 20,000 ft^2/d (40 ft x 500 ft/d).

   2. From figure 9, unadjusted drawdown 1 foot from a well pumping 300 gal/min is 3.6 feet, or 10.8 feet when pumped at 900 gal/min. Unadjusted drawdown 200 feet from a well pumping 300 gal/min is 1.2 feet, or 3.6 feet when pumped at 900 gal/min.

   3. Drawdown at one well influenced by the other pumping well will equal the sum of the drawdowns; therefore, the drawdown at either well 1 foot from the center of the well is about 14.4 feet.

   4. From figure 10, adjusted drawdown for dewatering is about 19 feet.

WATER QUALITY

The naturally occurring concentration of minerals in ground water is influenced largely by the soil and rock material through which the water moves. The degree of influence largely depends on ion exchange, residence time, chemical reactions with the materials, and solubility of the minerals. Chemical or petroleum spills, fertilizers, pesticides, trace organics, and sewage can alter the natural quality of ground water if such contaminants seep into the aquifer.

Water use primarily determines the acceptability of the water. Limits for major chemical constituents in water used for domestic consumption are shown at the bottom of table 3 as established by the Minnesota Pollution Control Agency (1978). Standards for other water uses, such as for fisheries, recreation, and agriculture, are available from the Minnesota Pollution Control Agency.

Water from wells in the outwash is generally suitable chemically for domestic consumption and most other uses. However, results indicate that in localized areas concentrations of selected constituents exceed Minnesota Pollution Control Agency (1978) recommendations for fisheries and recreation

Table 3.—Chemical analyses of

[Analyses by U.S. Geological Survey. Results

Sampling site locations	Depth of well (feet)	Date of collection	Alkalinity ($CaCO_3$)	Boron, dissolved (μg/L)	Calcium, dissolved	Organic carbon, dissolved	Chloride, dissolved	Fluoride, dissolved	Hardness (noncarbonate)	Hardness (total)	Iron, dissolved (μg/L)	Bicarbonate
Ground water												
128N33W17CCB	62	4-30-79	250	---	71	1.6	2.1	0.2	18	270	20	205
128N33W17CCB	62	9-18-79	220	<10	66	---	9.6	.1	0	220	5,100	180
128N33W05CAC	58	3- 8-79	320	---	73	2.9	1.7	.2	0	230	1,400	262
129N33W05CCB	27	4-30-79	180	---	56	6.4	22	.2	46	226	1,400	148
129N33W05CCB	27	9-18-79	150	<10	35	---	9.4	.1	14	164	570	123
129N33W21BBD	83	3- 8-67	290	---	93	---	5.8	.1	50	340	1,200	238
129N33W21BBD	83	11-28-79	310	<10	93	---	15	.2	33	343	1,400	254
130N33W04DBD	46	4-30-79	200	---	65	6.9	23	.1	20	220	9,800	164
130N33W04DBD	46	9-18-79	220	<10	66	---	9.6	.1	0	220	5,100	180
130N33W08BDD	60	6-22-64	290	---	92	---	2.0	.2	2	292	3,900	238
130N33W08BDD	60	11-28-79	330	<10	96	---	12	.2	25	355	2,100	271
130N33W17DBB	27	4-30-79	290	---	91	2.7	8.7	.1	44	334	60	238
130N33W17DBB	27	9-18-79	290	<10	92	---	7.7	.1	47	337	60	238
131N32W18BBC	27	3- 7-79	310	---	69	4.7	1.1	.2	0	310	2,000	254
131N32W18BCC	27	5- 1-79	220	---	64	4.6	1.5	.1	35	255	5,800	180
131N32W18BCC	27	9-11-79	250	<10	67	---	1.0	.2	0	250	5,500	205
131N34W27ABB	40	3- 8-67	270	---	92	---	9.4	---	50	320	110	221
131N34W27ABB	40	11-28-79	290	20	97	---	92	.1	59	349	10	238
132N33W26DCC	31	5- 1-79	200	---	80	1.4	32	.1	78	278	1,500	164
132N33W26DCC	31	9-18-79	220	---	70	---	5.8	.1	21	241	860	180
133N32W14CCD	24	5- 1-79	180	---	53	8.4	1.2	.1	0	180	2,900	148
133N32W14CCD	24	3- 6-79	180	---	52	7.1	1.3	.1	0	170	2,700	148
133N32W14CCD	24	9-18-79	260	10	79	---	2.1	.1	0	250	3,800	213
Surface water (Long Prairie River)												
129N33W20BAA	--	3- 5-79	250	---	50	---	31	0.1	0	250	1,300	205
129N33W20BAA	--	4-30-79	190	---	53	9.6	9.3	.1	16	210	110	156
129N33W20BAA	--	9-18-79	230	30	44	---	12	.1	0	230	30	189
132N32W05CCB	--	3- 6-79	280	---	64	---	13	.1	0	270	1,300	230
132N32W05CCB	--	5- 1-79	160	---	47	16	6.3	.1	15	180	180	131
132N32W05CCB	--	9-18-79	230	20	51	---	13	.1	4	230	<10	189
133N31W17BCA	--	3- 7-79	270	---	68	---	13	.1	0	280	2,800	221
133N31W17BCA	--	5- 1-79	160	---	48	10	6.8	.1	20	180	150	131
133N31W17BCA	--	9-18-79	240	20	52	---	15	.1	0	240	300	197
Recommended limits for domestic consumption (Minnesota Pollution Control Agency, 1978).							250	1.5			300	

‡ Limit for NO_3 as N; NO_2 is assumed to be negligible.

ground water and surface water
in milligrams per liter, except as noted]

Magnesium, dissolved	Manganese, dissolved (µg/L)	$NO_2 + NO_3$ as N, dissolved	pH	Phosphorus, dissolved	Potassium, dissolved	Dissolved solids (calculated sum)	Dissolved solids (tons/acre-foot)	Dissolved solids (residue on evaporation at 180°C)	Sodium-adsorption ratio	Silica, dissolved	Sodium, dissolved	Specific conductance (µmho/cm at 25°C)	Sulfate, dissolved	Water temperature (°C)
22	20	6.4	7.8	0.01	1.2	315	0.43	316	0.1	20	4.0	510	14	7.2
13	490	.09	7.4	<.01	1.4	265	.35	358	.1	19	3.4	440	14	10
24	80	<.01	7.6	.04	2.6	320	.43	317	.2	14	8.2	475	2.9	6.5
21	210	<.01	7.8	.01	1.9	273	.28	206	.2	5.2	7.0	390	37	7.2
21	110	.24	7.8	.01	1.2	179	.26	189	.1	5.3	3.8	340	5.4	11.5
26	70	---	7.1	---	1.2	---	---	420	.2	---	6.4	635	43	---
27	160	.21	7.7	.05	2.4	403	.54	396	.3	21	11	568	45	8.0
14	440	.01	7.3	.01	1.2	265	.38	377	.1	13	3.6	465	15	8.2
13	490	.09	7.4	<.01	1.4	265	.35	258	.1	19	3.4	440	14	10
22	180	---	7.7	---	1.8	---	---	399	.1	23	5.7	665	12	9.4
28	180	.03	8.0	.06	2.0	411	.44	324	---	23	11	580	32	8.0
26	10	4.5	7.3	.03	2.1	386	.53	393	.1	20	4.4	595	39	8.0
23	8	5.3	7.5	<.01	1.9	381	.48	353	.1	11	6.4	650	33	9.0
23	170	<.01	7.7	.09	1.4	315	.43	314	.2	22	6.0	535	3.2	6.0
23	200	.03	7.6	.01	1.4	256	.30	223	.2	17	6.3	520	3.9	9.0
19	250	.01	7.5	<.01	1.2	276	.37	275	.1	21	5.1	470	4.9	10
22	20	---	7.4	---	1.2	---	---	460	.2	---	8.0	650	38	---
25	1	4.5	7.3	.05	3.7	---	.68	503	---	13	3.6	570	25	8.0
19	160	.02	7.5	.01	1.4	319	.47	343	.1	16	3.5	500	45	7.5
16	120	.01	7.6	.01	1.3	268	.38	279	.1	15	3.1	480	23	9.0
9.6	260	.01	7.4	.18	.8	204	.29	210	.1	20	3.9	350	3.8	6.0
9.6	260	<.01	7.6	.19	.9	202	.28	205	.1	20	4.1	340	2.6	6.0
13	430	.01	7.5	.20	.9	280	.40	291	.1	20	45	480	.1	7.0
30	60	.08	7.6	.05	5.2	333	.46	337	0.6	19	23	582	16	---
18	80	.04	7.8	.03	4.0	231	.34	247	.2	9.7	5.3	440	17	6.1
28	50	.10	8.0	.02	3.8	258	.37	269	.3	14	9.9	510	1.0	16
26	1,700	.01	7.4	.02	3.9	326	.46	340	.3	20	12	590	16	---
14	40	.17	7.7	.03	3.4	198	.30	221	.1	5.4	4.2	325	20	6.9
26	20	.22	8.1	.02	3.0	265	.39	285	.3	13	11	515	2.1	17.5
26	2,100	<.01	7.4	.13	3.8	334	.47	344	.3	22	12	600	9.4	---
14	40	.11	7.8	.03	3.3	198	.30	223	.2	5.9	4.8	340	18	6.5
26	20	.13	8.4	.02	3.2	273	.39	285	.3	12	12	480	7.9	17
	50	‡10						500					250	

and for industrial consumption. The water is predominantly a calcium bicarbonate type, and is hard to very hard. Concentrations of hardness ranged from 164 to 355 mg/L.

Twenty-three water samples were collected from wells in the outwash and nine from the Long Prairie River (table 3). Most sites were sampled once in spring, when water levels and streamflow are relatively high, and again in fall, when levels and flow are relatively low. Three of the ground-water sites (two municipal and one creamery, 129N33W21BBD, 130N33W8BDD, and 131N34W27ABB, respectively) were sampled because they provide historical data for comparison with current data. The remainder of the sites are observation wells drilled specifically for the study. Each of the wells was pumped until pH and specific conductance stabilized. All samples were filtered and preserved for shipment to the U.S. Geological Survey Central Laboratory in Atlanta, Ga.

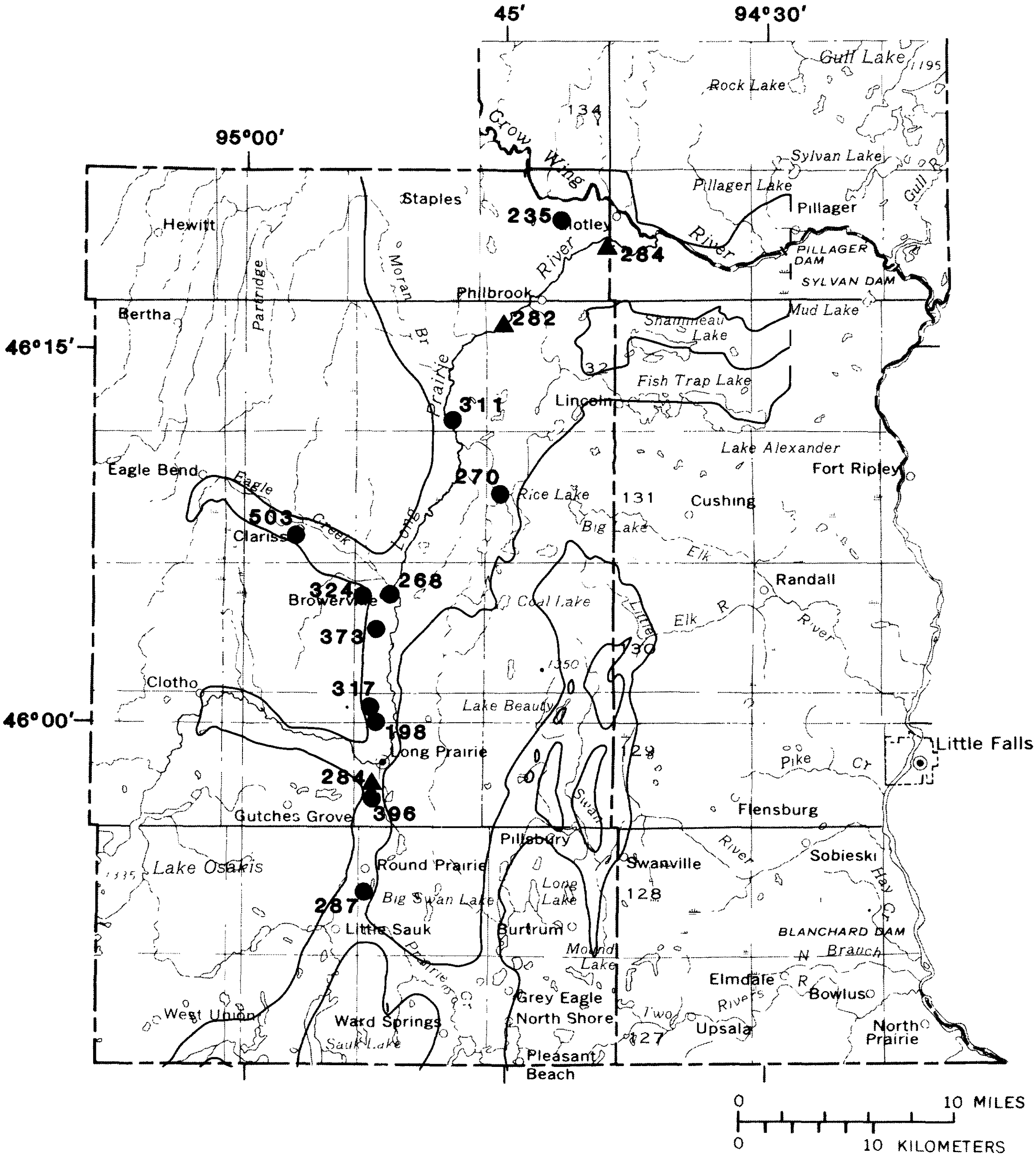
As indicated by the results in table 3, the quality of surface water and ground water is similar, indicating that ground water is the major contributor to streamflow. Generally, the ground water is suitable for most uses. Although data in table 3 suggest slight seasonal variations in most constituents, data are insufficient to establish trends.

Dissolved chlorides are essential to plants and animals, but excess concentrations may become toxic. High concentrations generally can be attributed to excess amounts of fertilizers, road deicing salts, and (or) sewage effluents. The recommended limits for chloride concentrations in water for domestic consumption as established by the Minnesota Pollution Control Agency (1978) is 250 mg/L. Chloride concentrations within the study area ranged from 1.0 to 92 mg/L.

The dissolved solids (listed as "residue on evaporation at 180°C") consist primarily of calcium, magnesium, and bicarbonate. High concentrations of these constituents may cause well-screen incrustation. Chemical reactions with manganese may produce staining and odor. The distribution of dissolved solids in ground water is shown on figure 11. The Minnesota Pollution Control Agency (1978) recommended limit for domestic consumption of dissolved solids is 500 mg/L. Concentrations within the study area ranged from 189 to 503 mg/L.

Iron is an essential element to both plant and animal metabolism, but can make water unsuitable for some uses in excessive amounts. Dissolved iron concentrations in ground water generally exceed the limit of 300 µg/L recommended by the Minnesota Pollution Control Agency for domestic consumption. For some uses, treatment may be necessary to reduce staining of fixtures and chemical reactions. Lindholm and others (1972) and Helgesen and others (1975) found that iron concentrations were generally high in the Pleistocene deposits. Its origin may be the "iron range" formation to the north. Slight increases in concentrations may also be from the dissolution of the black steel well casings.

Some chemical constituents, such as nitrate, may be desirable in certain concentrations for plant growth. However, in excessive concentrations, nitrate may produce extreme health hazards, especially to infants. High nitrate concentrations, such as those found near Clarissa, are usually indicative of a



EXPLANATION

270 ● Ground-water sampling site--Number is dissolved-solids concentration in milligrams per liter

282 ▲ Surface-water sampling site--Number is dissolved-solids concentration in milligrams per liter

Figure 11.--Concentration of dissolved solids

pollution source attributable to barnyards and sewage. Another source of nitrate is fertilizers. As irrigation becomes more intense, nitrate may accumulate in water bodies. One localized area in which nitrate concentrations in ground water are higher than normal is south of Long Prairie near Round Prairie. Figure 12 shows areal distribution of $NO_2 + NO_3$ as nitrogen. Although the laboratory determinations of NO_3-N includes NO_2 part of these analyses is assumed to be negligible compared to the NO_3. The Minnesota Pollution Control Agency (1978) recommends a NO_3 as N limit of 10 mg/L for domestic consumption. Concentrations in the study area ranged from less than 0.01 to 6.4 mg/L.

Manganese is an essential trace element for both plants and animals. In lower concentrations, manganese may react with other elements to produce objectionable taste, stains, and odors (U.S. Environmental Protection Agency, 1976, p. 179). Accumulation of manganese in ground water may occur with long-term application of fertilizers (Gough and others, 1979). The limit recommended by the Minnesota Pollution Control Agency (1976) for domestic consumption is 50 μg/L.

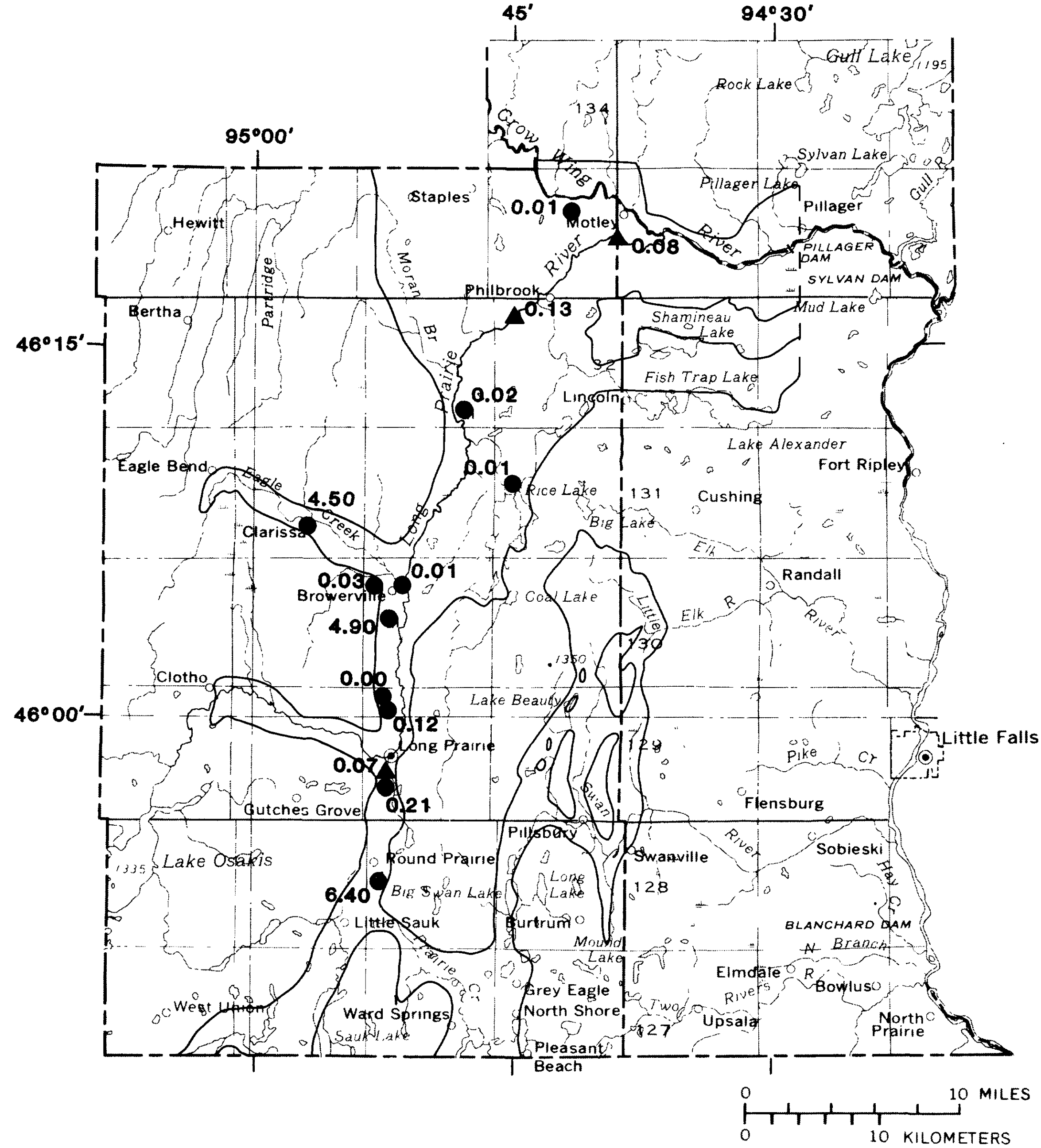
Boron, sodium, and salinity can be detrimental to crops if concentrations become too great. Small concentrations of boron are essential to plant growth, but high concentrations become toxic. The limit recommended by the Minnesota Pollution Control Agency for boron for agricultural use is 500 μg/L. The range of concentrations observed in ground water and surface water were relatively low (<10 to 30 μg/L).

The sodium-adsorption ratio (SAR), a computed ratio of sodium, calcium, and magnesium was developed by the U.S. Salinity Laboratory (1954) and is used as an indicator of the suitability of water for irrigation. The ground-water samples all show low sodium-adsorption ratios, ranging from 0.1 to 0.3.

Salinity or salt concentrations in the soil can also be extremely hazardous to crop growth. A method developed by the U.S. Salinity Laboratory (1954) rates salinity hazard based on the sodium-adsorption ratio and specific conductance. Water in the study area is in the medium salinity-hazard range, with specific conductance ranging from 325 to 665 μmhos/L (table 3). Salinity probably will not become a serious problem because of good leaching and drainage characteristics of the sandy soils.

Four wells were sampled for pesticide residuals. No trace was found of most pesticides, but residuals of atrazine were found at two sites and residuals of simetryne and 2,4-D were found at one site. Table 4 lists pesticides analyzed and the concentrations observed. None of these concentrations are at levels known to be a health risk to persons drinking the water. The 2,4-D limit for domestic water supplies is 100 μg/L (U.S. Environmental Protection Agency, 1976, p. 250). There are no set limits for atrazine and simetryne, and the concentrations found in these samples are not considered to be a health hazard.

Although the water generally is suitable for most uses, higher than normal concentrations of chemicals related to agricultural practices were found locally.



EXPLANATION

0.08 ● Ground-water sampling site--Number is dissolved nitrogen ($NO_2 + NO_3$ as N) in milligrams per liter

0.13 ▲ Surface-water sampling site--Number is dissolved nitrogen ($NO_2 + NO_3$ as N) in milligrams per liter

Figure 12.--Concentration of dissolved nitrogen ($NO_2 + NO_3$ as nitrogen)

Table 4.—Pesticide analyses of water from the surficial aquifer

[Values in micrograms per liter; 0.0 indicates concentration is below laboratory detection level of 0.1; 0.00 indicates concentration is below laboratory detection level of 0.01]

Physical and chemical characteristics	Well number			
	128N33W17CCB	129N33W05CDB	129N33W05CDB	130N33W04DBD
Depth of well (in feet)..........	40	20	20	25
Date of collection....	9-18-79	3- 8-79	9-18-79	9-18-79
Ametryne.............	0.0	0.0	0.0	0.0
Atratone.............	0.0	0.0	0.0	0.0
Atrazine.............	2.3	0.0	0.1	0.0
Cyanazine............	0.0	0.0	0.0	0.0
Cyprazine............	0.0	0.0	0.0	0.0
Prometone............	0.0	0.0	0.0	0.0
Prometryne...........	0.0	0.0	0.0	0.0
Propazine............	0.0	0.0	0.0	0.0
Silvex...............	0.00	0.00	0.00	0.00
Simazine.............	0.0	0.0	0.0	0.0
Simetone.............	0.0	0.0	0.0	0.0
Simetryne............	1.0	0.0	0.0	0.0
2,4-D................	0.01	0.00	0.00	0.00
2,4-DP...............	0.00	0.00	0.00	0.00
2,4,5-T..............	0.00	0.00	0.00	0.00

DIGITAL MODEL

The two-dimensional digital model of Trescott and others (1976) was used to simulate the ground-water-flow system and its response to stresses in part of the study area. The basic equation, whose solution is approximated by the model for an unconfined aquifer, may be expressed as:

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

where:

Kxx, Kyy = the principal components of the hydraulic conductivity tensor (Lt^{-1}),

Sy = 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).

A two-dimensional model was selected because flow in the aquifer is virtually horizontal. The modeled area is a single layer of relatively uniform glacial sand and gravel underlain and generally bordered by till of relatively low hydraulic conductivity. The strongly implicit procedure was used in the model to solve the simultaneous finite-difference equations representing the aquifer system.

Location of the Modeled Area

The modeled area, shown in figure 13, centers on the Long Prairie valley outwash. The modeled area is bordered by glacial outwash-till contacts, ground-water divides, and small outwash stringers that join the main aquifer. Areas not modeled were smaller outwash sands detached from the Long Prairie valley outwash; such as (1) the Scandia valley, (2) Swanville, (3) near Grey Eagle, and (4) near Sauk Lake where pumpage rates are insignificant.

Description of the Model

In order to simulate the aquifer's irregular boundaries, the model was subdivided into blocks by a variable grid containing 25 rows and 30 columns. Grid blocks ranged in size from 0.25 to 3 mi^2 (160 to 1,920 acres). The smallest blocks were assigned to an area near Browerville where ground-water development for irrigation is greatest. A variable grid was necessary to represent the boundaries accurately and provide greater detail in the highly developed areas. The model uses a block-centered scheme, which means calculations are made at the center of each block. This central point is referred to as a node. At each node, aquifer properties and hydraulic stresses are assigned average block values. The finite-difference grid is shown in plate 5A.

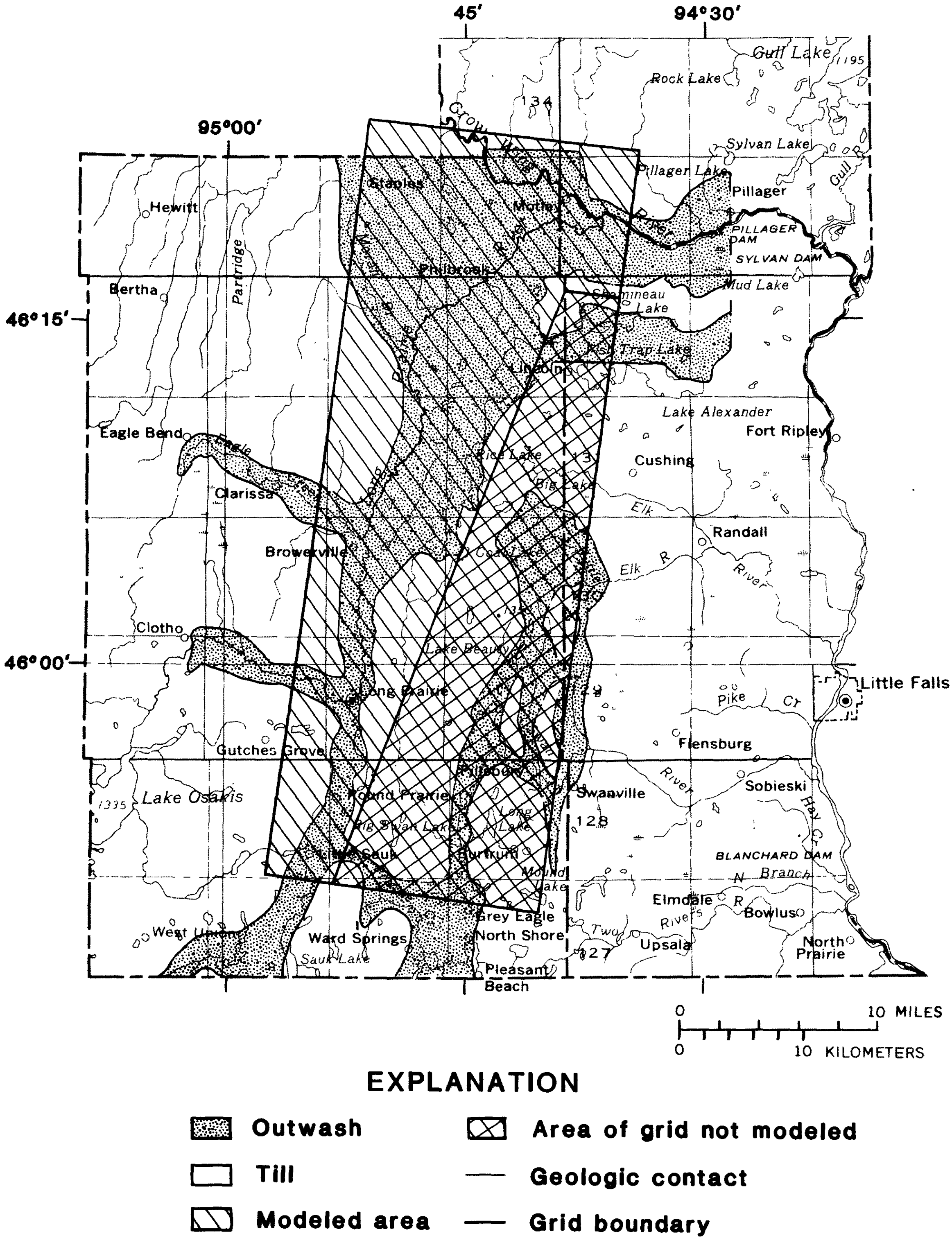


Figure 13.--Location of modeled area

Simulation of Model Boundaries and Streams

Selection and treatment of model boundaries is critical. The model must either simulate the boundary effects explicitly[1] placed far enough away from present or anticipated stresses so that model calculations are not significantly affected by the boundary. Boundaries may be treated as (1) constant head, (2) constant flux, or (3) head-dependent flux. A constant-head boundary allows as much flux across the model boundary as necessary to maintain initial water levels at the boundary regardless of stress imposed on the model. A lack of water-level declines in the stress area will result if this boundary is not placed far enough away from stress areas. A constant-flux boundary allows a predetermined and fixed amount of water across the boundary that does not change in response to simulated stress. The constant flux may be zero (impermeable boundary) or have a finite value. A head-dependent flux allows the model to simulate variable flux into or out of the aquifer in relation to the transmissivity and the difference between a model-computed head and a fixed head specified in the model.

Constant heads were assigned to nodes at the aquifer boundaries where significant amounts of water enter or leave the system as streamflow or ground-water flow. The remainder of the lateral boundary nodes were modeled as no-flow boundaries, which allow no inflow to the aquifer from the adjacent till. Nodes representing the location of major streams within the modeled area were modeled as head-dependent flux boundaries to simulate flow into or out of the aquifer as streambed leakage. Assignment of boundary types is shown in plate 5A.

Calibration of the Model

Before the model was used to simulate aquifer response to projected stresses, it was calibrated at steady state to assure that it represented average annual hydrologic conditions in the aquifer. Steady-state calibration was done by successively adjusting input parameters until calculated water levels and ground-water discharge to streams acceptably matched those observed in the field. Computed ground-water levels were accepted if they were within plus or minus 5 feet of water levels measured in observation and irrigation wells in October 1979. At that time, water levels and ground-water discharge to streams were approximately equal to average annual conditions. Computed ground-water discharge to streams was accepted if it was within plus or minus 30 percent of the streamflow gain measured in October 1979. The solution obtained by the steady-state model is not unique and similar results may be obtained by several combinations of parameter values. However, input parameters were adjusted within reasonable limits consistent with the conceptual model of the aquifer system. Table 5 shows a comparison of observed water levels with water levels computed by the calibrated model.

[1] Boundary must be simulated so that model responses mimic natural responses.

Table 5.—Comparison of computed and observed water levels for the calibrated steady-state model

Block number (row, column)	Computed water level (altitude in feet above sea level)	Observed water level, October 1979 (altitude in feet above sea level)	Difference (Computed minus observed in feet)
5, 12	1,268	1,267	+1
6, 8	1,286	1,284	+2
7, 13	1,266	1,267	-1
7, 15	1,262	1,262	0
8, 14	1,264	1,261	+3
8, 18	1,258	1,259	-1
10, 8	1,279	1,282	-3
10, 25	1,249	1,249	0
11, 2	1,305	1,307	-2
15, 15	1,277	1,276	+1
17, 27	1,251	1,254	-3
18, 19	1,263	1,260	+3
18, 25	1,239	1,240	-1
21, 28	1,231	1,233	-2
23, 27	1,246	1,244	+2

The approximate water budget for the calibrated steady-state model is:

Inflow

	Cubic feet per second
Recharge from precipitation.................	68.2
Leakage from streams........................	2.8
Total..........	70.0

Outflow

	Cubic feet per second
Leakage to streams..........................	46.4
Pumpage.....................................	3.2
Evapotranspiration..........................	20.4
Total...........	70.0

For model calibration, certain hydrologic characteristics of the ground-water system were fixed based on available data. An evapotranspiration rate equivalent to 22.5 inches per year (Lindholm and others, 1972) was used in the model. The evapotranspiration rate was assumed to be at full potential when water levels are at land surface and to decrease linearly to zero when water levels fall below 5 feet.

Pumpage for the calibrated model was based on 1978 records of the Minnesota Department of Natural Resources. A total pumpage of 2.1 Mgal/d was divided among 30 pumping centers that coincided with the field locations of the wells. Locations of these pumping centers are shown in plate 5B.

During model calibration, the values of several hydrologic properties were varied to determine the sensitivity of the model to changes in these parameters. Factors that caused the greatest differences between computed and observed water levels were variations in areal recharge, flow across lateral boundaries, and leakage coefficients of the streambed. The following schemes were used to determine sensitivity of each of the major factors.

Average annual areal recharge, based on several years of record, was estimated to be 8 inches. However, annual recharge rates of 4, 8, and 12 inches were applied at steady state to determine model response. Table 6 shows the difference between computed and observed water levels at representative blocks for annual areal recharge rates of 4, 8, and 12 inches. Specific blocks listed contain observation wells. An annual recharge rate of 8 inches provides the best overall match of water levels and compares favorably with estimates of recharge in adjacent outwash areas (Lindholm, 1970; 1980; Helgesen, 1977).

The lateral boundaries were modeled as no-flow, which do not allow the model to simulate any ground-water flow across the boundaries into or out of the aquifer. Model sensitivity was tested by simulating various amounts of leakage across the boundaries based on the local hydraulic gradient and comparing the calculated water levels with the observed water levels. The addition of leakage at lateral boundaries greatly dampened model response to changes in other model parameters at nodes adjacent to the boundaries. Simulation of no-flow boundaries produced the best overall results and they were used for model calibration and subsequent model experiments.

The sensitivity of the model to stream leakage was tested by varying the leakage coefficients in several model simulations. Table 7 shows the difference between computed ground-water discharge to streams and the observed discharge upstream from the Philbrook and Motley gaging stations. Ground-water discharge rates computed by the model for streambed leakage coefficients of 0.1 and 1.0 (ft/d) are similar and both match observed discharge in October 1978 and October 1979 quite well. However, a leakage coefficient 0.1 (ft/d)/ft was accepted for model calibration and used in subsequent simulations because it represents a more restrictive hydraulic connection between the aquifer and the stream. This value also compares favorably with stream-leakage coefficients in nearby outwash areas of similar geologic setting (Larson, 1976; Lindholm, 1980). Use of the leakage coefficient of 0.1 (ft/d)/ft also produced the best match of computed to observed water levels at nodes adjacent to stream nodes.

Table 6.—Difference between computed and observed (October 1979) water levels for different recharge rates

Block (row, column)		Annual areal recharge (inches): 4		8		12	
		Computed water level (feet)	Computed minus observed water level (feet)	Computed water level (feet)	Computed minus observed water level (feet)	Computed water level (feet)	Computed minus observed water level (feet)
5,	12	1,267	0	1,268	+1	1,269	+2
6,	8	1,283	-1	1,286	+2	1,288	+4
7,	13	1,265	-2	1,266	-1	1,267	0
7,	15	1,261	-1	1,262	0	1,263	+1
8,	14	1,263	+2	1,264	+3	1,266	+5
8,	18	1,257	-2	1,258	-1	1,259	0
10,	8	1,278	-4	1,279	-3	1,280	-2
10,	25	1,247	-2	1,249	0	1,251	+2
11,	2	1,303	-4	1,305	-2	1,307	0
15,	15	1,274	-2	1,277	+1	1,279	+3
17,	27	1,248	-6	1,251	-3	1,252	-2
18,	19	1,261	+1	1,263	+3	1,264	+4
18,	25	1,237	-3	1,239	-1	1,241	+1
21,	28	1,228	-5	1,231	-2	1,231	-2
23,	27	1,244	0	1,246	+2	1,246	+2
Total		----	-29	----	-1	----	+18

Table 7.—Comparison of observed and model-computed ground-water discharge to the Long Prairie River

[All values are expressed in cubic feet per second]

Stream reach	Observed ground-water discharge		Computed ground-water discharge			
	Date		Leakage coefficient [(ft/d)/ft]			
	Oct. 26, 1978	Oct. 29, 1979	1.0	0.1	0.01	0.001
Long Prairie to Philbrook.	36	43	37	35	24	9
Long Prairie to Motley.	38	65	53	50	36	19

Model Experiments

After calibration of the model at current steady-state conditions in the aquifer, the model was used to estimate response of the aquifer to several possible combinations of water-supply development and climatic conditions. The model provides managers with a tool for estimating regional trends in aquifer response to drought and ground-water development. However, because the model was calibrated to current steady-state hydrologic conditions rather than to long-term data, the model results must be used with caution. The accuracy and validity of the results can be determined only by collecting additional water-level data as development occurs and using that data to recalibrate the model and demonstrate its ability to simulate aquifer responses through time. Drawdowns computed by the model are based on simplified assumptions and actual drawdowns in the field will probably differ. In addition, computed drawdowns are averaged over the entire grid block; therefore, computed values will not be as great as actual drawdowns at specific wells.

Experiment 1 simulates aquifer response to increased pumping at existing pumping centers with an average recharge rate of 8 inches per year and pumpage of 5.2 million gallons per day (1978 pumpage multiplied by 2.5). Computed results suggest that at steady state (1) water-level declines may be less than 1.5 feet regionally and (2) reduction of aquifer discharge to streams would be less than 2 percent.

Experiment 2 simulates aquifer response to decreased recharge with present pumping rates. A drought of 4 years was simulated, during which the aquifer storage coefficient was assumed to be 0.2 and recharge was reduced by half.

Recharge was assumed to be 4 inches annually and pumpage was 2.1 million gallons per day. Model results indicate that (1) water levels by the end of the 4-year cycle may decline locally by as much as 4 feet and (2) aquifer discharge to streams may be reduced 5 percent. The distribution of drawdowns for experiment 2 is shown in plate 5B.

Experiment 3 simulates aquifer response to a drought of 1 year combined with increased pumpage. Aquifer storage coefficient was assumed to be 0.2, recharge was assumed to be 4 inches, and pumpage was simulated at 5.2 million gallons per day (1978 pumpage multiplied by 2.5) to simulate the additional pumpage necessary for adequate moisture to crops. Pumping was timed to simulate seasonal agricultural ground-water withdrawals, whereby 120 days of pumping is followed by 245 days of nonpumping. Model results suggest that, after 120 days of pumping, water levels could decline locally by as much as 6 feet. The distribution of drawdown for experiment 3, after 120 days of pumping, is shown in plate 6A. Model results also suggest that 245 days after pumping stopped drawdowns may locally still be as much as 1.5 feet. The residual drawdown suggests that the system would not fully recover from the combined effects of drought and increased pumpage by the end of the cycle. Computed ground-water discharge to the streams after 120 days of pumping was reduced by 10 percent, but the discharge virtually recovers after the 245-day period.

Experiment 4 simulates the aquifer's response to additional ground-water development and below-normal precipitation. Placement of additional pumping centers was based on areas of maximum transmissivity and saturated thickness and areas of expected development, as projected by the Todd County Soil Conservation District. Twenty-three pumping centers were added to the model, as shown in plate 5A. A drought of 4 years was simulated during which recharge was reduced to 4 inches annually. Because of the drought, 1978 rates for individual pumping centers were multiplied by 2.5 to simulate the additional pumpage necessary for adequate moisture to crops. This same increased rate of pumping was also applied to the 23 hypothetical pumping centers (pl. 5B), bringing total pumpage simulated in experiment 4 to 7.7 million gallons per year. Computed results indicate that (1) water levels at the end of the 4-year cycle may decline by as much as 9 feet locally and (2) aquifer discharge to streams may be reduced by 20 percent. This distribution of drawdown for experiment 4 is shown in plate 6B.

Table 8 is a summary of the results of the four experiments simulated by the model. Although the results indicate that each of the modeled experiments would result in water-level declines and reductions in streamflow, with proper development and management the aquifer is capable of accommodating additional withdrawals.

Table 8.—Summary of experiments used to simulate changes in pumpage and recharge

Experiment	Conditions of experiment	Aquifer response to experiment
1	a. 8 inches recharge. b. 5.2 million gallons per day pumpage.	Water levels decline less than 1.5 feet regionally, and reduction of ground-water discharge to streams is less than 2 percent.
2	a. 4 inches recharge. b. Simulated drought of 4 years. c. 2.1 million gallons per day pumpage.	Water levels decline by as much as 4 feet locally, and reduction of ground-water discharge to streams is 5 percent.
3	a. 4 inches recharge. b. Simulated drought of 1 year. c. 1.9 billion gallons pumped in 120 days followed by 245 days recovery.	After 120 days of pumping, water levels decline by as much as 6 feet locally, and reduction of ground-water discharge to streams is 10 percent. After 245 days of recovery, water levels recover to 1.5 feet of drawdown regionally and reduction of aquifer discharge to streams is less than 2 percent.
4	a. 4 inches recharge. b. Simulated drought of 4 years. c. 7.7 million gallons per day pumpage.	Water levels decline by as much as 9 feet locally, and reduction of ground-water discharge to streams is 20 percent.

SUMMARY

The surficial-outwash aquifers are the largest source of ground water in Todd County and parts of Cass and Morrison Counties. The aquifers cover 250 mi^2 and extend from Round Prairie to Motley, where they converge with outwash of the Wadena sand plain. Outwash thickness ranges from 0 to 150 feet and averages about 40 feet. Depth to water varies with topography, but water levels are generally less than 30 feet below land surface. Saturated thickness ranges from 0 to 140 feet. Annual water-level fluctuations average less than 5 feet. Well yields range from 10 to 2,000 gal/min.

Aquifer material ranges from very fine sand to medium gravel, but consists mostly of medium to very coarse sand. Aquifer tests indicate that transmissivity ranges from 4,600 to 18,500 ft^2/d and storage coefficient ranges from 0.10 to 0.25. Locally the aquifer is capable of supplying as much as 2,000 gal/min to a properly constructed well.

Average annual precipitation based on 65 years of record at Long Prairie Weather Station is 25.93 inches. Annual precipitation during 1978 and 1979 was 24.17 and 28.63 inches, respectively. Average annual recharge to the aquifer was estimated to be 8 inches. Annual recharge for 1979 was estimated to be 10.2 inches.

A flow-duration curve based on 8 years of record at the Long Prairie station indicates that streamflow equals or exceeds 75 ft^3/s 50 percent of the time. Base-flow measurements made on October 26, 1978, and October 29, 1979, indicate that the Long Prairie River was gaining 0.85 ft^3/s and 1.3 ft^3/s per river mile, respectively, due to ground-water inflow.

Both ground water and surface water are generally chemically suitable for domestic consumption and most other uses. However, results indicate that in localized areas concentrations of selected constituents exceed Minnesota Pollution Control Agency recommendations for fisheries and recreation, and for industrial consumption. The water is a hard to very hard calcium bicarbonate type. Dissolved solids consist primarily of calcium, magnesium, and bicarbonate ions, and concentrations ranged from about 200 to 400 mg/L. Locally, dissolved iron concentrations exceed acceptable limits. Nitrate and chloride concentrations are generally low; however, concentrations in local areas are higher than baseline data indicate. Several samples analyzed for pesticides indicate local contamination of ground water by residues of atrazine, simetryne, and 2,4-D.

The observation-well network created to meet the objectives of the project was used to establish baseline water quality and water-level elevations. The network can also be used for continuation of the monitoring program for documentation of long-term trends.

Results of the digital model experiments suggest that, with proper development, the aquifer system probably is capable of accommodating additional withdrawals. Results of one experiment, in which average annual recharge was reduced from 8 to 4 inches for 4 years and pumping was increased from 2.1

million gallons per day to 7.7 billion gallons per day, suggest that water levels would locally decline only about 9 feet and that discharge to streams would only be reduced by about 20 percent. Validity of these results, however, can not be verified. Because of the lack of long-term historical data, the model could not be verified through time. The model can only be verified by collecting additional water-level data as development occurs and comparing it with model results. Ultimately the model could be recalibrated with the new field data and validity and accuracy of simulations could be verified.

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