APPRAISAL OF THE SURFICIAL AQUIFERS IN THE POMME DE TERRE AND CHIPPEWA RIVER VALLEYS, WESTERN MINNESOTA

By W. G. Soukup, D. C. Gillies, and C. F. Myette

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Dallas L. Peck, Director

For additional information write to:

District Chief
U.S. Geological Survey
702 Post Office Building
St. Paul, Minnesota 55101
Telephone: (612) 725-7841

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ILLUSTRATIONS

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CONVERSION FACTORS

Multiply inch-pound unit	By	To obtain SI (metric) unit
inch (in.)	25.40	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square foot (ft^2)	0.09294	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06308	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
hydraulic conductivity, foot per day (ft/d)	0.3048	meter per day (m/d)
transmissivity, foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level. NGVD of 1929 is referred to as sea level in this report.

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ABSTRACT

The surficial sands in the Pomme de Terre and Chippewa River valleys in Grant, Pope, Stevens, and Swift Counties have been studied to determine the occurrence, availability, and quality of ground water in these aquifers.

In the northern part of the Pomme de Terre and Chippewa River valleys, the aquifers consist of coarse sand and gravel ranging from 0 to 100 feet in thickness; transmissivities range from 0 to 35,000 feet squared per day in narrow, steep-sided erosional valleys. In the north, well yields commonly exceed 1,000 gallons per minute and may be as much as 4,000 gallons per minute locally. Farther south, the deposits are medium to fine grained, range from 0 to 90 feet thick, and reach a maximum width of 10 miles near Benson, Minnesota. Transmissivities range from 0 to 25,000 feet squared per day. Wells may yield as much as 1,500 gallons per minute locally. Southeast of Clontarf, well yields generally do not exceed 500 gallons per minute because the deposits are thinly saturated and fine grained.

Ground water in the surficial aquifer is a mixed calcium magnesium-sulfate bicarbonate type that is chemically suitable for most uses. Concentrations of most constituents analyzed were below limits recommended by the Minnesota Pollution Control Agency for drinking water, but concentrations of manganese, iron, nitrite plus nitrate, and dissolved solids exceed recommended limits locally. Salinity, as indicated by the specific conductance (values ranged from 580 to 1,000 micromhos per centimeter) was in the medium to high range at several locations.

An analytical model was used to estimate the effect on streamflow of pumpage from the surficial aquifer in the narrow, 50-mile reach of the Pomme de Terre River valley in Stevens and Grant Counties. The model indicates that the 43 existing wells pumping at maximum potential yields could reduce streamflow by 55 cubic feet per second. Addition of 23 wells also pumping at maximum potential yields could reduce streamflow by 77 cubic feet per second; this rate exceeds low base flow of the Pomme de Terre River.

Finite-difference models were used to simulate flow in the surficial aquifer along the Pomme de Terre River near Appleton in Swift County and along the Chippewa River between Cyrus in Pope County and Danvers in Swift County.

In the Appleton area, model analyses indicate that pumping lowered water levels as much as 3 feet from 1973-80 and reduced streamflow by about 14 cubic feet per second. Additional regional water-level declines of 1 to 2 feet, and up to 4 feet locally near aquifer-till boundaries, can be expected after about 4 years if pumping continues at the 1980 rate and areal recharge from precipitation is near normal. However, simulation of increased pumping rates and decreased areal recharge during a 3-year drought indicates that water levels may decline as much as 9 feet near aquifer-till boundaries and streamflow may be reduced by about 41 cubic feet per second, which is about 95 percent of the available flow in the Pomme de Terre River at the 55-percent flow duration. Model results also suggest that, during the first year of a drought, the combined pumpage from wells operated during 1980 along the Pomme de Terre River in Stevens and Grant Counties and in the Appleton area could reduce streamflow to zero during base flow. Model-computed streamflow deficiencies are 48 and 60 cubic feet per second at the 55- and 70-percent flow duration, respectively. Under such conditions, pumping could not be sustained at the rates simulated unless there was sufficient water stored in the stream channel or streamflow was augmented.

In the Cyrus-Benson area, model results indicate that under 1980 development and average areal recharge, dynamic equilibrium would be reached in less than 4 years and additional drawdown would be less than 2 feet. A 3-year drought coupled with increased pumping from irrigation wells operated during 1980 would lower water levels as much as 6 feet and reduce flow in the Chippewa River by about 26 cubic feet per second. At maximum hypothetical development in terms of the number of wells and normal areal recharge, water levels would be lowered as much as 9 feet and streamflow would be reduced about 12 cubic feet per second. At maximum hypothetical development, drought conditions and increased pumping would lower water levels as much as 12 feet and reduce flow in the Chippewa River by about 30 cubic feet per second, which equals about 75 percent of available streamflow at the 70-percent flow duration.

INTRODUCTION

Withdrawals of ground water increased dramatically in western Minnesota during 1975-80, primarily because of increased irrigation following the 1976-77 drought. Prior to 1976, for example, the MDNR (Minnesota Department of Natural Resources) had received only 38 applications to irrigate in Swift County, as compared to 105 applications in 1977 alone. As of the end of 1982 there were 204 active irrigation permits in Swift County (Minnesota Department of Natural Resources, oral commun., 1983). Likewise, the MDNR has investigated a number of well-interference complaints, several of which were valid. Therefore, in order to manage the water resources to the mutual benefit of agricultural, industrial, municipal, and domestic interests, a thorough understanding of the geology and hydrology is essential. Because of the need for resource information, the U.S. Geological Survey, in cooperation with the Minnesota Department of Natural Resources, Division of Waters, and the Pomme de Terre and Chippewa Ground-Water Study Steering Committee, began a 4-year study (1979-83) to appraise the ground-water resources in the Pomme de Terre and Chippewa River valleys of Chippewa, Grant, Pope, Stevens, and Swift Counties.

Purpose and Scope

The purpose of this report is to provide an appraisal of ground water in the surficial outwash aquifers in the Pomme de Terre and Chippewa River valleys of Chippewa, Grant, Pope, Stevens, and Swift Counties.

Specific objectives of the report are to (1) map the areal extent and thickness of the surficial aquifers in the Pomme de Terre and Chippewa River valleys, (2) determine hydrologic characteristics of the aquifers, (3) estimate the potential yield of each aquifer, (4) describe the chemical quality of the water, and (5) determine the probable effects of development on each aquifer through mathematical and (or) numerical simulation. A similar study of confined-drift aquifers is presently (1984) underway in the study area.

Location and Description of the Study Area

The study area, located in west-central Minnesota about 150 miles west of Minneapolis and St. Paul, encompasses about 1,100 mi^2 extending across Chippewa, Grant, Pope, Stevens, and Swift Counties (fig. 1). The Pomme de Terre and Chippewa Rivers are tributaries to the Minnesota River to the south. The topography is generally flat or gently rolling. Relief, however, varies from more than 100 feet along the valley sides in Grant County to less than 5 feet on the outwash fan in Swift County. Average annual precipitation is about 25 inches, with 70 percent occurring from May through September (Larson, 1976). Winter precipitation is stored as snow until the spring thaw.

Previous Investigations

Early hydrologic investigations of the study area were made by Hall and others (1911) and Thiel (1944). More detailed hydrologic studies were done near Lake Emily by Van Voast (1971) and Wolf (1976), and near Appleton by Larson (1976). The glacial geology was described by Leverett (1932), Wright and Ruhe (1965), and Wright (1972). Pomme de Terre River outwash deposits were described by Sandeson (1919). Glacial Lake Benson and Lake Agassiz outwash deposits are discussed in Matsch and Wright (1967). Hydrologic reconnaissances of the Pomme de Terre and Chippewa Rivers watersheds were made by Cotter and Bidwell (1966) and Cotter and others (1968), respectively. A preliminary investigation and data summary containing well logs, water levels, and geologic sections for Swift County was completed by Fax and Beissel (1980).

Methods of Investigation

Field work for this part of the study was completed during a 2-year period beginning October 1, 1979. Geologic and hydrologic maps were prepared from soils maps, drillers' logs, lithologic logs of 250 augered test holes, and maps prepared for a previous study (Larson, 1976). Transmissivity and storage coefficients were determined from seven aquifer tests, including one made during this study and six from previous studies. Estimates of hydraulic conductivity were made based on grain-size analysis of sand and gravel samples taken during test augering.

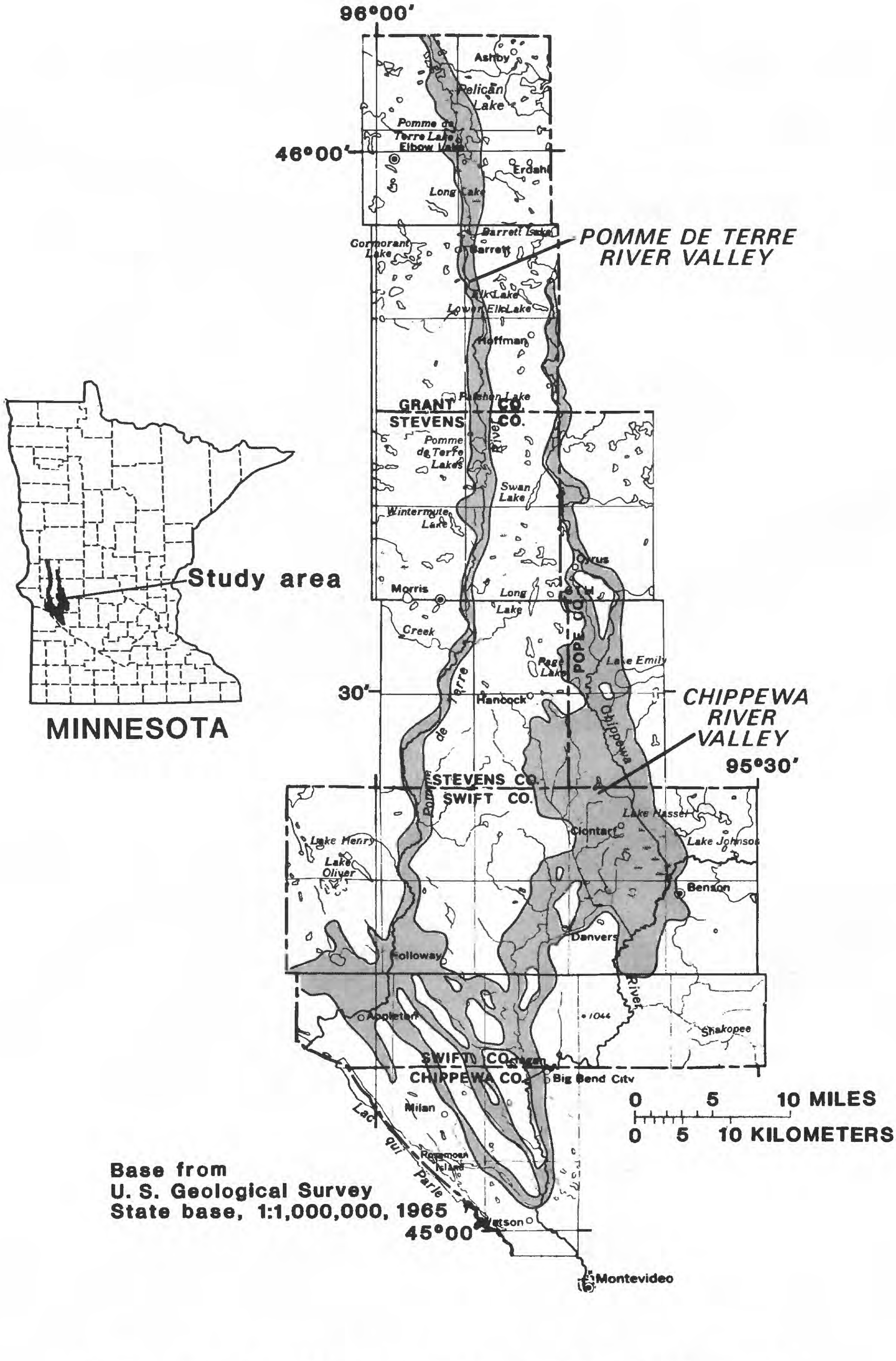


Figure 1.--Location and extent of the study area

A network of 60 observation wells (measured biweekly) and 3 wells equipped with continuous recorders was used to determine ground-water fluctuations. Ground-water samples were collected periodically at nine well locations for determination of dissolved inorganic constituents, trace metals, and nutrients. Water-level measurements from approximately 120 irrigation wells, 60 observation wells, and 250 augered test holes were used to determine the configuration of the water table. Base-flow measurements were made at 38 sites on the Pomme de Terre and Chippewa Rivers to estimate ground-water discharge to streams and induced infiltration from streams to the ground-water system.

An analytical model was used to determine the rate at which water might be diverted from the Pomme de Terre River by pumping wells in the northern part of the study area. Two finite-difference ground-water-flow models were constructed to simulate flow in the surficial outwash aquifers along the Pomme de Terre River in the southern part of the study area near Appleton in Swift County, and along the Chippewa River between Cyrus in Pope County and Danvers in Swift County (including the Benson area).

Both two-dimensional finite-difference models were calibrated to steady-state conditions based on hydrologic data collected during the current and a previous study (Larson, 1976). The Appleton area model was also calibrated by use of an 8-year transient simulation of historic development. Each model was then used to simulate hypothetical pumping and drought conditions and determine the possible effects on regional ground-water levels and streamflow.

Well and Test-Hole 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 the public lands. The study area is in the fifth principal meridian and base-line system. The first segment of the well or test-hole number indicates the township north of the base line, the second the range west of the principal meridian, and the third the section in which the test hole is situated. 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 2. The letters are assigned in a counterclockwise direction beginning in the northeast quarter. Within one 10-acre tract successive well numbers, beginning with 1, are added as suffixes. Figure 2 illustrates the method of numbering a well or test hole. The number 122N40W20AAD01 indicates the first test hole or well located in the SE ¼, NE ¼, NE ¼, section 20, township 122 N., range 40 W.

Acknowledgments

Support received from the Pomme de Terre and Chippewa Ground-Water Study Steering Committee, the irrigation associations, the various county Soil and Water Conservation Districts, and the commissioners of Grant, Pope, Stevens, and Swift Counties was greatly appreciated. Special thanks also are given to the land owners for their permission to auger test holes and install observation wells and to the irrigators for their cooperation in supplying information and use of their equipment for aquifer tests.

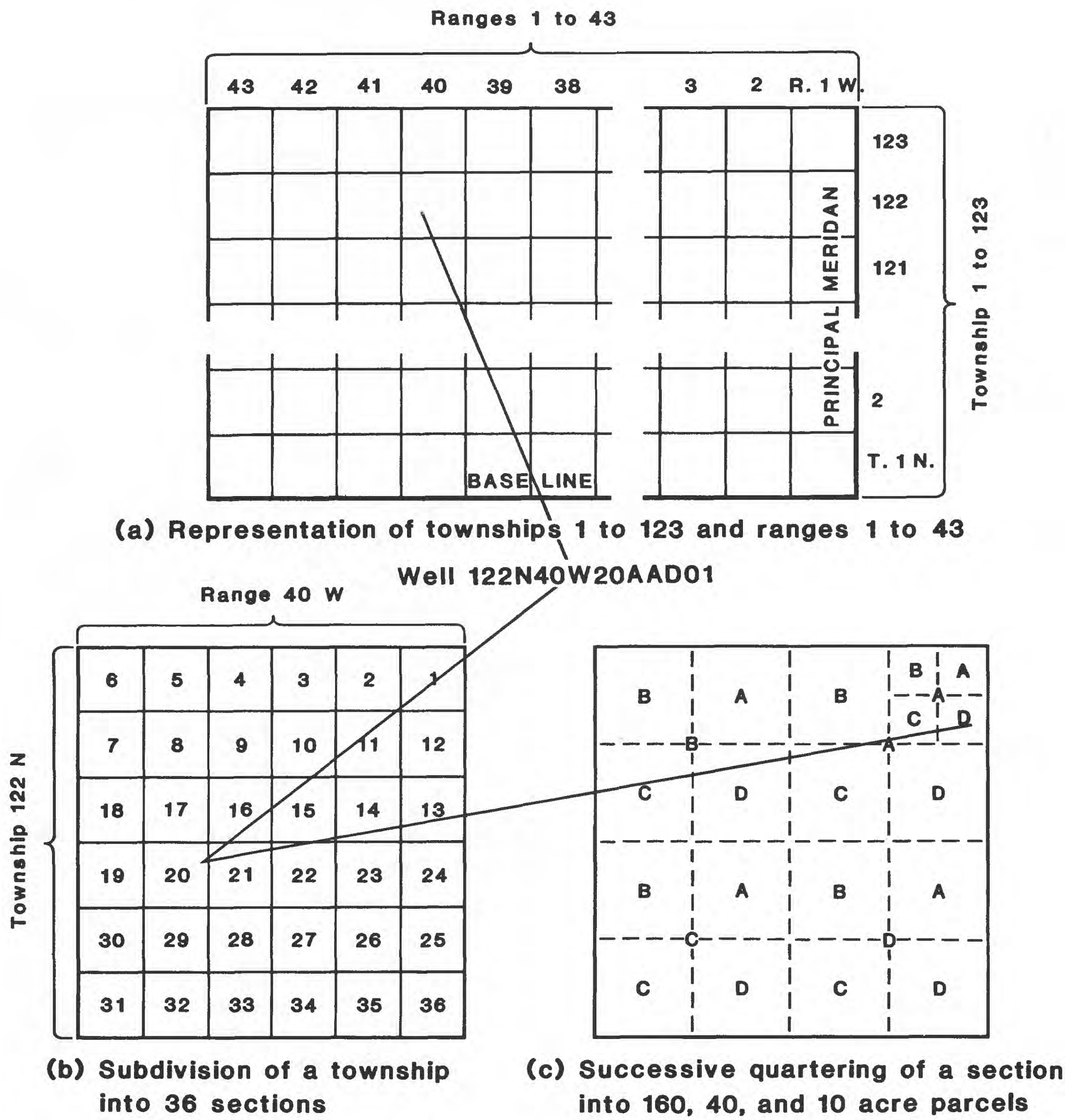


Figure 2.--Well and test-hole numbering system

GEOLOGY

Stratigraphy

The bedrock underlying the project area consists of Precambrian crystalline rock overlain by Cretaceous sandstone and shale. The Cretaceous deposits mostly occur in the southern part of the area and vary in thickness from 0 to 150 feet. Glacial deposits of Quaternary age overlie Cretaceous or Precambrian rocks and form the present land surface. The deposits consist of till and outwash and range in thickness from less than 100 feet near the Minnesota River to 400 feet in Grant County (Cotter and Bidwell, 1966).

Depositional History of Glacial Deposits

The most recent advance of glacial ice into southwestern Minnesota was the Des Moines lobe of the Wisconsin Glaciation (Wright and Ruhe, 1965; Wright, 1972). Ice movement was probably in the form of alternating advances and retreats. Each advance deposited a conglomerate of clay, sand, and rock fragments (till), whereas each retreat was characterized by the melting of ice and deposition of sand and gravel by glacial streams.

Melt-water streams often changed position and discharge, causing changes in their erosive and depositional characteristics. As a result, outwash deposits differ in areal extent, thickness, and grain size. In some locations, deposits of sand are buried by till, forming buried aquifers.

The Pomme de Terre and Chippewa River valleys were natural drainageways for melt water and have accumulated thick sand and gravel deposits (Wright and Ruhe, 1965). However, the actual sequence of glacial events is not entirely clear. The divide between the two rivers was probably breached several times, causing changes in deposition along certain reaches. In general, flow was fast in the north, eroding deep valleys and depositing thick sequences of coarse sand and gravel. In the south, slow-moving water cut laterally, forming wide but thinner deposits of medium sand.

At one time, drainage was probably blocked and water was impounded in a shallow basin forming Glacial Lake Benson (Wright, 1972). Broad alluvial fans of medium sand were deposited by glacial streams entering the lake from the north. Finer sand and silt were carried out into the lake and were deposited south of the city of Benson. In Grant County, Glacial Lake Agassiz was formed in a similar manner as Glacial Lake Benson. Sand and gravel were deposited along the lake shore forming a beach ridge that can be traced for tens of miles.

Hydrogeology

Water-table conditions predominate in the surficial aquifer, which consists of outwash sand and (or) gravel. The aquifer is bounded laterally and underneath by till. Plate 1 outlines the areal extent of the surficial aquifer and its saturated thickness, which is the difference between the water table and the base of the aquifer. In the northern part of the study area, sand and gravel deposits range from 0 to 100 feet thick and are, for the most part, contained in steep-sided erosional valleys. Saturated thickness ranges from 0 to 80 feet. Figures 3 and 4 are representative hydrogeologic sections of the valley-fill deposits. (Lines of section are shown on Plate 1.) These deposits generally consist of coarse sand and gravel.

In some areas, large blocks of glacial ice prevented the deposition of outwash in the valley, leaving till at the present-day land surface. An example of this is shown in figure 5, which is a hydrogeologic section in northern Grant County. In the southern part of the study area, the surficial aquifer consists of fine to medium sand and gravel deposited in a broad shallow basin. Thickness of the deposits ranges from zero at the lateral boundaries to about 90 feet. The average saturated thickness is about 25 feet; it ranges from 0 to 80 feet. Figure 6 is a representative hydrogeologic section of the broad shallow basin near Clontarf.

The hydraulic conductivity, which is a measure of the ease with which water flows through an aquifer, was estimated based on the relation between grain-size distribution and hydraulic conductivity determined for a previous investigation in the study area (Larson, 1976, p. 9-10). Grab samples of material from each auger test hole were examined in the field and assigned values of hydraulic conductivity based on predominant grain size (table 1). In addition, lower hydraulic conductivity values were assigned to poorly sorted materials and higher to well-sorted materials. Transmissivity was then calculated for each of the auger test holes as hydraulic conductivity times saturated thickness.

Table 1.—Estimated hydraulic conductivity of surficial aquifer

[after Larson, 1976]

Predominant grain size (Wentworth scale)	Estimated hydraulic conductivity (ft/d)
Clay or silt (<0.0625 mm)	<10
Sand, very fine (0.0625 to 0.125 mm)	10-70
Sand, fine (0.125 to 0.250 mm)	70-130
Sand, medium (0.250 to 0.5 mm)	130-400
Sand, coarse or very coarse (0.5 to 2.0 mm)	130-540
Gravel (>2.0 mm)	130-670

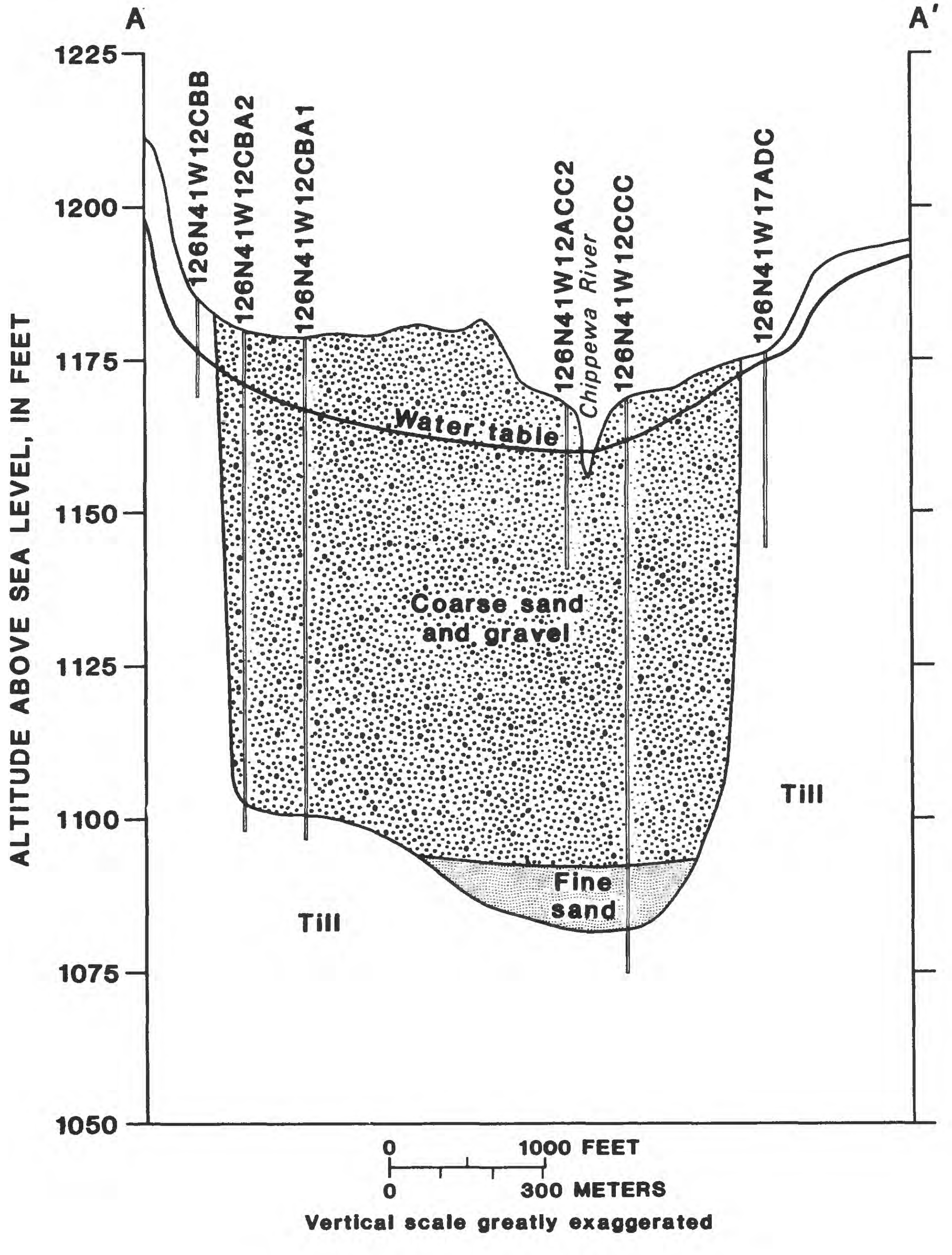


Figure 3.--Hydrogeologic section along line A-A' (shown on Plate 1)

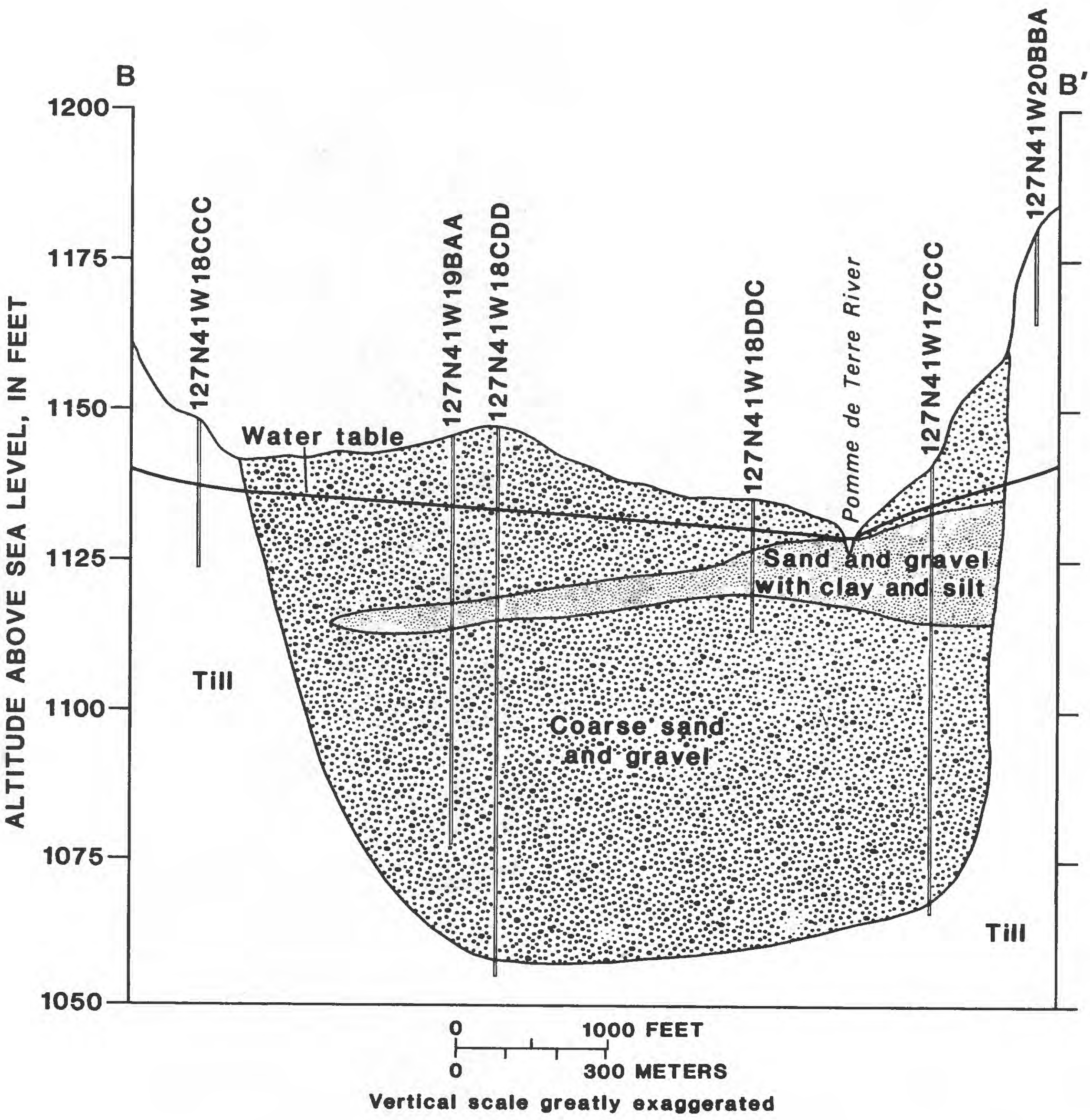


Figure 4.--Hydrogeologic section along line B-B' (shown on Plate 1)

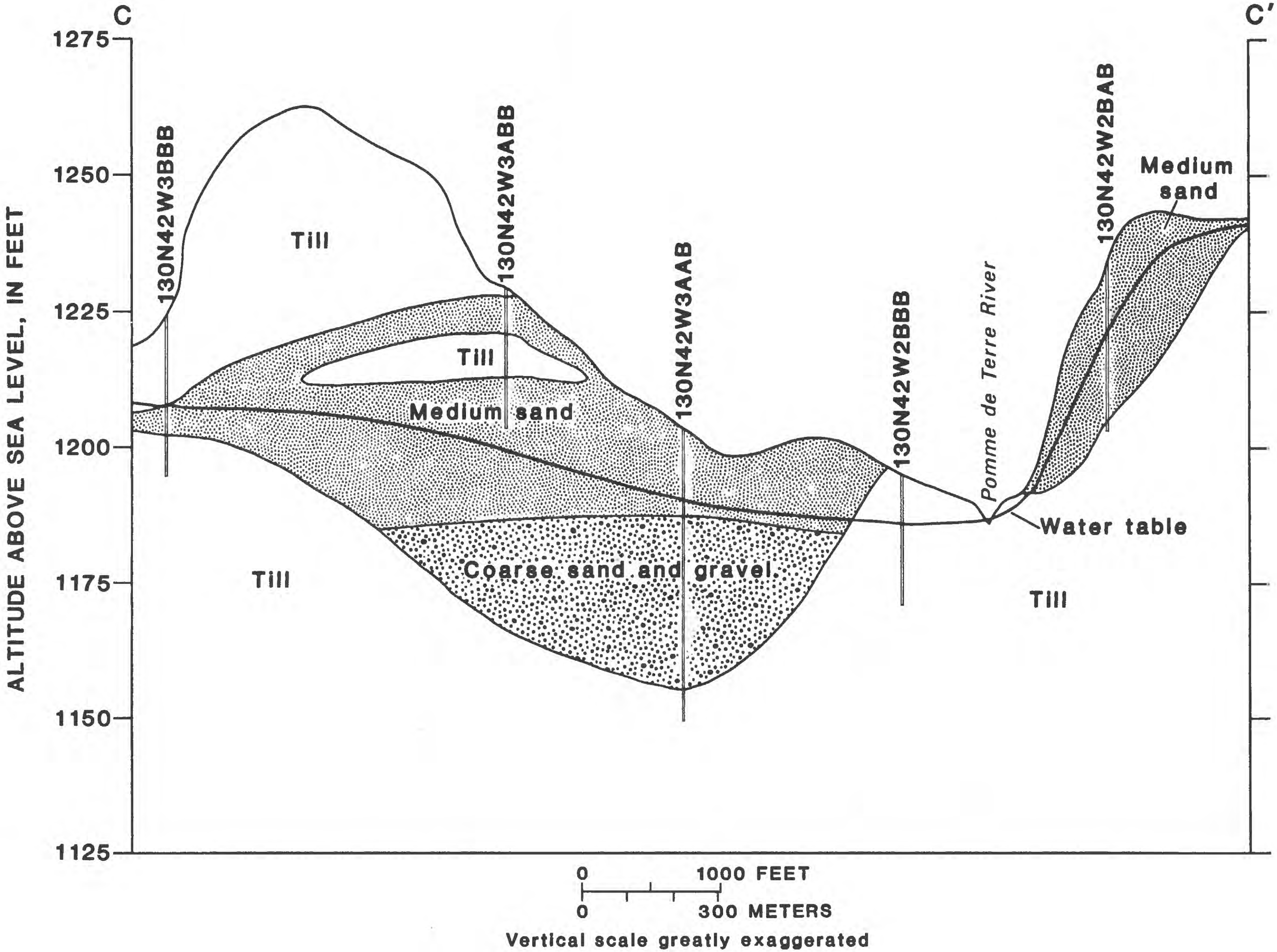


Figure 5.--Hydrogeologic section along line C-C' (shown on Plate 1)

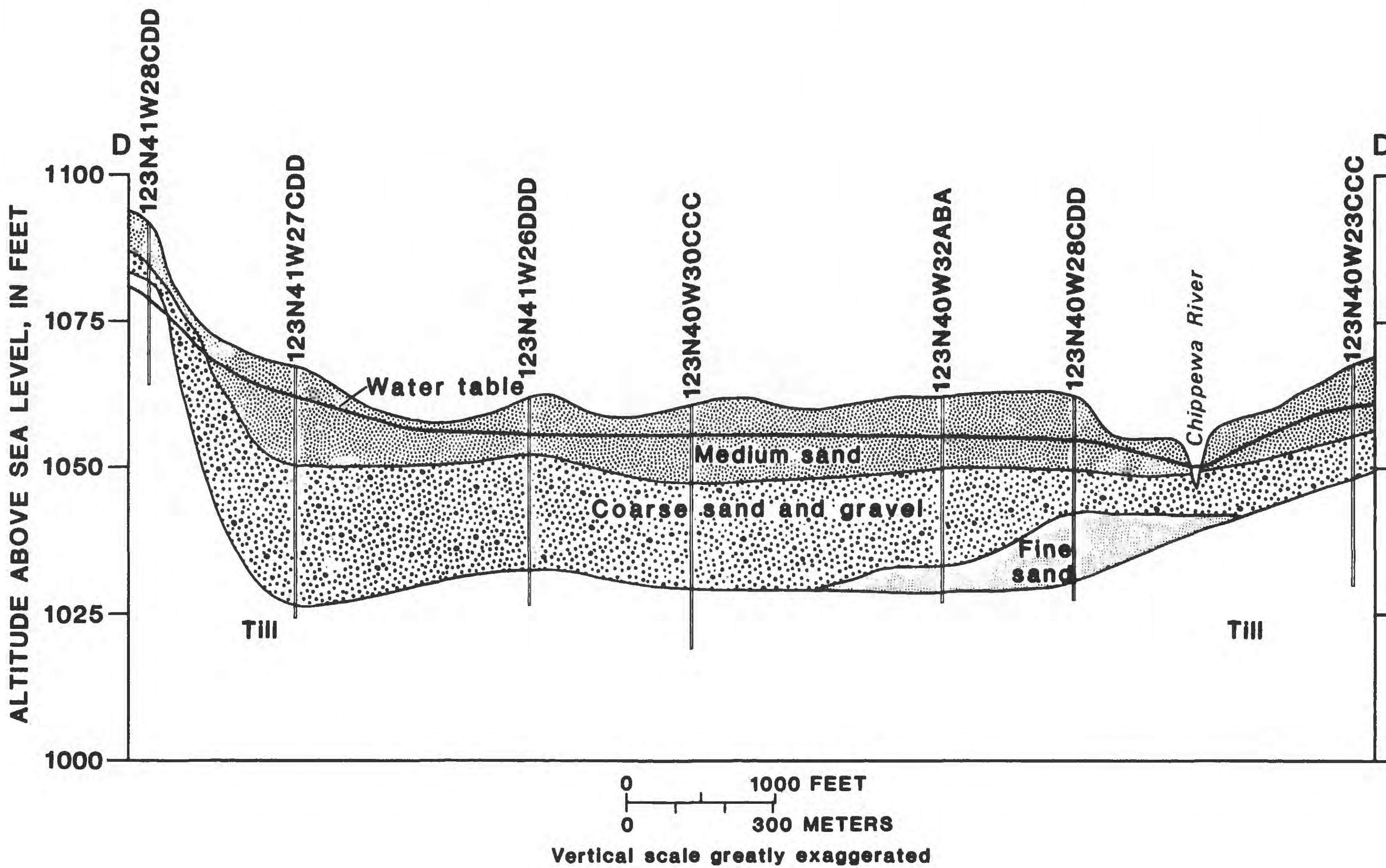


Figure 6.--Hydrogeologic section along line D-D' (shown on Plate 1)

Transmissivity and storage-coefficient values also were determined by aquifer tests at seven locations. Results of the tests are shown in table 2.

Table 2.—Results of aquifer tests

Location	Length of test (hours)	Pumping rate (gal/min)	Transmissivity (ft^2/d)	Storage coefficient	Conducted by:[1]
121N42W31BDB	44	475	9,600	0.15	USGS
120N43W02CBD	56	1,150	14,700	.2	USGS
122N42W29BAC	65	495	31,000	.27	USGS
121N41W21ADA	53	700	13,300	---	MDNR
123N40W18CCC	64	360	12,000	.16	MDNR
123N41W26AAC	4	575	23,000	---	MDNR
121N43W22BCB	20	850	24,000	---	MDNR

[1] USGS is U.S. Geological Survey; MDNR is Minnesota Department of Natural Resources

Methods used to calculate transmissivity and storage coefficients are from Boulton (1963) and Stallman (1965) as described by Lohman (1972). The test results are site specific; however, the values can be used as a guide to estimate hydraulic properties in areas where the lithology is similar to that of a specific test site.

Plate 2 shows the areal distribution of transmissivity values in the surficial aquifer. In the northern part of the study area, transmissivity values are as high as 35,000 ft^2/d, reflecting the greater saturated thickness and large grain size of the outwash. Farther south, the transmissivity is generally lower, with maximum values of 25,000 ft^2/d.

GROUND WATER

Direction of Flow

The configuration of the water table, based on water-level measurements in 180 wells made during October 26-November 9, 1980, is shown on plate 3. Water levels measured in test holes at the time of drilling also were used to guide contouring of the water table between observation wells. Ground-water flow is from areas of high head to areas of low head and generally is perpendicular to the water-level contours. Regionally, ground-water flow is from north to south toward the Minnesota River (pl. 3) at a fairly uniform gradient of about 4 ft/mi. Locally, ground water moves from the valley sides through the surficial sand and discharges into the Pomme de Terre and Chippewa Rivers. However, because the hydraulic conductivity of the till at the aquifer boundary is low, the amount of leakage across the boundary from the till is considered to be a small part of the ground-water budget.

Water-Level Fluctuations

Water levels in the surficial aquifer fluctuate seasonally and on a long-term basis in response to changes in recharge to the aquifer from precipitation. Figure 7 shows the general relation between water-level fluctuations and precipitation for 1970-79. For major disruptions in the normal pattern of precipitation, the relation between water-level fluctuations and precipitation is fairly obvious. For example, during the drought of 1976 and early 1977, precipitation was below normal and ground-water levels were the lowest recorded for the 10-year period. However, in 1978, precipitation was near or above normal and ground-water levels returned to what they had been during years prior to 1976.

Within individual years, ground-water levels generally are highest during spring and lowest in winter. However, water-level fluctuations are not always directly related to the amount of precipitation; they are affected also by the timing of precipitation, the rate of evapotranspiration, soil-moisture conditions, and the form of precipitation (rain or snow). Figure 8 shows the relationship between precipitation and evapotranspiration at the West-Central Experiment Station, Morris, Minnesota, (U.S. Department of Commerce, 1979) and representative ground-water-level fluctuations at site 123N40W04BDA during 1979. The most pronounced rise in ground-water level occurred during late March and April because of snowmelt and removal of the frost barrier; however, most precipitation occurred in June. Several small rises in water level (not shown) occurred in June, October, and November and can be correlated with heavy rainfall. During winter, ground-water levels continued to decline because there was virtually no areal recharge and discharge to streams continued.

Areal Recharge

Most recharge to the surficial aquifer occurs in early spring as snowmelt percolates through the overlying material to the water table. Occasionally during the growing season, water from a few heavy storms will infiltrate the land surface in quantity sufficient to exceed soil and plant-moisture requirements and cause additional recharge to the aquifer. This is especially common in late fall when evapotranspiration is diminished.

Due to the imperfect correlation between precipitation and ground-water levels, recharge values were determined from hydrographs by the method shown in figure 9. In this approach, the volume of water associated with a change in water level in the water-table aquifer is estimated by multiplying the specific yield by the water-level change (Larson, 1976, p. B7). For calculations of

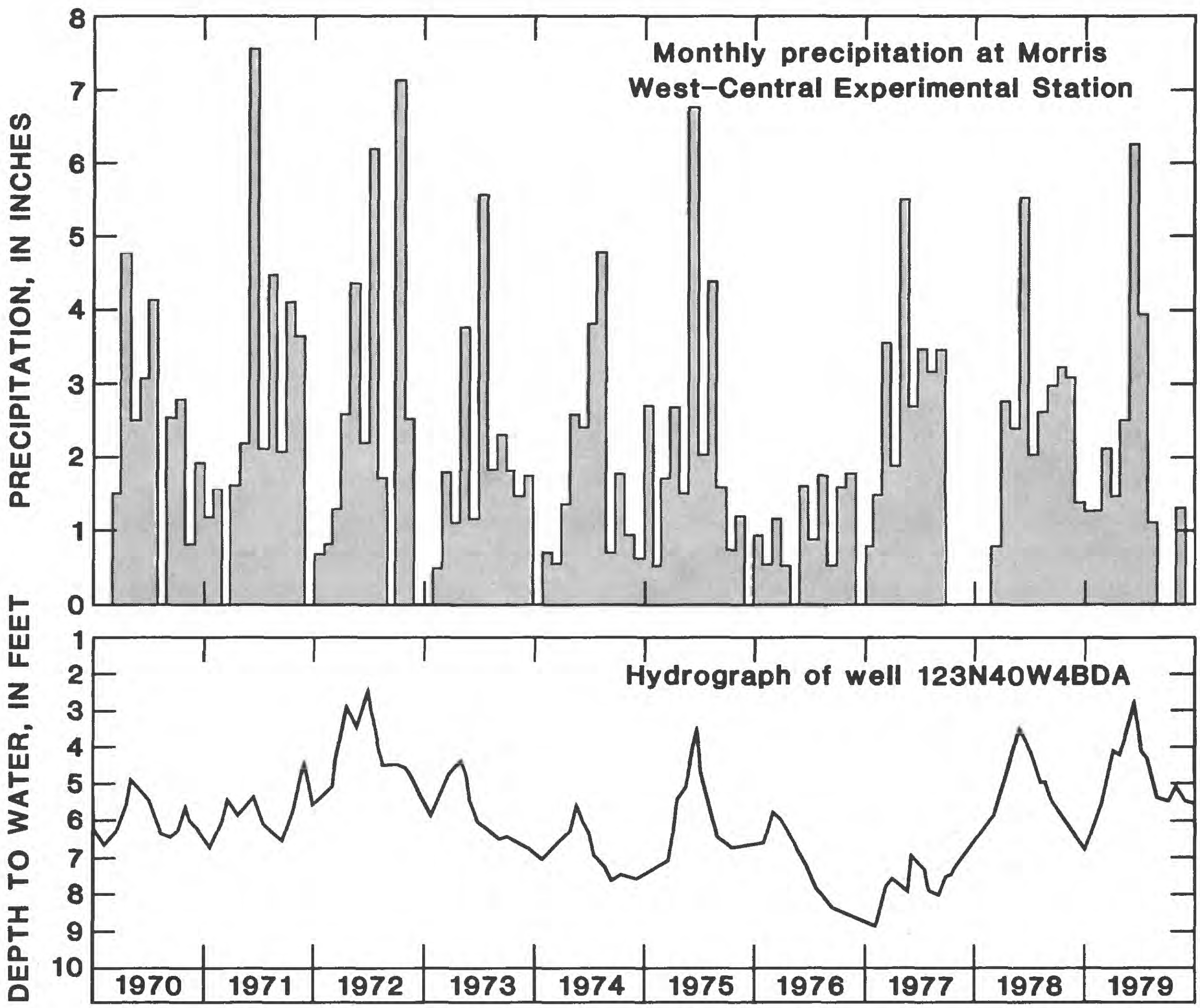


Figure 7.--Relation between ground-water-level changes and monthly precipitation near Morris, Minnesota, 1970-79

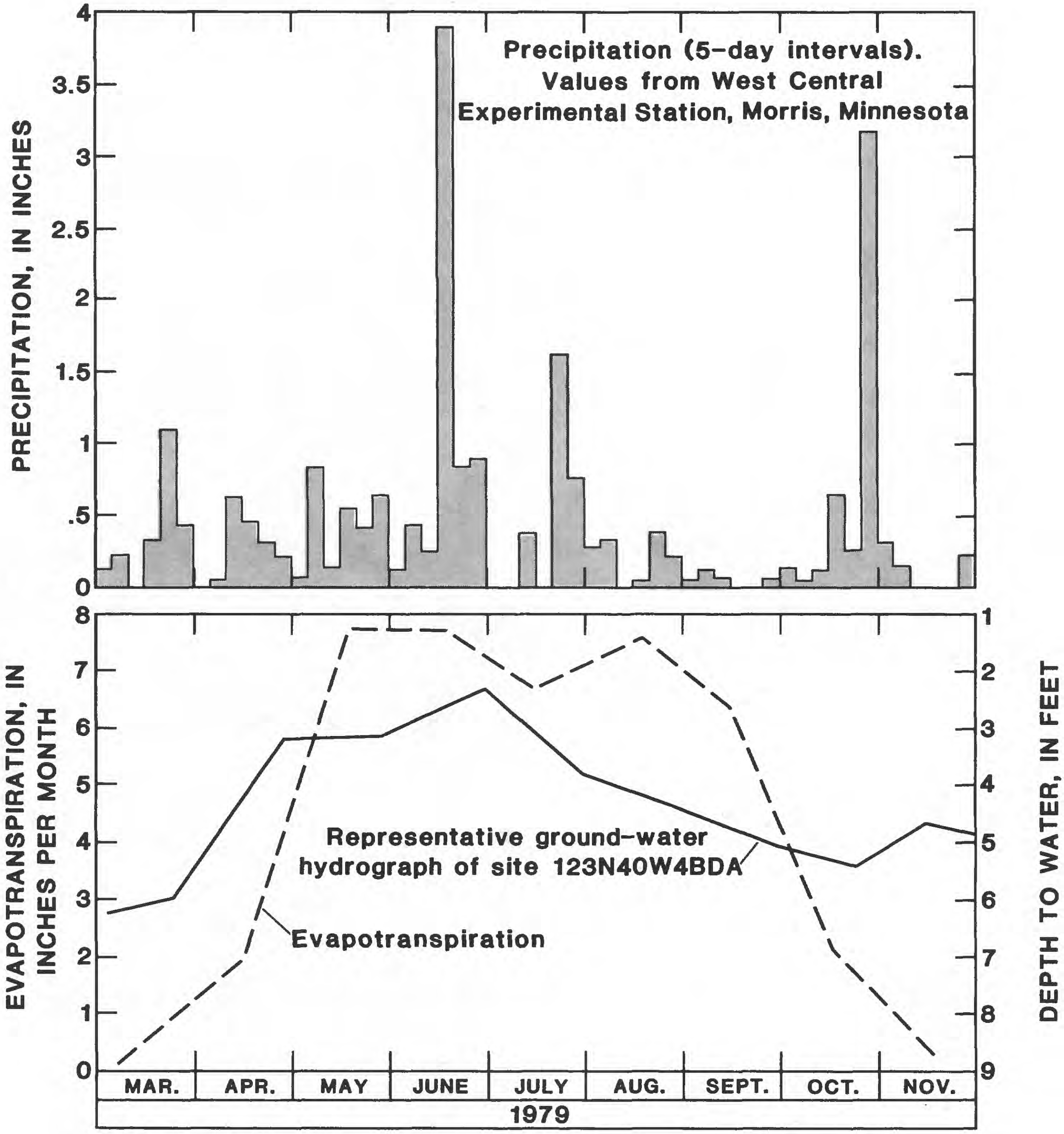
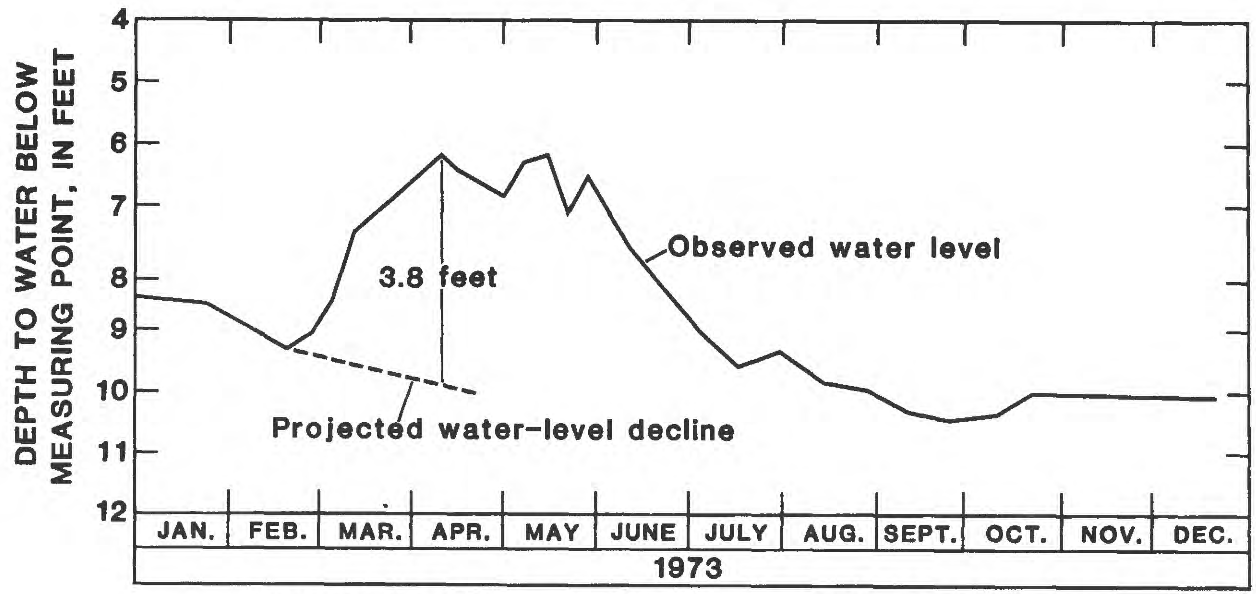


Figure 8.--Relation of evapotranspiration, precipitation, and ground-water level at Morris, Minnesota, during 1979



HYDROGRAPH FOR OBSERVATION WELL 120N42W4DDD

Recharge (due largely to snowmelt and early spring rain)=(water-level rise) X (estimated specific yield)
=3.8 feet X 0.2
=0.76 feet
=9.1 inches

Figure 9.--Method of estimating recharge to the surficial aquifer during spring (modified from Larson, 1976)

recharge, an average specific yield of 0.2 was used. Recharge values calculated at observation-well locations throughout the area were then averaged for each year to obtain the areal-recharge values shown below:

	1973	1974	1975	1976	1977	1978	1979	1980
annual areal recharge (inches).............	4.8	5.3	5.2	3.4	4.1	7.1	8.5	6.3

Discharge

Discharge from the aquifer occurs by leakage into streams and lakes, evapotranspiration, and pumpage. Base-flow measurements were made during May and November 1980 at 18 locations along the Pomme de Terre River and at 20 locations along the Chippewa River to estimate gains in streamflow attributable to ground-water discharge. The weather was clear and dry for several days before both sets of base-flow measurements were made. However, during the May 1980 base-flow measuring period, most irrigation wells in the Pomme de Terre valley had been pumping for several days. Total gain in streamflow to the Pomme de Terre River between Mill Pond in Grant County and Appleton in Swift County (pl. 1) was measured at 45 and 23 ft^3/s during May and November 1980, respectively (U.S. Geological Survey, 1981, p. 303-304; U.S. Geological Survey, 1982, p. 336-337). Total gain in streamflow to the Chippewa River between Ellingson Lake in Grant County and Watson in Swift County (pl. 1) was 80 and 44 ft^3/s during May and November 1980, respectively (U.S. Geological Survey, 1981, p. 304-306; U.S. Geological Survey, 1982, p. 337-339). The flow-duration curve (fig. 10) shows that flow in the Pomme de Terre River at Appleton during May and November 1980 fell on about the 40 and 55 percentiles, respectively. The most recent flow-duration table for the Chippewa River at Milan (about 12 miles south of Danvers) indicates that flow equalled the 27 and 39 percentiles in May and November, respectively.

Most evapotranspiration occurs during the summer months when crop-moisture demands and the temperature are high. Although most evapotranspiration occurs at the land surface and in the unsaturated zone, water is also lost to evapotranspiration from the ground-water system where the water table is less than about 5 feet below land surface. This means that where the water table is high, water that percolated to the water table in the spring may be removed from the aquifer by evapotranspiration later in the summer. The maximum evapotranspiration rate from a free water surface in the study area is 23 in/yr, as calculated by the Thornthwaite method (Cotter and Bidwell, 1966). The actual rate of evapotranspiration from the aquifer system, however, depends on several factors including depth to the water table, temperature, type of vegetation, and type of soil.

Pumpage from wells also accounts for a significant part of ground-water discharge. In 1980, about 650 and 440 million cubic feet of water was pumped from the surficial aquifers along the Pomme de Terre and Chippewa Rivers, respectively. These figures were calculated on the assumption that each

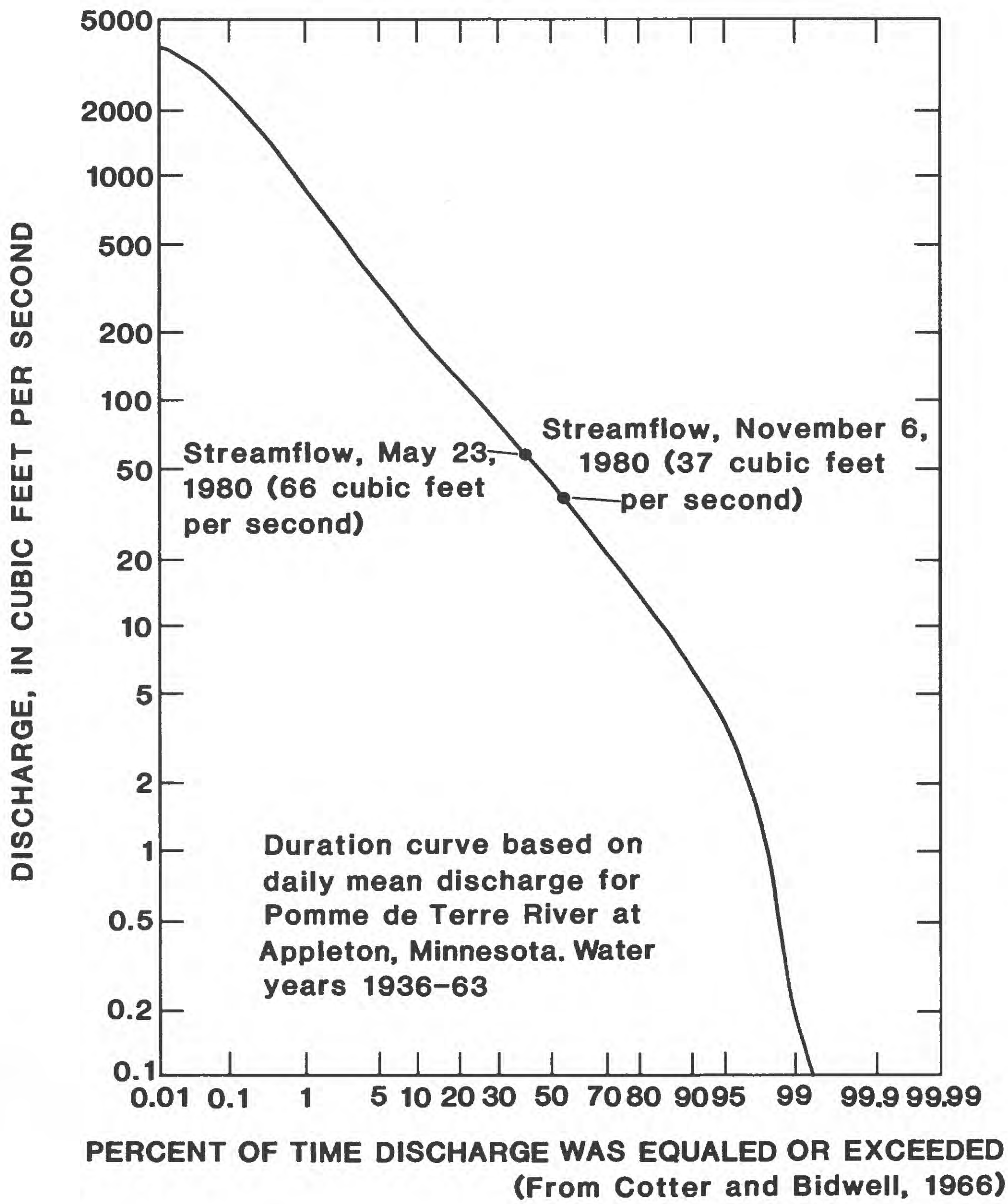


Figure 10.--Flow-duration curve for the Pomme de Terre River at Appleton, Minnesota

irrigation system applied 8 inches of water to all irrigated farmland during 1980 (Jerry A. Wright, University of Minnesota Extension Office, Morris, Minn., written commun., 1981). Actual pumpage probably was slightly less than these estimates because most center-pivot irrigation systems water a circular area that is slightly smaller than the square field in which they are installed.

Potential Yield of Surficial Aquifers

The yield of a well completed in the surficial aquifer depends on the saturated thickness and transmissivity of the aquifer and the efficiency of the well. Calculations of potential yield were made by use of the nonequilibrium equations of Theis (1935) as described in Lohman (1972) and the correction for water-table aquifers of Jacob (1944) to account for reduction in transmissivity due to dewatering. In applying this technique for estimating yields of individual wells, the following assumptions were made:

1. The aquifer is homogeneous.

2. The well is screened over the entire saturated thickness of the aquifer, is 100 percent efficient, and is 24 inches in diameter.

3. The specific yield of the aquifer is 0.20.

4. There is no areal recharge to the aquifer.

5. Drawdown, after 30 days of pumping is equal to two-thirds of the original saturated thickness. Theoretically, this corresponds to 90 percent of the maximum yield for unconfined aquifers and is generally accepted as the optimum design specification (Edward E. Johnson, Inc., 1966, p. 107-108).

6. Interference from other pumping wells and the effects of hydrologic boundaries are negligible.

Although these assumptions rarely are completely satisfied in nature, the method produces a quantitative estimate of the water-yielding potential of an aquifer at a given location. From figure 11, the estimated potential yield can be determined if the saturated thickness and transmissivity are known. For example, wells in an area where the saturated thickness is 30 feet and the transmissivity is 10,000 ft^2/d, can be expected to yield about 550 gal/min.

Plate 4 shows the estimated potential yield of wells in the surficial aquifer. Yields commonly exceed 1,000 gal/min in the northern part of the study area, and yields greater than 4,000 gal/min potentially can be obtained from wells in local areas where the aquifer material is thick and coarse grained. Farther south, the thin, finer-grained deposits reduce potential well yields greatly. Estimated yields range from less than 100 to about 1,500 gal/min. However, yields of 100 to 500 gal/min are more typical. In some areas south of Clontarf, several wells must be used in conjunction to produce sufficient water for a typical irrigation system. In low-yield areas, irrigators often pump from streams, ponds, or deeper aquifers if they can be located.

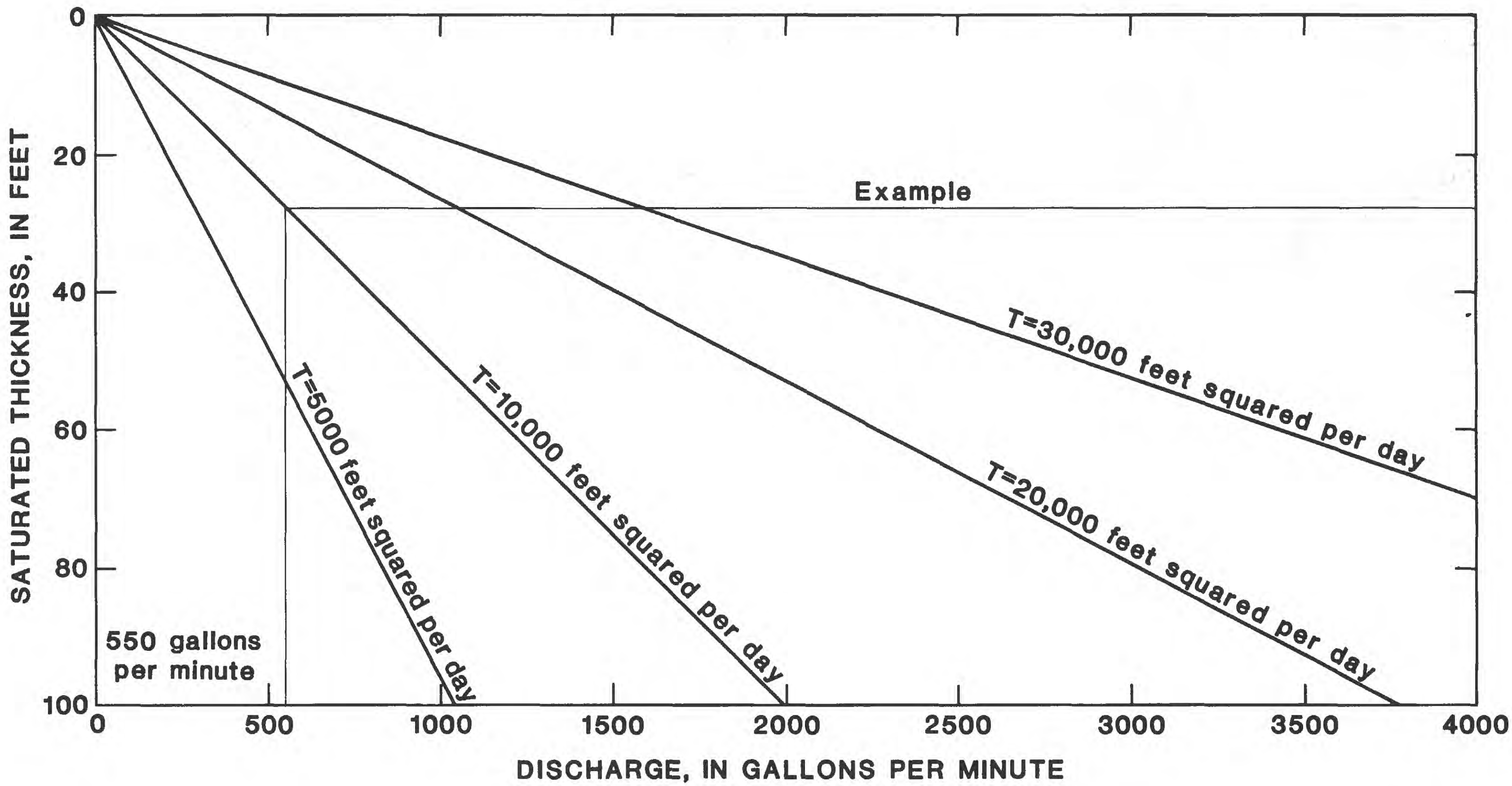


Figure 11.--Relation of transmissivity and saturated thickness to potential well yield

Actual well yields may differ from the potential values shown on plate 4 due to interference from other wells or the effects of nearby hydrologic boundaries such as streams or the aquifer boundary. Figure 12 illustrates the effects of hydrologic boundaries and interference from nearby wells. As a well withdraws water from the surficial aquifer, a cone of influence develops around the well causing water in the aquifer to move toward the well. If the cone of influence intercepts a stream or lake (fig. 12), a part of the ground water naturally discharging into the stream or lake will be diverted toward the well. If the well pumping rate is high enough, the local gradient may be reversed and surface water may flow into the aquifer. In both cases, when the pumping rate is balanced by diversion of water from the stream or lake, the cone of influence will stabilize. Depending on the distance between the well and the stream or lake, this stabilization of the cone of influence (for a given pump rate) may occur in less than 30 days and before the drawdown in the well is as great as two-thirds the original saturated thickness. This would leave additional available drawdown and allow the well to be pumped at a higher rate than shown on plate 4.

Conversely, if the cone of influence of a well pumping at a given rate intercepts the surficial aquifer-till boundary (fig. 12) in less than 30 days, the rate of water-level decline may suddenly increase and the drawdown in the well may exceed two-thirds the original saturated thickness. If this happens, the pumping rate may not be sustainable and may have to be reduced so that the drawdown does not exceed two-thirds the original saturated thickness. The resulting pumping rate would be less than that shown on plate 4 for a particular location. Similarily, if two wells mutually interfere (fig. 12), both the transmissivity and the available drawdown are reduced. As a result of this, the pumping rate attainable when drawdown is equal to two-thirds the original saturated thickness would be less than shown on plate 4. In areas where the saturated thickness is small, two or more wells are commonly installed within several hundred feet of one another and pumped simultaneously to obtain the desired quantity of water.

WATER QUALITY

Water samples were collected from nine wells in the surficial aquifer in November 1980 and April 1981. Prior to collection of the samples, wells were pumped using a peristaltic pump until temperature, specific conductance, and pH values stabilized. The samples were analyzed in the laboratory for common chemical constituents and trace metals. Results, listed in table 3, indicate that ground water is a mixed calcium magnesium-sulfate bicarbonate type that is suitable for most uses. However, in local areas, concentrations of manganese, iron, nitrite plus nitrate, and dissolved solids exceed standards of the Minnesota Pollution Control Agency for domestic consumption (Minnesota Pollution Control Agency, 1978, p. 12). Several of the constituents whose concentrations are important for health or agricultural reasons are discussed below.

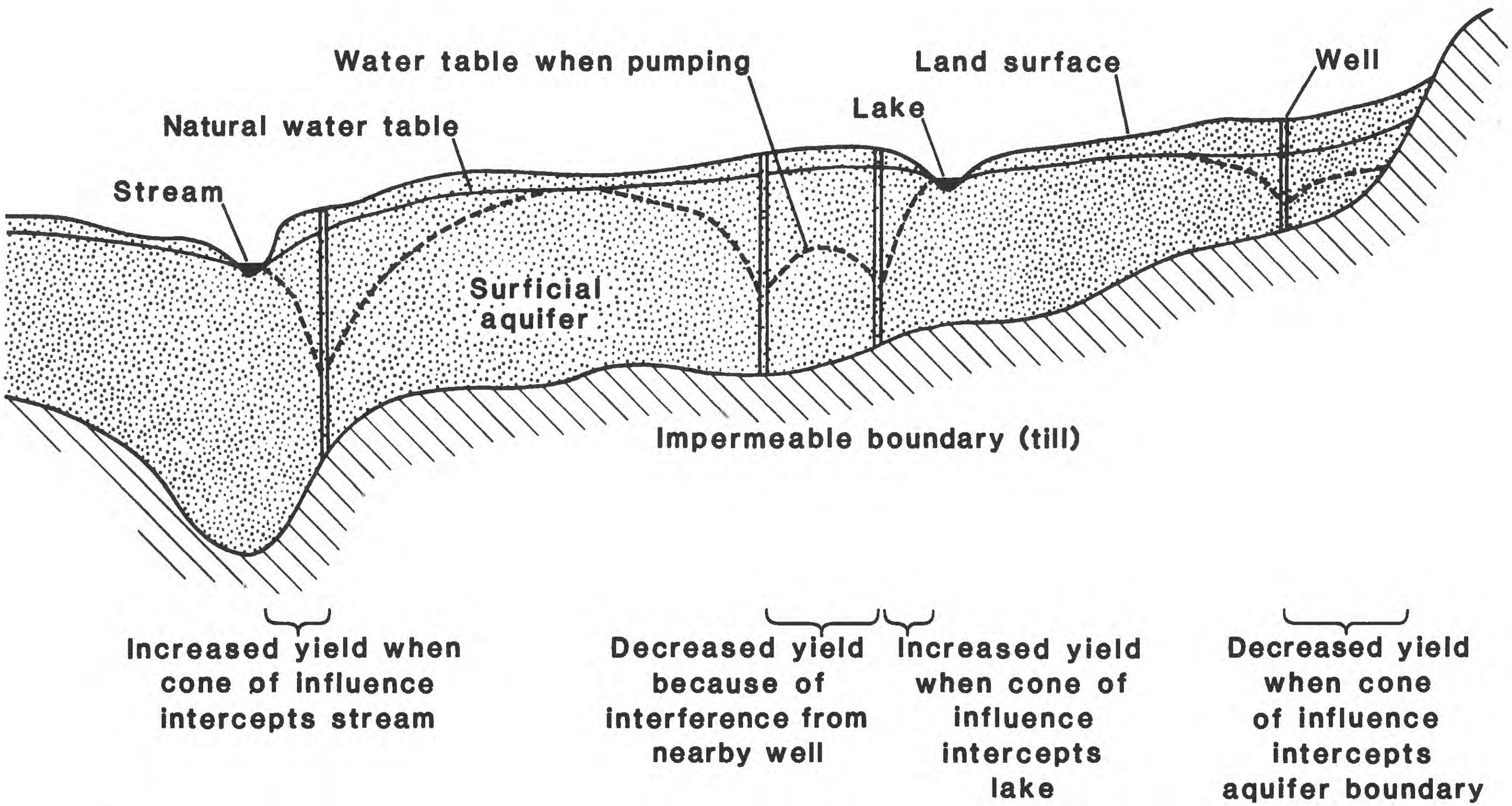


Figure 12.--Schematic hydrogeologic section showing the effects of hydrologic boundaries and nearby wells on the potential yield of wells

Table 3.—Chemical analyses of ground-water

Location	Date of collection	Depth of well (feet)	Specific conductance, field (umhos/cm at 25°C)	pH, field (units)	Water temperature (°C)	Hardness, total (mg/L as $CaCO_3$)	Hardness, noncarbonate (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Cl)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L, as Na)	Sodium-adsorption ratio (SAR)
120N41W28CCD	11-13-80	25	650	7.9	9.0	290	—	64	32	11	0.3
	4-23-81	25	580	7.8	10.0	320	100	74	33	9.5	.2
120N43W14BCC	11-13-80	—	880	8.0	13.0	400	—	81	48	23	.5
121N40W08AAA	11-13-80	20	660	7.6	9.0	290	—	75	25	9.3	.2
	4-23-81	20	625	8.2	10.0	340	89	88	29	10	.2
123N40W18CCC	10-14-80	30	1000	7.7	10.0	460	190	110	45	12	.2
	4-23-81	30	960	7.6	8.0	550	300	130	54	15	.3
124N42W35BBB	11-14-80	20	900	7.5	9.0	380	—	91	36	20	.5
	4-22-81	—	800	7.2	9.0	380	120	53	59	40	.9
125N40W06CCA	11-13-80	35	800	7.8	9.0	360	—	79	39	7.7	.2
	4-23-81	35	725	7.8	8.0	410	120	93	43	7.8	.2
126N41W32BBC	11-12-80	35	660	8.7	9.5	350	—	75	39	15	.4
	4-23-81	35	740	7.8	7.0	380	98	87	39	12	.3
127N41W12BAB	11-13-80	35	650	7.7	9.0	300	—	65	34	5.5	.1
	4-23-81	35	680	7.7	8.0	370	120	80	41	5.5	.1
129N41W19DCC	11-13-80	35	840	7.5	9.0	370	—	90	36	22	.5
	4-24-81	35	750	7.6	9.5	410	100	100	40	22	.5

Recommended limits for domestic consumption, Minnesota Pollution Control Agency, 1978

[1] U.S. Environmental Protection Agency recommended limit for nitrate. Concen

samples collected during 1980 and 1981

Potassium, dissolved (mg/L as K)	Alkalinity, lab (mg/L as $CaCO_3$)	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, dissolved (mg/L, 180°C)	Solids, dissolved (mg/L, calculated)	Nitrite plus nitrate, dissolved (mg/L as N)	Phosphorus, dissolved (mg/L as P)	Boron, dissolved (mg/L as B)	Iron, dissolved (mg/L as Fe)	Manganese, dissolved (ug/L as Mn)
3.2	—	110	—	0.3	27	—	—	0.00	0.02	0.06	1.1	220
2.8	220	110	7.2	0.3	28	405	400	.02	.03	.04	2.7	230
7.3	—	120	—	0.2	27	—	—	.03	.01	.13	.23	670
3.7	—	100	—	0.3	25	—	—	.00	.05	.11	2.5	480
3.4	250	110	2.6	0.3	28	435	426	.03	.03	.10	3.4	510
4.1	270	150	—	0.3	28	—	558	.23	.04	.10	2.0	400
4.9	250	180	4.6	0.3	28	581	615	.03	.01	.11	6.4	310
5.2	—	210	—	0.2	25	—	—	.10	.02	.14	.69	210
5.7	260	190	10	0.2	29	569	545	.02	.01	.13	1.1	320
5.5	—	120	—	0.2	21	—	—	.04	.02	.00	.63	960
4.8	290	120	14	0.2	23	508	485	.79	.02	.05	.26	1000
4.5	—	140	—	0.2	22	—	—	.11	.00	.10	.39	190
4.2	280	140	4.6	0.2	22	512	480	.19	.01	.08	1.9	210
2.8	—	37	—	0.3	25	—	—	12	.04	.03	.12	10
2.4	250	40	36	0.2	26	458	444	14	.04	.02	.15	10
4.5	—	160	—	0.2	27	—	—	.01	.04	.15	1.5	190
4.1	310	150	2.1	0.2	27	543	535	.02	.03	.13	2.6	180
		250	250	1.5		500		10[1]			0.3	50

tration of nitrite in ground water is usually negligible compared to nitrate.

Boron is essential for certain crops, yet concentrations exceeding 0.5 mg/L can be harmful to semitolerant crops (Hem, 1970). Typically, boron concentrations are below dangerous levels in surficial aquifers; they averaged 0.09 mg/L in the study area. The highest value was 0.15 mg/L—well below the suggested limit of 0.75 mg/L (U.S. Environmental Protection Agency, 1976, p. 47) for agricultural use.

The median iron concentration in ground water from the surficial outwash is 1.1 mg/L—over three times the recommended limit (0.3 mg/L) for domestic use (Minnesota Pollution Control Agency, 1978). Concentrations ranged from 0.12 to 6.4 mg/L. Normal consumption of iron by humans ranges from 7 to 35 milligrams per day and averages 16 milligrams per day. The recommended limit for iron in water is intended to prevent objectionable tastes or laundry staining and is of aesthetic rather than toxicological significance (U.S. Environmental Protection Agency, 1976, p. 154).

Nitrogen is a nutrient required for plant growth. It occurs in several forms and becomes a health risk when the nitrate form exceeds 10 mg/L as nitrogen (U.S. Environmental Protection Agency, 1976, p. 202-203). High concentrations may occur in ground water due to land-use activities such as feedlots, septic tank leaching, and agricultural fertilizer applications. Although the U.S. Environmental Protection Agency recommended limit of 10 mg/L applies to nitrate only, one can usually assume that in ground water the limit can also apply to nitrite plus nitrate because nitrite concentrations are usually negligible compared to nitrate. Accordingly, concentration of nitrate in both water samples from well 127N41W12BAB probably exceeds the drinking water limit. However, nitrate concentrations in samples from all other wells were less than 1.0 mg/L.

Dissolved solids (residue on evaporation at 180°C) consist primarily of sodium, calcium, magnesium, manganese, bicarbonate, and sulfate. High concentrations of dissolved solids are undesirable in drinking water because of possible physiological effects, objectionable taste, and higher costs because of plumbing corrosion or water treatment. Physiological effects include laxative effects from sodium and magnesium sulfates and other adverse effects from sodium (U.S. Environmental Protection Agency, 1976, p. 394). Concentrations of dissolved solids, ranging from 405 to 581 mg/L (table 3), exceed Minnesota Pollution Control Agency recommended limits in localized areas. Mean concentration in water samples was 501 mg/L.

Sulfate, although not toxic to plants or animals, can have a laxative effect on humans (U.S. Environmental Protection Agency, 1976). Higher than normal levels of sulfate generally are a result of sewage effluents, agricultural byproducts, or natural dissolution of gypsum. Sulfate concentrations in the study area do not exceed Minnesota Pollution Control Agency recommended limits for domestic consumption and range from 37 to 210 mg/L (table 3). Mean concentration was 129 mg/L.

The suitability of water for irrigation is estimated from two major indicators: salinity and sodium-adsorption ratio (Fireman and Hayward, 1955, p. 321). The sodium-adsorption ratio (SAR) represents the amount of sodium ions present with respect to calcium and magnesium ions. If the ratio is medium to high (above 10), sodium may be exchanged for calcium and magnesium adsorbed on the soil, which can destroy the soil structure and reduce permeability. In surficial outwash aquifers, this ratio is generally less than one. Ground water sampled in the study area had an SAR range from 0.1 to 0.9, and averaged 0.3.

Salinity, or total dissolved solids, can inhibit plant growth by increasing the osmotic pressure in the soil, thereby reducing the amount of water adsorbed by the roots (U.S. Salinity Laboratory, 1954). The specific conductance of water is used to determine the relative salinity hazard of irrigation water. The specific conductance measured at the time of collection averaged 760 micromhos per centimeter and ranged from 580 to 1,000 micromhos per centimeter, which results in a medium to high salinity hazard (U.S. Salinity Laboratory, 1954). No areal trend in specific conductance was evident, however.

SIMULATION OF GROUND-WATER FLOW

Two types of hydrologic models were constructed to simulate ground-water flow in the surficial aquifers. The purpose of the models was to develop a better understanding of the hydrogeology and to estimate, based on this knowledge, the effect of changes in climatic and pumping stress on the system. The first model type is based on an analytical solution of the flow equation developed by Theis (1941) that uses nonequilibrium-flow theory to calculate water derived from streamflow. This model was applied to a narrow, 50-mile reach of the Pomme de Terre River valley in Stevens and Grant Counties where wells are generally within 0.5 mile of the river. The second model type is based on a finite-difference approximation of the solution of the flow equation in two dimensions using a digital-computer program developed by Trescott and others (1976). This model was used along the southern parts of the Pomme de Terre and Chippewa Rivers where the aquifer is much wider and the geology more complex. The areas included in the models are shown in figure 13.

Analytical-Model Analysis

The Pomme de Terre River valley in Grant and Stevens Counties is about 1.5 miles wide, fairly straight, and contains medium to coarse outwash deposits. Wells pumping from this aquifer are generally less than 0.5 mile from the river and, therefore, derive part of their water from the river. This percentage depends on the distance of the well from the river, interference from other pumping wells, the rate and duration of pumping, the transmissivity and storage coefficient of the aquifer, and the hydraulic conductivity and thickness of the river-bottom material.

Large ground-water withdrawals for irrigation during a drought could significantly reduce flow of the Pomme de Terre River. To test the possible effects of pumping on streamflow, two development schemes were simulated using the analytical model: (1) wells that operated during 1980 pumping at maximum potential rates and (2) maximum hypothetical development with additional wells and maximum potential pumping rates. Maximum pumping rates were determined for

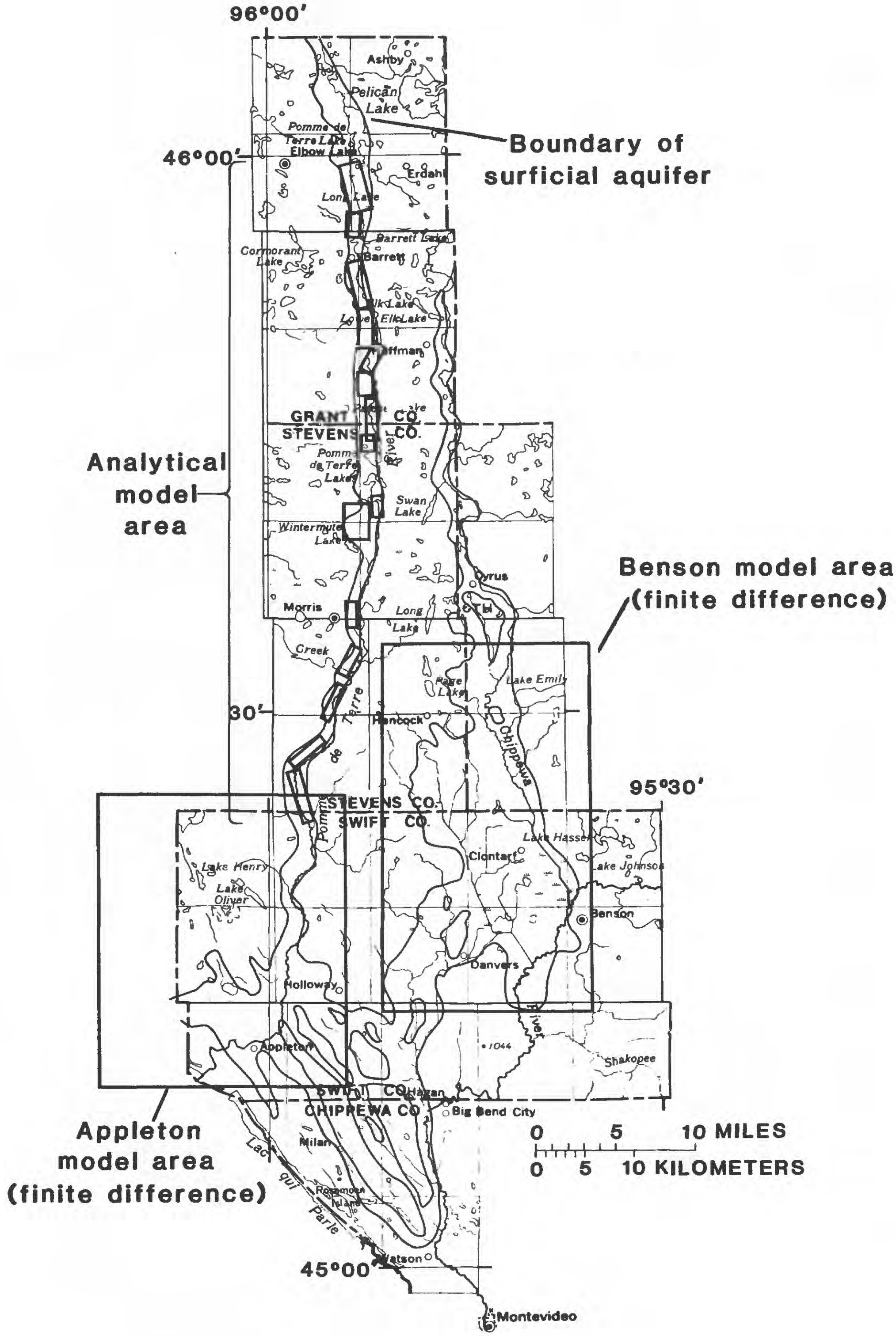


Figure 13.--Location of analytical and finite-difference model areas

these schemes using the image-well theory described by Ferris and others (1962). The advantage of this method over that used to estimate the potential yields on plate 4 is that in computing the pumping rate of each well, the method accounts for the effects of hydrologic boundaries and the interference of other pumping wells. Placement of hypothetical wells was based on areas with sufficient transmissivity and saturated thickness to supply adequate water for irrigation.

In order to accurately model the meandering pattern of the aquifer and the Pomme de Terre River, the model area was divided into 15 rectangular blocks, as shown in figure 14. The model blocks were designed such that the long edges of each block correspond to the river and the surficial aquifer-till boundary. Each block was positioned so that the river and the till boundary are approximately parallel and so that all present and hypothetical pumping wells are in between these hydrologic boundaries (fig. 14). Note that for each block, pumping is simulated on only one side of the river. Also, model blocks were simulated independently and were not allowed to interfere with one another. A computer program developed by D. L. Mazzaferro (U.S. Geological Survey, Hartford, Conn., written commun., 1978), and previously used in Minnesota by Miller (1982, p. 22-26), was used to speed the mathematical computations for the image-well method. The following assumptions are inherent in this method for computing pumping rates:

1. The Pomme de Terre River is a recharge boundary and penetrates the entire saturated thickness of the aquifer.

2. The surficial aquifer-till contact is a no-flow boundary.

3. The specific yield of the surfical aquifer is 0.2.

4. There is no recharge from precipitation during the 30-day period.

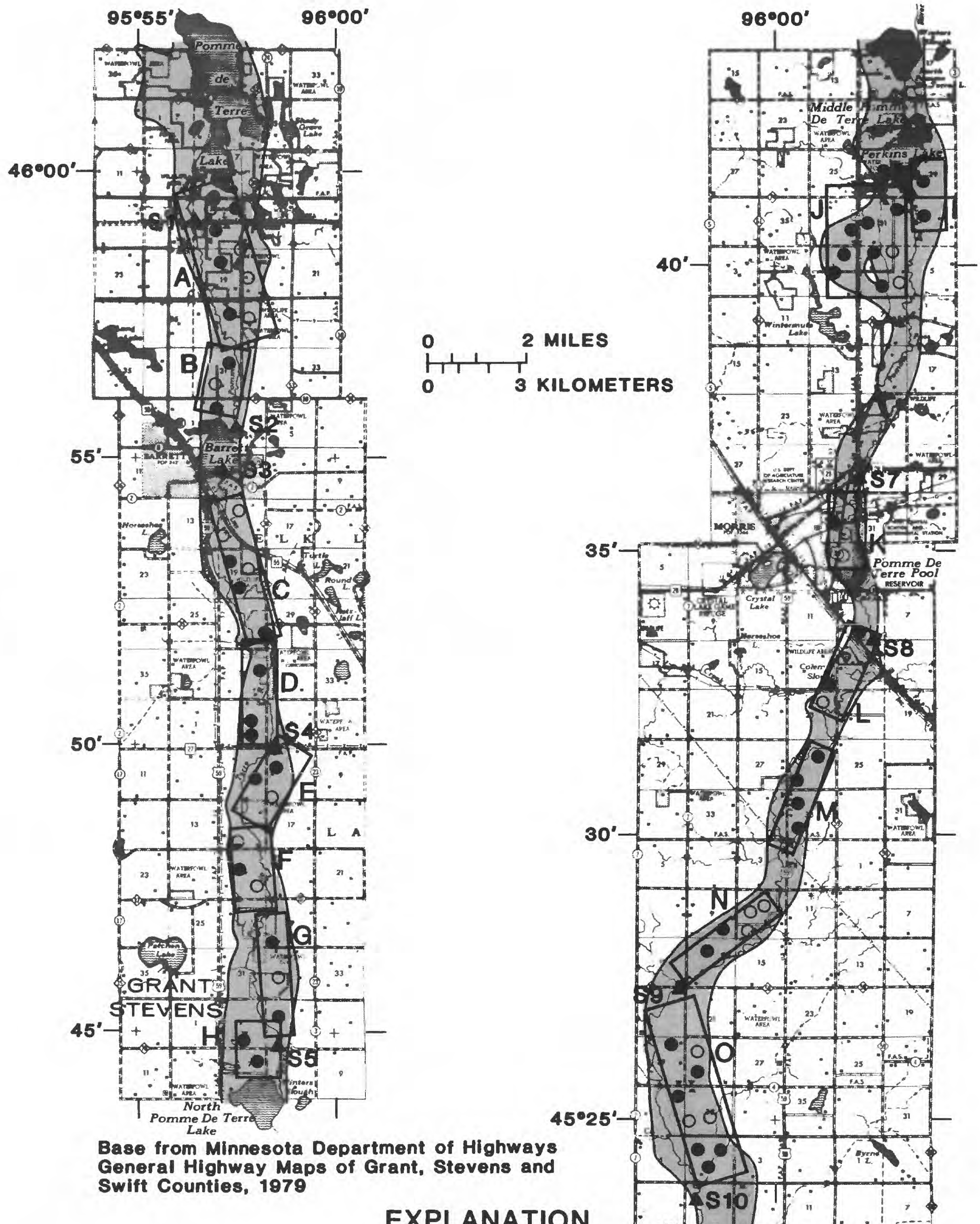
5. Wells are pumped for 30 days and there is no return flow to the ground-water system or the stream.

6. Drawdown in the wells during pumping does not exceed two-thirds the original saturated thickness.

7. Pumping wells are screened throughout the entire saturated thickness of the aquifer and are 100 percent efficient.

8. Pumping wells within a model block interfere with one another but do not interfere with wells in any other model block.

After the pumping rate was calculated for each well by use of the image-well method (Ferris and others, 1962), the percentage of water being diverted from the river after 30 days was estimated by use of the method developed by Theis (1941) and the chart developed by Theis and Conover (1963). In this method, the percentage of water being diverted is determined based on the aquifer specific yield and transmissivity, the distance between the well and the stream, and the duration of pumping (30 days). Percentage of pumpage



Base from Minnesota Department of Highways General Highway Maps of Grant, Stevens and Swift Counties, 1979

EXPLANATION

○ Hypothetical well

● Present (1980) well

A [●● ○] Model block

▲S7 Streamflow-measurement site

Surficial aquifer

Figure 14.--Location of model blocks for the analytical model

diverted from the river was then multiplied by the pumping rate for each well calculated by the image-well method to obtain the rate of diversion. The remaining pumpage was derived from aquifer storage.

Table 4 lists total pumping rates and streamflow diversions for each model block for both the present development and hypothetical development schemes. In the present development scheme, total simulated pumpage for the 30-day period is 2,017 million gallons from 43 wells, which is equivalent to application of about 10.8 inches per year of irrigation water. This compares with an estimated 1,494 million gallons pumped in the model area in 1980, which is equivalent to an application rate of about 8.0 inches per year. In the hypothetical development scheme, the number of irrigation wells was increased to 66. Total simulated pumpage was 2,811 million gallons, which is equivalent to an application rate of about 9.8 inches. For both schemes, the total rates of streamflow diversion and aquifer storage depletion after 30 days were about 53 and 47 percent of pumping, respectively.

In order to estimate streamflow available for diversion to pumping wells, discharge measurements were made at various locations along the Pomme de Terre River (fig. 14) on May 21-23 and November 6-7, 1980, (table 5). The two sets of measurements were intended to represent a typical range from high base flow in the spring to low base flow in the fall. The May measurements were made at a time when flow at the continuous-record gaging station at Appleton (about 20 miles downstream) was at about the 40-percent flow duration, meaning that the flow (66 ft^3/s) has been equalled or exceeded 40 percent of the time during the period of record. May 1980 streamflow may have been slightly affected by diversion to pumping wells because many irrigation wells in the model area had been pumping for several days when the measurements were made.

In November 1980, the flow at the gage in Appleton (37 ft^3/s) was at about 55-percent flow duration. Streamflow in November 1980 was probably affected by ground-water pumping during the irrigation season, even though pumping had ceased about 2 months before the November measurements. This is because streamflow diversion will continue long after pumping ceases to satisfy aquifer storage depletion. Jenkins (1968) provides methods for estimating these residual effects of pumping for any time after pumping ceases. As Jenkins points out, streamflow diversion will continue after pumping ceases at a significant rate for a period of time several times the duration of pumping. Also, depending on the aquifer properties and the location of pumping with respect to the stream, the maximum rate of streamflow diversion may actually occur after pumping ceases.

November streamflow also was affected at several locations along the study reach by lakes through which the river flows (see table 5 and fig. 14). Apparently, streamflow was reduced by accumulation of water in storage in Barrett Lake between measurement sites S-2 and S-3 (fig. 14); in North Pomme de Terre, Middle Pomme de Terre, and Perkins Lakes between sites S-5 and S-6; and in Pomme de Terre Pool at Morris between sites S-7 and S-8. In all, about 13 ft^3/s of streamflow was lost to lake storage. The outlets of Barrett and Perkins Lakes and Pomme de Terre Pool have small dams that can be used to control lake level.

Table 4.—Computed rates of ground-water pumping and diversion from the Pomme de Terre River after 30 days for the analytical model

1980 development					Hypothetical development				
Model block	Number of wells	Pumping rate (gal/min)	Percentage diverted from river	Diversion rate (ft^3/s)	Model block	Number of wells	Pumping rate (gal/min)	Percentage diverted from river	Diversion rate (ft^3/s)
A	4	3742	64	5.3	A	8	5802	59	7.4
B	2	1691	59	2.2	B	3	2369	49	2.6
C	3	2570	70	4.0	C	6	4983	58	6.5
D	3	3005	29	1.9	D	3	3005	29	1.9
E	2	2636	75	4.4	E	3	3232	75	5.4
F	1	1617	20	0.7	F	3	4269	39	3.7
G	2	1762	57	2.2	G	3	2520	61	3.4
H	2	3079	33	2.3	H	2	3079	33	2.3
I	2	2748	47	2.9	I	2	2948	47	2.9
J	7	5440	45	5.5	J	9	6732	48	7.2
K	1	1702	27	1.0	K	3	4049	34	3.1
L	2	3358	47	3.5	L	3	3720	47	3.9
M	4	4863	73	7.9	M	4	4863	73	7.9
N	2	942	68	1.4	N	5	2776	73	4.5
O	6	7537	58	9.8	0	9	10,715	61	14.6
Totals	43	46,692[1]	53	55.0	—	66	65,062[2]	53	77.3

[1] For 30-day period, total volume of simulated pumpage is 2,017 million gallons, equivalent to application of 10.8 inches of irrigation water.

[2] For 30-day period, total volume of simulated pumpage is 2,811 million gallons, equivalent to application of 9.8 inches of irrigation water.

Table 5.—Comparison of streamflow diversions computed by the analytical model with observed flow in the Pomme de Terre River

Model blocks[1]	Cumulative computed diversions (ft^3/s)		Observed streamflow (ft^3/s)		
	1980 development	Hypothetical development	May 21-23, 1980	Nov. 6-7, 1980	Site[1]
---	---	---	33.4	19.4	S-1
A-B	7.5	10.0	37.8	20.6	S-2
---	---	---	37.3	13.5	S-3
A-D	13.4	18.4	42.2	17.0	S-4
A-H	23.0	33.2	48.5	19.7	S-5
---	---	---	50.0	14.3	S-6
A-J	31.4	43.3	55.6	23.6	S-7
A-K	32.4	46.4	52.5	23.1	S-8
A-N	45.2	62.7	61.8	28.4	S-9
A-O	55.0	77.3	60.1	35.3	S-10

[1]Downstream order

Table 5 lists streamflow diversions due to pumping from wells computed by the analytical model for groups of model blocks. Diversions can be easily compared with observed streamflows in May and November 1980. For the present (1980) development scheme, model-computed cumulative diversions do not exceed May 1980 streamflows. However, computed cumulative diversions do exceed November 1980 streamflow at model block H (site S-5) and downstream. For the hypothetical development scheme, model-computed cumulative diversions exceed May 1980 streamflow at model block N (site S-9) and exceed November 1980 streamflow at model block D (site S-4). According to the analytical model, whenever cumulative diversions at a point exceed measured streamflow, the Pomme de Terre River would cease to flow and would become pooled. Streamflow records for the gage at Appleton indicate that during 1976 and 1977, flow in the Pomme de Terre River was less than 5 ft^3/s for several weeks at a time in the summer and fall (U.S. Geological Survey, 1977, p. 323; U.S. Geological Survey, 1978, p. 94).

The analytical model simulation illustrates that the potential for ground-water pumpage to greatly reduce and even eliminate streamflow is significant. It is also apparent that some reaches of stream might be more greatly affected than others. However, there are several important assumptions and factors both internal and external to the model that would tend to reduce the effects on streamflow indicated by the model. First, the 30 days of continuous pumping simulated is not typical of irrigation practices. Normally, wells are pumped for several days and then turned off for several days with time for ground-water levels to partly recover before pumping begins again. Although the total volume of pumpage simulated in both pumping schemes is reasonable for an entire irrigation season (table 4), in practice, the pumpage is likely to be spread out over a longer period of time (possibly 60 to 90 days).

Secondly, in estimating the effects of pumpage on streamflow, the preceding analysis assumes that storage capacity in the stream channel is negligible. This, of course, is not the case. Rather, the Pomme de Terre River channel has considerable storage capacity, particularly where the river flows through the several lakes discussed previously. It is likely that, as streamflow and stream stage are reduced during the irrigation season, water will drain out of storage in the lakes and cause streamflow to be sustained at higher rates and for longer times than would be possible if the lakes were not there. Drainage of water from lake storage could be increased by lowering the control at the lake outlets and allowing lake levels to fall. In addition, even if flow in the river were to cease, pumpage from wells could be sustained for a significant period of time by diverting water stored in the stream channel and in the lakes through which the river flows.

In conclusion, it should be noted that, because of the simplifying assumptions and because the analytical model has not been verified by use of field data, model results are not predictive. Rather, they are indicative of the possible magnitude of effect on streamflow and must be interpreted in the context of the properties of the entire hydrologic system. The analytical model is extremely useful as a tool to understand how the hydrologic system responds to pumping stress. The model results can also provide insight into management techniques that may maximize the efficient use of both the ground- and surface-water systems. However, the model can not provide definitive answers to specific questions related to the time and space distribution of ground and surface water. Such questions could only be answered through the use of a fully integrated ground- and surface-water model that had been verified by successful simulation of well-documented hydrologic events.

Finite-Difference-Model Analysis

Two finite-difference ground-water-flow models were constructed to simulate the surficial aquifers along the southern parts of the Pomme de Terre and Chippewa Rivers. One model, referred to in this report as the "Appleton area model," encompasses the surficial aquifer along the Pomme de Terre River near Appleton and extends upstream to the southern end of the analytical model. The second model encompasses the surficial aquifer along the Chippewa River between Cyrus in Pope County and Danvers in Swift County. This model is referred to in this report as the "Benson area model." Both model areas are shown in figure 13.

The computer program used for the finite-difference models was developed by Trescott and others (1976) and approximates the solution to the ground-water-flow equation in two dimensions. Before applying this computer program and constructing the digital models, a conceptual model of ground-water flow in the surficial aquifer system was developed. The conceptual model consists of qualitative descriptions of the characteristics and behavior of the system and simplifying assumptions that must be made to facilitate computer modeling. The major elements of the conceptual model are:

1. Ground-water flow is predominantly horizontal.

2. Flow regionally is from north to south and locally from valley sides toward the river.

3. Water flows into the Chippewa and Pomme de Terre Rivers as a function of the difference between river stage and aquifer head.

4. Areal recharge is from precipitation, occurs predominantly in March and April, and is uniform throughout the model area.

5. The amount of water moving across the lateral and underlying till contact is negligible and the till contact can be considered a no-flow boundary.

6. The rate of evapotranspiration from the water table is greatest at the land surface and declines linearly to zero at a depth of 5 feet below land surface.

7. Water pumped from the aquifer and used for irrigation is consumed by evapotranspiration and return flow to the aquifer is negligible.

8. Pumping rates are based on a specified application rate over all irrigated acreage, even though the area actually watered by center-pirot systems may be slightly smaller.

Appleton Area Model

The Appleton area model encompasses the surficial aquifer associated with the Pomme de Terre River valley in the vicinity of Appleton, which is the most intensely irrigated part of the study area. The objectives of this model were to (1) use 8 years of data on pumping, areal recharge, and water levels to calibrate the model and (2) use the calibrated model to evaluate the potential effects of future climatic and pumping stresses on ground-water levels and streamflow.

Model construction

The variably spaced finite-difference grid for the Appleton area model contains 31 rows and 36 columns (fig. 15). Grid spacings within rows vary from 0.25 to 1.0 mile to allow detailed simulation of the narrow aquifer along the Pomme de Terre River and the heavy irrigation pumping in that area. Grid spacing within columns is a uniform 0.5 mile.

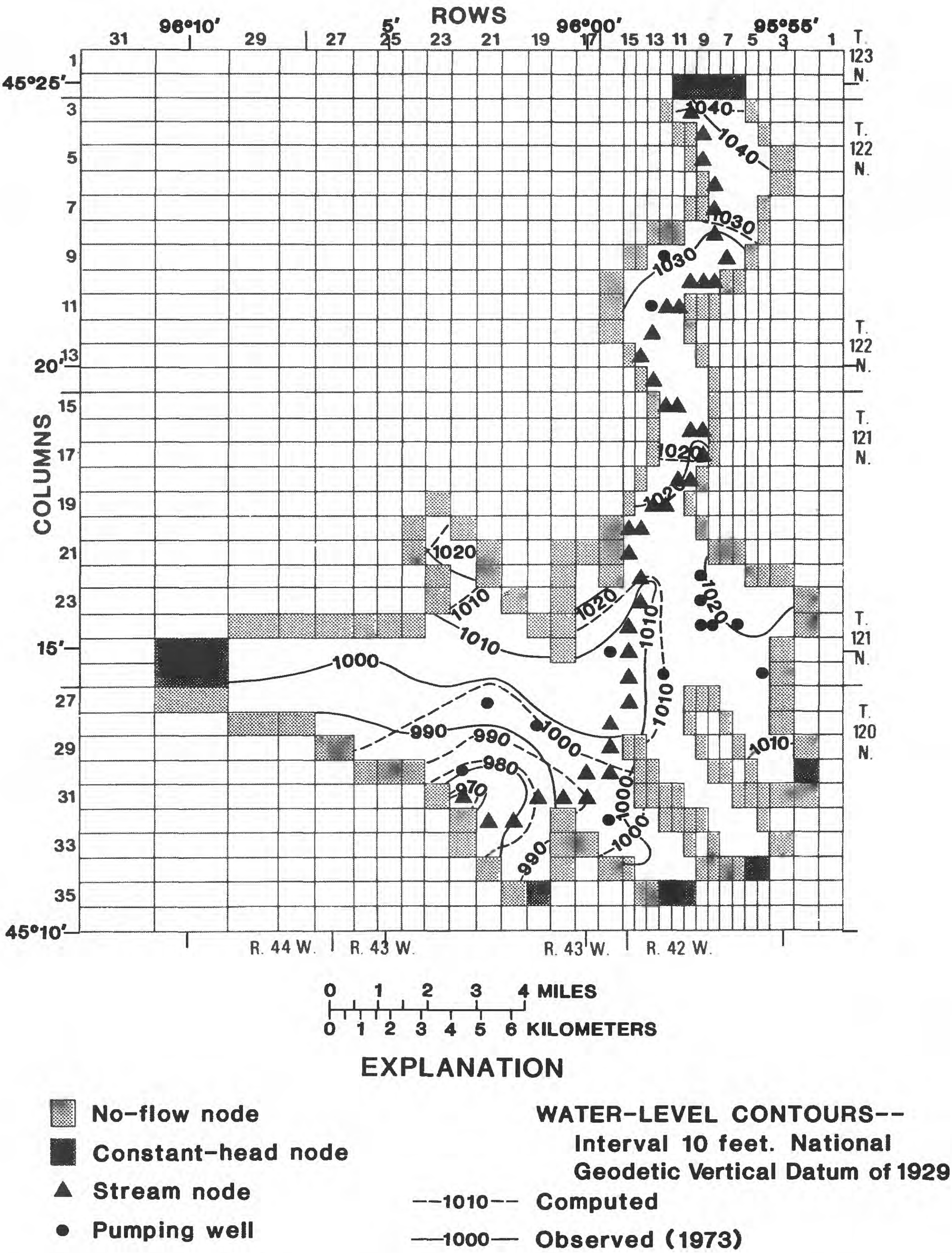


Figure 15.--Comparison of observed and computed water levels for steady-state calibration of Appleton area model

The lateral boundaries of the aquifer were simulated by use of two types of model nodes: no flow and constant head (fig. 15). No-flow nodes were assigned to all areas of till-outwash contact where flow from the adjacent till was considered to be negligible. Constant-head nodes were used on the northern, southern, and extreme western boundaries of the model where the surficial aquifer extends beyond the model area. Heads along these boundaries were set to average water levels observed in the aquifer during 1973. This type of boundary simulation is valid as long as the hydraulic gradient in the vicinity of the boundary does not change significantly in response to simulated stress. However, erroneous quantities of flow across these boundaries may be computed by the model if simulated stress is allowed to substantially change the gradients. The results of subsequent model simulations indicated that no significant stresses in the model reached the constant-head boundaries and, therefore, their use did not significantly affect model results.

Head-dependent flux nodes were used to simulate the hydraulic connection between the Pomme de Terre River and the aquifer. These nodes allow leakage back and forth from the river to the aquifer based on heads in the river and aquifer and on the vertical hydraulic conductivity and thickness of the streambed. Under nonpumping steady-state conditions, the aquifer head is greater than the river head and flow is from the aquifer into the river. As stress in the model lowers the aquifer head, the leakage from the aquifer to the river is reduced proportionally. If the aquifer head drops below the river head, the direction of flow is reversed and water from the stream leaks to the aquifer.

Because water-table conditions were simulated, the transmissivity of the surficial aquifer was computed by the model as the product of saturated thickness (pl. 1) and hydraulic conductivity. To approximate the distribution of transmissivity shown in plate 2, a uniform hydraulic conductivity of 260 ft/d was used. This value is similar to that used by Larson (1976, p. B21) in a previous study of the area.

The semipermeable streambed was assigned a leakage coefficient of 0.1 (ft/d)ft^{-1}, which is equal to the vertical hydraulic conductivity of the streambed divided by its thickness. This value is similar to that used in previous investigations by Larson (1976, p. B22) and Lindholm (1980, p. 53).

Steady-state calibration

The purpose of the steady-state calibration was to assure that the hydrologic properties of the surficial aquifer previously determined and the types of boundaries selected could be combined to produce a reasonable simulation of the system. The reasonableness of the simulation was determined by comparing model-computed water levels with those observed in 1973 (Larson, 1976, pl. 1.C), which was prior to the period of major pumping for irrigation. In this simulation, the areal recharge was applied uniformly throughout the model area and was set at about 5 inches per year to represent a long-term average. Evapotranspiration from the aquifer was simulated only where the water table was less than 5 feet below land surface. The maximum evapotranspiration rate was set at 20 inches per year where the water table was at the land surface, based on data collected by the University of Minnesota West-Central Experimental Station at Morris. The simulated rate of evapotranspiration was decreased linearly to zero where the water table was 5 feet below land surface. The average long-term pumping rate for each of 14 irrigation wells operating within the model area during 1973 (fig. 15) was estimated to be about 35 million gallons per year, which is equivalent to an application of 8 inches of irrigation water. For the steady-state calibration, pumping was simulated as if it was spread out over the entire year instead of being concentrated during the rather brief irrigation season. This was done to simulate the long-term, average effects of pumping.

Minor adjustments in input data were necessary to provide a good match of computed and observed water levels. The adjustments, however, were within reasonable limits and were consistant with the conceptual model of the aquifer system. Table 6 lists a comparison of computed and observed water levels and indicates that differences were 2 feet or less at all observation-well locations. Figure 15 is a map showing observed and computed water levels for the model area and indicates generally good agreement. Computed water-level contours follow the same general configuration as observed values, indicating similar flow paths. Table 7 lists the sources and discharges for the steady-state calibration and shows that areal recharge was the primary source. Only 0.3 ft^3/s was transmitted through constant-head nodes into the aquifer, accounting for about 1 percent of the total sources. Sixty-six percent of the water discharged from the aquifer is through leakage into the Pomme de Terre River. The computed leakage rate of 13.7 ft^3/s compares favorably with the 18.4 ft^3/s and 7.2 ft^3/s rates estimated from the base-flow measurements made in May and November 1980, respectively. Evapotranspiration from the water table accounted for only 22 percent of discharge from the aquifer. This indicates that the area of the model where the water table was less than 5 feet below land surface was relatively small.

Table 6.—Comparison of computed and observed water levels for selected observation wells for steady-state calibration of the Appleton area model

		Water-level altitude (feet above sea level)		
Well location	Model row, column	Model computed	Observed (1973)	Difference (computed minus observed)
122N42W21BBB	9,9	1,028	1,030	-2
121N42W30DAD	11,24	1,012	1,014	-2
120N43W02DDD	17,28	1,003	1,002	+1
120N43W13DDD	15,32	998	1,000	-2
120N42W04DDD	4,28	1,015	1,013	+2
121N44W27CCC	29,25	1,005	1,003	+2
121N42W17ABB	11,19	1,016	1,018	-2

Table 7.—Computed water budget for steady-state calibration of the Appleton area model

	Mechanism	Rate (cubic feet per second)	Percentage of total flow rate
Sources:	Areal recharge	20.5	99
	Constant head	.3	1
	Total	20.8	100
Discharges:	Pumping	2.0	10
	Evapotranspiration	4.6	22
	Leakage to river	13.7	66
	Constant head	.5	2
	Total	20.8	100

After the steady-state calibration was accepted, the sensitivity of the values of various hydrologic properties was tested by varying the model input values and observing the difference in computed water level. The streambed leakage coefficient was varied from 0.01 (ft/d) ft^{-1} to 1.0 (ft/d) ft^{-1}, producing a maximum difference in water level of less than 1.0 foot. Variations in the hydraulic conductivity and evapotranspiration rates through a reasonable range of values produced insignificant changes in water level computed by the model. Areal recharge, however, was a sensitive parameter when varied between 3 and 8 inches (the low and high values determined from hydrographs from 1972-80). The differences in computed water levels for different recharge rates were uniform throughout the model.

Transient calibration

In order to establish that the model could accurately simulate changes in ground-water flow and water level with time, the model was used to simulate historical climatic and pumping stresses in the surfical aquifer from 1973 through 1980. For modeling purposes, each of the 8 years were divided into four pumping periods as shown in table 8. Areal recharge, evapotranspiration, pumping rate and the number of pumping wells were varied as appropriate among pumping periods and from year to year to simulate actual field-stress conditions (table 8). Pumping period 1 represents fall and winter months (August through March) when areal recharge and pumping are minimal. The second pumping period (early April) represents snowmelt when most areal recharge occurs. Period 3 is a 75-day period between snowmelt and the irrigation season when evapotranspiration is high but soil moisture is generally sufficient to sustain crop growth. The fourth pumping period represents the 30-day irrigation season

Table 8.—Input data used in transient calibration of Appleton area model

[Areal recharge in inches, evapotranspiration (ET) in inches per year, pumping rate in million gallons per day, and equivalent application rate in inches]

Pumping period (annually)	Duration (days)	Model input	1973	1974	1975	1976	1977	1978	1979	1980
1	245	Areal recharge	—	—	—	—	—	—	2.5	3.0
August		ET[1]	14	14	14	14	14	14	14	14
through		Pumping rate	—	—	—	—	—	—	—	—
March		Number of wells	—	—	—	—	—	—	—	—
2	15	Areal recharge	4.8	5.3	5.2	3.4	4.1	7.1	6.0	3.3
		ET[1]	28	28	28	28	28	28	28	28
Early		Pumping rate	—	—	—	—	—	—	—	—
April		Number of wells	—	—	—	—	—	—	—	—
3	75	Areal recharge	—	—	—	—	—	—	—	—
mid-April		ET[1]	28	28	28	28	28	28	28	28
through		Pumping rate	—	—	—	—	—	—	—	—
June		Number of wells	—	—	—	—	—	—	—	—
4	30	Areal recharge	—	—	—	—	—	—	—	—
		ET[1]	28	28	28	28	28	28	28	28
July		Pumping rate	12.2	11.1	25.1	101.3	90.5	77.1	77.1	112.2
		Equivalent application rate[2]	6.0	5.5	6.0	17.5	9.0	7.5	5.5	8.0
		Number ofwells	14	18	30	41	71	81	90	95

[1]Rate given is maximum evapotranspiration rate where water table is at land surface. Rate decreases linearly to zero at depth of 5 feet below land surface.

[2]Values from Jerry A. Wright, University of Minnesota Extension Office, Morris, Minn., written communication, 1981.

in July. As discussed earlier, irrigation pumping is generally spread out over a longer period of time, more than 30 days. However, total pumping simulated was about the same as the amount actually pumped during each year, 1973-80.

Initial model input parameters were the same as those used in the steady-state calibration. A specific yield of 0.2 was used for transient simulations.

The results of the 8-year transient simulation are shown in figure 16 as computed and observed water-level hydrographs for selected observation wells in the Appleton area. Generally, there is good agreement between observed and computed water levels (with pumping). In early runs of this simulation, computed water levels for 1979-80 did not satisfactorily match observed water levels. However, addition of some areal recharge during pumping period 1 for these 2 years (table 8) produced a much better simulation. It should be noted that a number of the peaks representing seasonal high water levels in the simulated hydrographs are displaced somewhat in time from the observed peaks (fig. 16A, 1978-80, for example). This is because spring recharge was always simulated in pumping period 2 (early April) to facilitate modeling regardless of when spring recharge actually occurred.

Table 9 shows model-computed water budgets at the end of pumping period 4 for 1973, 1976, and 1980. These years were chosen because they represent the range of conditions related to precipitation, areal recharge, and pumping rate and intensity during the period of the transient simulation. In 1973, precipitation was near normal (fig. 7), areal recharge was about average (table 8), and pumping was minimal (table 8). In contrast, in 1976, precipitation was below normal (fig. 7), areal recharge was below average (table 8), and the pumping rate and number of wells increased sharply (table 8). In 1980, both areal recharge and the application rate of irrigation water were about average, but the total pumping rate was larger than in 1976 because the number of wells had more than doubled (table 8).

The flow rates shown in table 9 reflect the maximum effect of irrigation pumping on the system at the end of the 30-day pumping period. The rates indicate the source of water necessary to sustain the pumping. Note that areal recharge is not shown as a source because no recharge was applied to the model during pumping period 4 (see table 8). Thus, the primary source of water to sustain the pumping is aquifer storage, which is why water levels decline sharply during the irrigation season (fig. 16).

The effect of increased pumping on leakage to the Pomme de Terre River is also evident in table 9. Model results indicate that at the end of the irrigation season in 1973, about 15.5 ft^3/s were discharging from the aquifer into the Pomme de Terre River. At the end of the irrigation season in 1976 and 1980, only about 0.1 and 1.4 ft^3/s, respectively, were discharging into the river. This means that, at the peak of the irrigation seasons in 1976 and 1980, all but a very small amount of ground water normally discharging to the river was diverted by the pumping. This diversion should have resulted in net decreases in streamflow at the end of the irrigation season within the model area of about 15.4 and 14.1 ft^3/s for 1976 and 1980, respectively, as compared to 1973. However, these computed decreases in streamflow could not be verified in the field because streamflow measurements were not made at either the

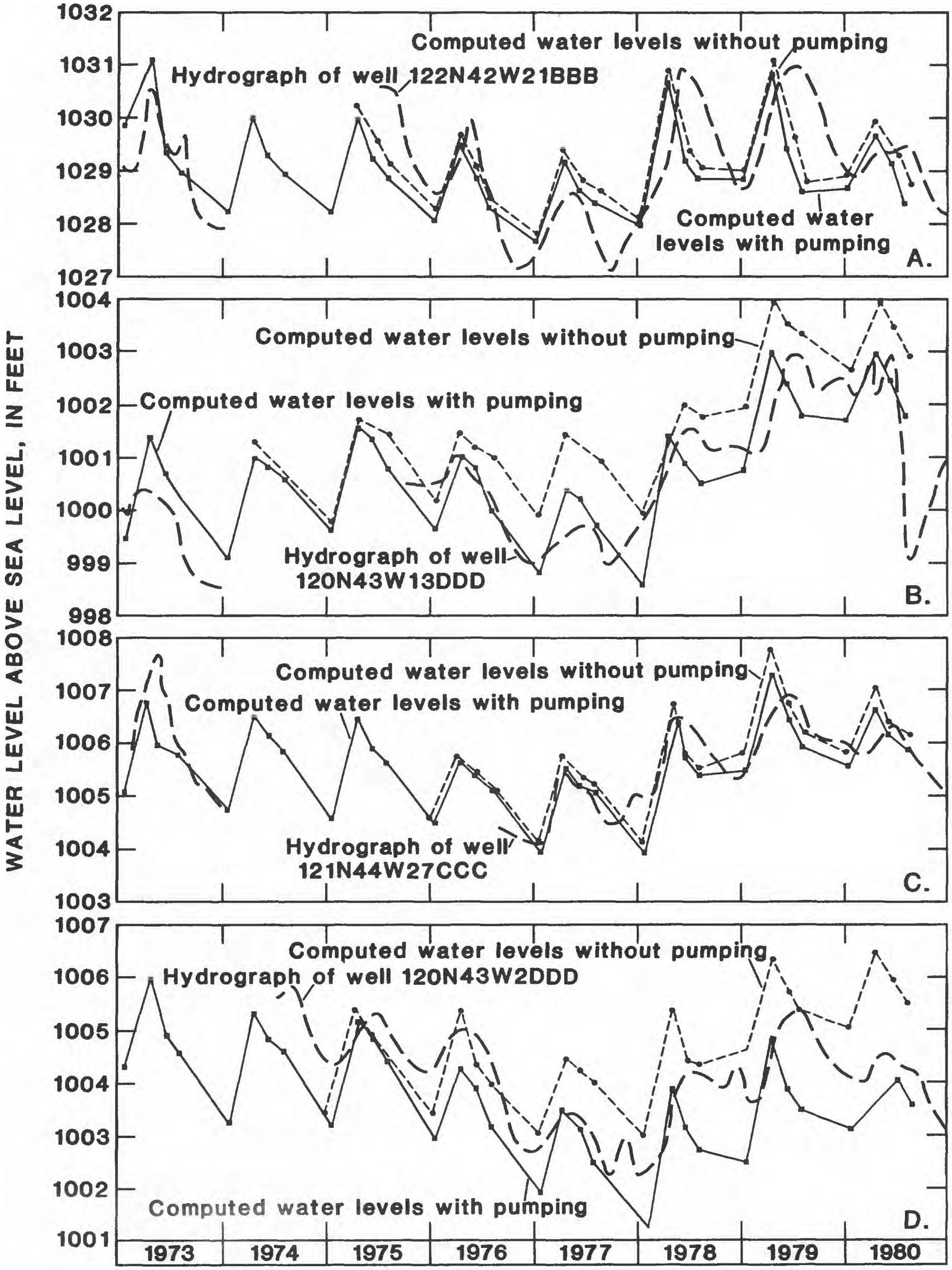


Figure 16.--Computed and observed water levels for selected observation wells in the Appleton area, 1973-80

Table 9.—Computed water budgets at the end of pumping period 4 for selected years for the transient calibration of the Appleton area model

[Values are in cubic feet per second]

Mechanism	1973	1976	1980
	Sources		
Storage	40.7	161.9	181.6
Constant head	0.2	0.3	0.9
Total	40.9	162.2	182.5
	Discharges		
Evapotranspiration	6.1	4.8	6.6
Leakage into river	15.5	0.1	1.4
Pumpage	18.8	156.8	173.6
Constant head	0.5	0.5	0.9
Total	40.9	162.2	182.5

necessary times or locations in 1973 or 1976. It should be noted that the rates of leakage to the river shown in table 9 represent the net rate for the model area. Locally, flow may be either toward or away from the river depending on the local hydraulic gradient.

To estimate the effect on water level that pumping alone has had over the 8-year period, another transient simulation was made without pumping (see fig. 16). The difference between the two simulated hydrographs represents the cumulative net effect of pumping on water levels since 1973. After 8 years, water levels within 2 or 3 miles of the Pomme de Terre River computed with pumping generally were less than 1 foot lower than water levels without pumping (fig. 16 A and C). At two locations near the till boundaries, however, about 3 feet of cumulative drawdown had been produced by pumping from 1973-80 (fig 16 D). This simulation illustrates that although computed water levels do largely recover after the irrigation season, there is a residual computed drawdown that is carried over and accumulated year after year.

Model application

Once calibrated, the model was used to simulate two hypothetical development plans that project climatic and pumping stresses beyond 1980. The results of these simulations can be used to estimate regional trends in aquifer response to future ground-water development. However, caution should be used in planning development based solely on the model simulations. Drawdowns computed by the model are based on simplified assumptions and are of value only in assessing regional water-level changes. Actual water-level changes will differ from computed values, and local changes at individual wells will be much greater.

The first developed scheme (plan 1) is a continuation of the transient calibration using the same input data for areal recharge, evapotranspiration, pumping rate, and number of wells as was used for 1980 (table 8). In 1980, the number of pumping centers approached potential maximum development in the modeled area and, therefore, was not changed in subsequent years of plan 1. The simulation was allowed to run beyond 1980 until the residual effects of an irrigation season carried over to the next year were minimal. The objectives of this simulation were to determine the amount of additional drawdown to be expected under present development conditions and to determine how long it would take for residual effects to cease.

Figure 17 is a contour map of the additional drawdown resulting from simulation of plan 1 and is the amount to be expected under present development. In many areas, drawdown is less than 1 foot. However, additional drawdown of over 3.0 feet can be expected in several areas close to till boundaries. The cessation of residual effects from the previous irrigation season occurred at different times throughout the model, largely depending on the location of wells, the Pomme de Terre River, and till boundaries. Residual effects ceased within about 1 year in areas along the Pomme de Terre River and in the northern part of the model where drawdowns were less than 1.0 foot. In other areas, such as just north of Appleton where additional drawdown was over 4 feet, residual effects carried over for about 4 years. This means that there would be no additional drawdown after 4 years of simulation, provided all simulated stresses remained unchanged.

Plan 2 was designed to estimate the effects of a 3-year drought similar in severity to that of 1976. Areal recharge was reduced to 3.4 inches per year (table 8) and the application rate for irrigation water was increased to 17.5 inches. The total pumping rate from the 95 pumping wells (fig. 17) was about 230 Mgal/d for 30 days during each year of the simulation. The computed drawdown after 3 years is shown in figure 18. Water levels declined generally less than 3.0 feet along the river but as much as 9.0 feet in some areas near till boundaries.

Table 10 lists model-computed water budgets at the end of pumping period 4 for each of the 3 years simulated in plan 2 (3-year drought). As with the transient calibration (table 9), the flow rates represent the maximum effect on the system at the end of the 30-day irrigation season. Also, areal recharge is not a source and pumping is sustained primarily by removal of water from aquifer storage. The contribution from inflowing constant-head boundaries is

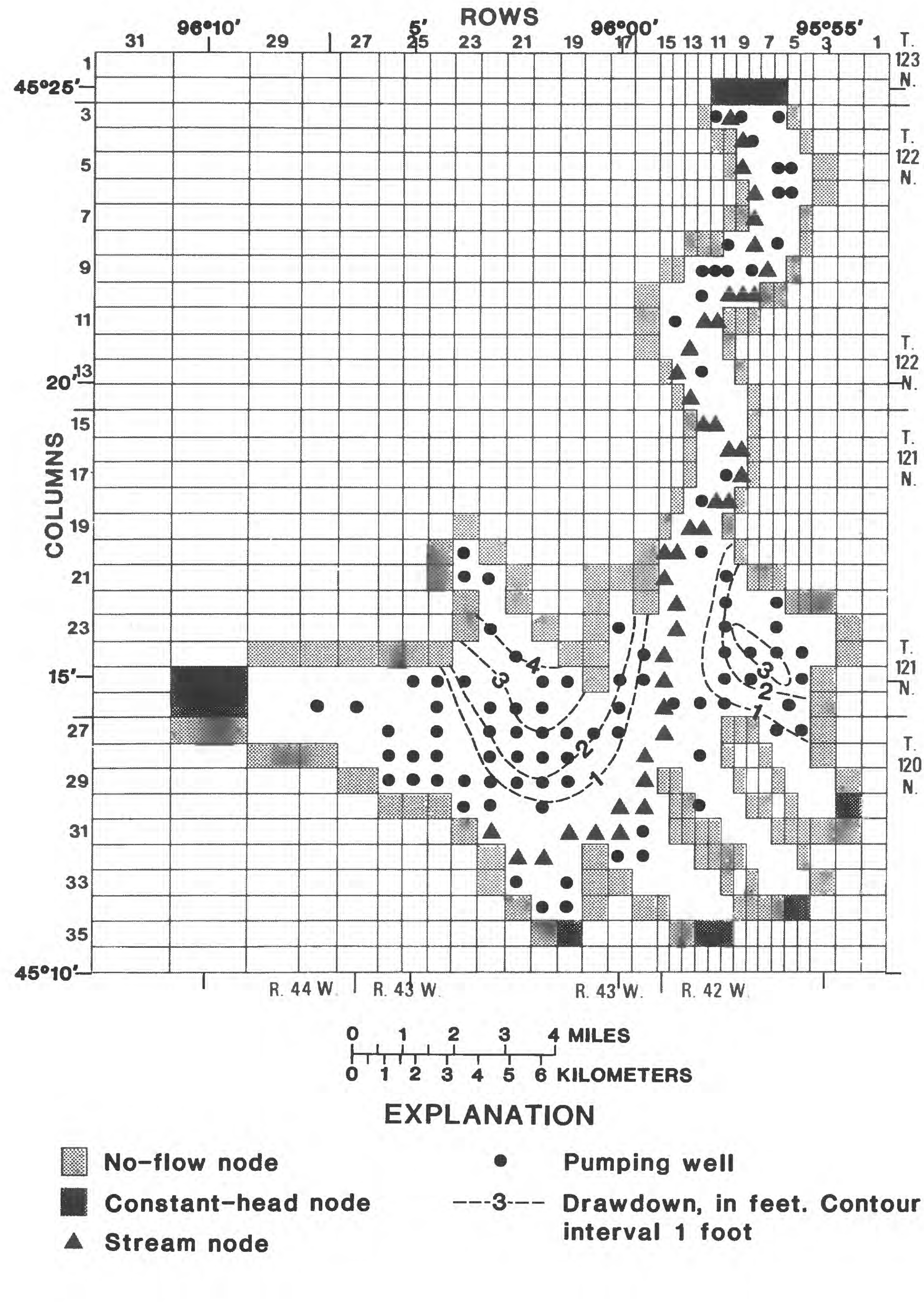


Figure 17.--Computed drawdown for simulation of Plan 1 in the Appleton area model

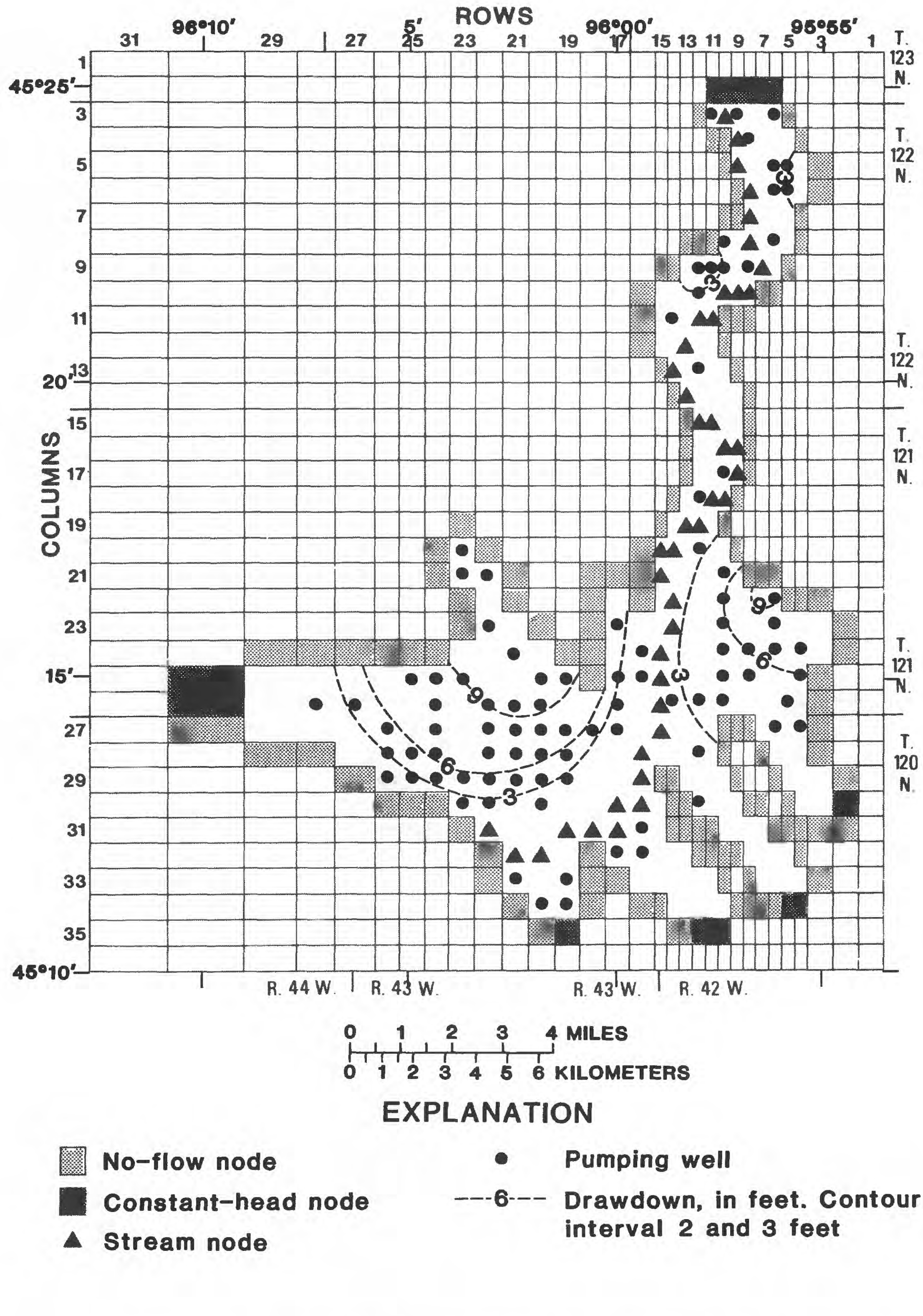


Figure 18.--Computed drawdown for simulation of Plan 2 in the Appleton area model

Table 10.—Computed water budgets at the end of pumping period 4 for simulation of plan 2 in the Appleton area model

[Values in cubic feet per second]

Mechanism	Year 1	Year 2	Year 3
	Sources		
Storage	339.9	331.7	327.8
Leakage from river	14.9	22.2	25.6
Constant head	2.7	3.0	3.1
Total	357.5	356.9	356.5
	Discharges		
Evapotranspiration	2.9	2.3	2.1
Pumpage	354.0	354.1	354.0
Constant head	0.5	0.5	0.4
Total	357.4	356.9	356.5

very small (less than 1 percent of pumpage). Table 10 indicates that pumpage for this simulation (354 ft^3/s) is about twice the pumpage for 1980 (173.6 ft^3/s, table 9). This is because, although the number of wells was the same in both simulations, the application rate for irrigation water for plan 2 (17.5 inches) was about twice the 1980 rate (8.0 inches, table 9). The most significant difference between these results for plan 2 and the transient calibration (table 9) is that there is a net leakage of water from the river into the aquifer at the end of the simulated irrigation season (pumping period 4). Net leakage from the river at the end of pumping period 4 increases significantly from year to year (table 10). This means that at the end of the first year of the simulated drought, net diversion of flow in the Pomme de Terre River within the model area would be about 30 ft^3/s, as compared to 1973 (prior to major ground-water development). The streamflow diversion would equal the sum of leakage into the river in 1973 (15.5 ft^3/s, table 9) plus the leakage from the river for plan 2 (14.9, table 10). Net model-computed diversions of streamflow at the end of the irrigation season in the second and third years would be about 38 and 41 ft^3/s, respectively, as compared to 1973.

To assess the availability of streamflow to support ground-water pumpage, computed streamflow diversion was compared with natural base flows of the Pomme de Terre River prior to major ground-water development, the 55- and 70-percent flow durations. The 55-percent flow duration was chosen because it represents flow conditions in November 1980 when discharge measurements were made on the Pomme de Terre River. At the 55-percent flow duration (37 ft^3s, figure 10) there would be sufficient streamflow in the Appleton model area to sustain the pumping simulated in plan 2, provided that there were no diversions of flow upstream from the model area. However, if the effects of plan 2 simulated in the Appleton area model (table 10) and the 1980-development scheme simulated by the analytical model (table 5) in Stevens and Grant Counties were combined for the first year of a drought, total streamflow diversion would be about 85 ft^3/s. Under such conditions, model results indicate that deficiency in streamflow in the Appleton model area could be about 48 ft^3/s and the Pomme de Terre River would cease flowing. At the 70-percent flow duration (U.S. Geological Survey gaging-station files, St. Paul), the deficiency in streamflow could be about 60 ft^3/s. Unless there was sufficient water in storage in the river channel, it would not be possible to sustain the irrigation pumping rates simulated in the two model schemes combined.

It must be noted that the model results can not be considered to be precise predictions of the effect of irrigation pumpage on streamflow because of the assumptions and uncertainties in the model analyses. However, the model analyses are rigorous enough to suggest that under certain conditions, such as a drought, flow in the Pomme de Terre River may not be sufficient to sustain irrigation pumpage even at 1980 levels of development. This conclusion is supported by the fact that during the drought of 1976, flow in the Pomme de Terre River at Appleton was less than 1 ft^3/s for three consecutive weeks in August and September (U.S. Geological Survey, 1977, p. 323).

Benson Area Model

The Benson area model encompasses the surficial aquifer in the Chippewa River valley between Cyrus in Pope County and Danvers in Swift County (fig. 13). Because of a lack of detailed water-level and pumpage data in this area, long-term transient calibration of the model was not possible. Unlike the Pomme de Terre River valley, irrigation development has progressed slowly. However, based on land-use estimates by the U.S. Soil Conservation Service and potential yield of the surficial aquifer, pumpage of ground water for irrigation could nearly double present development. Therefore, the purpose of a numerical simulation in this area was to simulate (1) present aquifer development and ground-water flow at steady state, and (2) aquifer responses to possible changes in climatic conditions and increases in pumping.

Model construction

A 27-row by 41-column finite-difference grid was designed for the Benson area model (fig. 19). Because of the broad area and low density of irrigation wells, a uniform grid spacing of 0.5 mile was used.

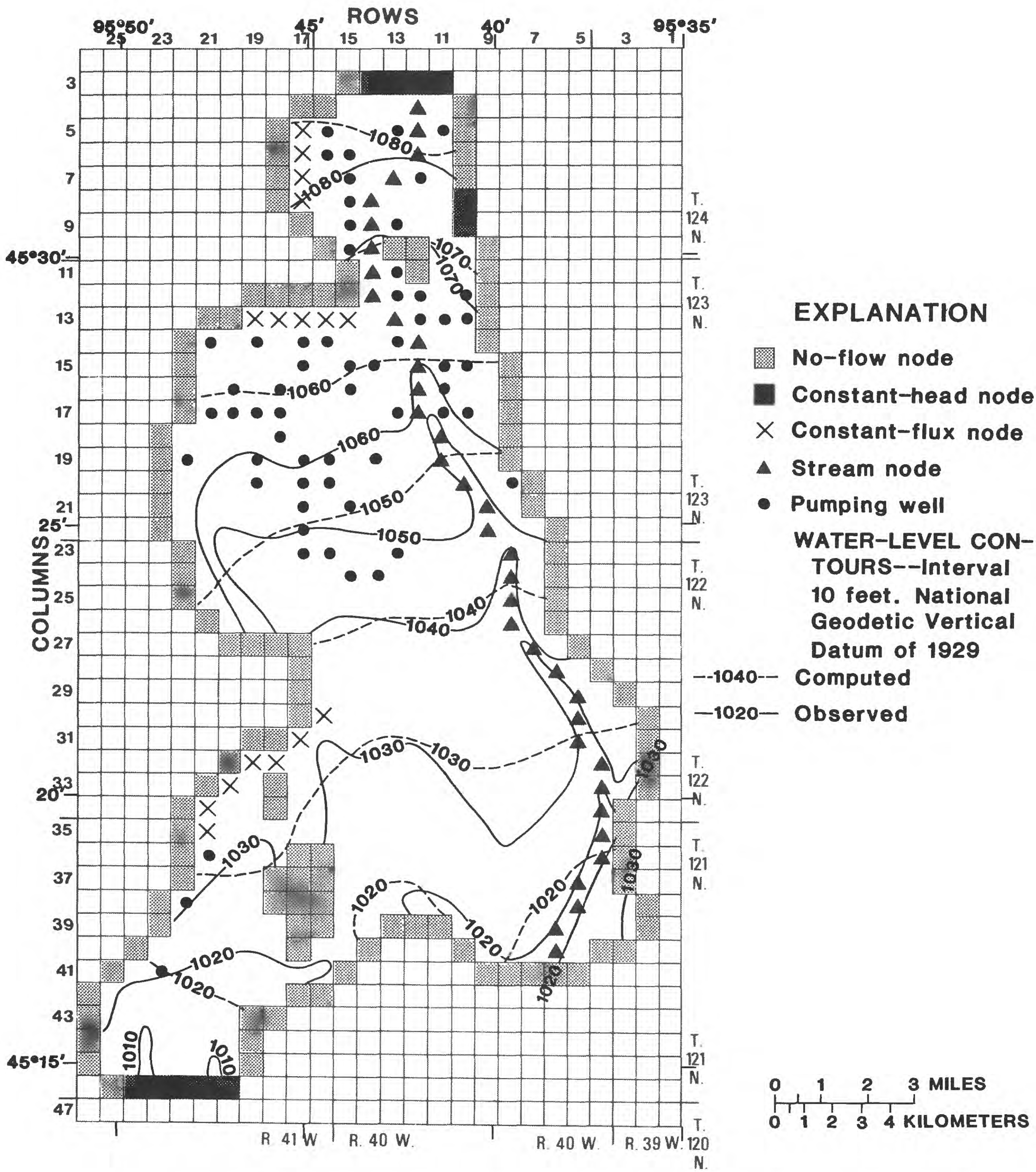


Figure 19.--Comparison of observed and computed water levels for the steady-state calibration of the Benson area model

The lateral boundaries of the aquifer were simulated similarly to the Appleton area model. Boundary nodes were either no flow or constant head. No-flow nodes were assigned to all areas of till-outwash contact, and constant-head nodes were used in the northern, northeastern, and southern ends of the system where the aquifer extends beyond the model area along the river. Head-dependent-flux nodes were used to simulate the hydraulic connection between the Chippewa River and the aquifer.

In order to simulate the distribution of transmissivity shown on plate 2, a uniform hydraulic conductivity of 400 ft/d and the saturated thickness shown on plate 1 were used in the model. The value of hydraulic conductivity used in the Benson area model is higher than that used in the Appleton area model because of the coarser aquifer materials in the Benson area. The streambed (Chippewa River) was assigned the same leakage coefficient as was used in the Appleton area model, 0.1 (ft/d) ft^{-1}.

Steady-state calibration

Steady-state calibration of the Benson area model was performed by simulating long-term average conditions in the aquifer. Model-computed water levels and leakage to the stream were compared with water levels measured in October 26 to November 9, 1980, and with stream discharge measured in May and November 1980, respectively. A uniform areal recharge rate of about 5 inches per year and a maximum evapotranspiration rate at the land surface of 20 inches per year were used in the steady-state calibration. As in the Appleton area model, the evapotranspiration rate was decreased linearly from the maximum at the land surface to zero at a depth of 5 feet. Thus, evapotranspiration was simulated only where the water table was less than 5 feet below land surface. Pumping from each of the 60 irrigation wells shown in figure 19 was simulated at the 1980 rate, about 35 million gallons per year. This is equivalent to an application of 8 inches of irrigation water. Pumping was simulated as if it were spread out over the entire year and totaled about 2,550 million gallons per year including non-irrigation pumping.

During the steady-state calibration of the model, a poor simulation of head was obtained along the western boundary. Subsequent test drilling revealed that the aquifer extended some distance to the west under the clay-till surface. The areal extent and hydraulic characteristics of this part of the aquifer are not known. However, flow from the west is apparently entering the aquifer in these areas and a good match of heads could not be achieved without simulating the flow. To account for this boundary condition, constant-flux nodes were used (fig. 19). Constant-flux nodes allow water to flow into the simulated system at a constant rate regardless of other stress simulated in the model. The rates were adjusted until the best match with observed water-level gradients was obtained. The computed water-level configuration for the steady-state calibration is compared with observed water levels in figure 19, and a comparison of computed and observed water levels for selected observation wells is shown in table 11. Sensitivity tests similar to those conducted for the Appleton area model indicated that the Benson area model was largely insensitive to evapotranspiration, hydraulic conductivity, and the stream leakage coefficient when values of these properties were doubled or halved.

Table 11.—Comparison of computed and observed water levels for selected observation wells for steady-state calibration of the Benson area model

Well location	Model Row, Column	Water-level altitude in feet above sea level: Model computed	Observed (October-November 1980)	Difference (computed minus observed)
124N41W30BCC	16, 7	1,079	1,080	-1
124N40W33DCC	11, 11	1,070	1,069	+1
123N40W18CCC	16, 16	1,061	1,062	-1
123N40W30DAD	15, 20	1,054	1,053	+1
122N40W20AAD	13, 29	1,035	1,034	+1
122N40W33DCC	10, 34	1,028	1,026	+2
121N41W10DAB	21, 38	1,025	1,024	+1

Table 12 presents the computed sources and discharges for the steady-state calibration of the Benson area model. Table 12 indicates that model-computed leakage to the river is a much smaller percentage (28) of total ground-water flow in the Benson area model than the percentage (66) computed for the Appleton area model (table 6). The nearly parallel east-west water-level contours in figure 19 further support this conclusion. In addition, because of the generally shallower water table and larger number of wetlands, evapotranspiration losses from the ground-water system are much larger in the Benson area (48 percent of discharges) than in the Appleton area (22 percent of discharges). Also, the quantity of pumpage simulated in the calibration of the Benson area model was considerably larger than that simulated for steady-state calibration of the Appleton area model. All these factors combine to produce the relatively low computed leakage to the stream in the Benson model. Interestingly, the computed leakage to the Chippewa River, 13.6 ft^3/s (table 12), did not correspond well to the observed streamflow gains for the Chippewa River between Cyrus and Danvers of 27 and 37 ft^3/s in May and November 1980, respectively (U.S. Geological Survey, 1981, p. 304-305 and U.S. Geological Survey, 1982, p. 337-338). This is not surprising, however, considering that the measured streamflows represented the 27- and 39-percent flow duration and

Table 12.--Computed water budget for steady-state calibration of the Benson area model

	Mechanism	Rate (cubic feet per second)	Percentage of total flow
Sources:	Areal recharge	44.5	90
	Constant head	3.2	6
	Constant flux	1.8	4
	Total	49.5	100
Discharges:	Pumping	10.8	22
	Evapotranspiration	23.9	48
	Leakage into river	13.6	28
	Constant head	1.2	2
	Total	49.5	100

were likely much too high for the gains in streamflow to be attributed to ground-water discharge alone. At the 50-percent flow duration, streamflow would have been about 60 percent of the flow measured in November 1980 and streamflow gain within the model area would have been considerably smaller. Therefore, the model-computed leakage to the river is probably reasonable, and because computed and observed water levels match well, the model was accepted as calibrated.

Model application

After the model was calibrated, it was used to estimate the effects on water levels and streamflow produced by several hypothetical ground-water-development plans. The simulations are transient, not steady-state, and incorporate the storage properties of the system. Transient analyses were necessary because the important stresses on the ground-water system (areal recharge and pumping) are highly seasonal and can not be adequately simulated as time-averaged steady-state phenomena. However, because the model was not calibrated under transient conditions, it is largely an untested tool for performing these analyses. Therefore, model results can not be regarded as precise predictions of how the aquifer will respond to future stress. Rather, the results are indicative of what may occur even though the accuracy of the model for transient simulations is not known. In addition, drawdowns computed by the model are averaged over the entire area of each grid block (0.5 mile across). Drawdowns in individual wells located at the center of a block will be considerably larger than the drawdowns computed by the model. Despite these uncertainties and simplifications, the model results can still be very useful for understanding how the system works and for planning future ground-water development accordingly.

Table 13 summarizes the four hypothetical development plans that were simulated with the model. The plans were designed to consider the effects of drought, increased application rate of irrigation water, and increased number of irrigation wells.

Table 13.—Summary of hypothetical development plans simulated with the Benson area model

Plan	Length of simulation, in years	Annual areal recharge, in inches	Pumping rate, in million gallons per day	Equivalent application rate, in inches per year	Number of wells
1. Present development, average conditions	4	4.8	80	8	60
2. Present development, drought conditions	3	3.4	170	17	60
3. Hypothetical development, average conditions	4	4.8	170	8	139
4. Hypothetical development drought conditions	3	3.4	360	17	139

The cycling and duration of pumping periods and the rates of evapotranspiration were the same as used for the Appleton area model (table 8). All areal recharge was simulated during pumping period 2 (15 days) and all pumping was simulated during pumping period 4 (30 days). New well locations in hypothetical development plans 3 and 4 were based on the potential yield and land use of each site. Areas outside the areal extent of the surficial outwash, or that had a potential yield of less than 100 gal/min, were not considered for modeling. A specific yield of 0.2 was used in all transient simulations.

Plan 1 simulates the 1980 well development, areal recharge of 4.8 inches annually, and a pumping rate equivalent to application of 8 inches of irrigation water. The model simulation approached dynamic equilibrium in about 4 years, which means that the carry-over effects from year to year were negligible. The resulting water levels were less than 2 feet lower than those for the steady-state calibration (fig. 19). Sources and discharges for this simulation are shown in table 14. These data indicate that at the peak of the irrigation season, the river would still be gaining water from ground-water discharge overall, but that streamflow would be reduced by about 9.6 ft^3/s, as compared with the steady-state calibration (table 12). Table 14 also indicates that the rate of water loss to evapotranspiration is greater for plan 1 than for the steady-state calibration. This is because the maximum evapotranspiration rate used for pumping period 4 was 28 inches per year, whereas the long-term rate used for the steady-state calibration was 20 inches per year.

Table 14.—Computed water budgets at the end of pumping period 4 for simulation of plans 1 to 4 in the Benson area model

[In cubic feet per second]

Mechanism	Plan 1 1980 development, average conditions	Plan 2 1980 development, drought conditions	Plan 3 Hypothetical development, average conditions	Plan 4 Hypothetical development, drought conditions
		Sources		
Leakage from river......	—	12.7	—	16.9
Storage.................	160.3	266.5	285.2	547.4
Constant head...........	3.8	5.3	3.8	5.1
Constant flux...........	1.8	1.8	1.8	1.8
Total...................	165.9	286.3	290.8	571.2
		Discharges		
Evapotranspiration......	36.4	23.3	25.2	15.2
Leakage into river......	4.0	—	1.2	—
Pumpage.................	124.2	262.2	262.8	554.8
Constant head...........	1.3	0.7	1.7	1.3
Total...................	165.9	286.2	290.9	571.3

Plan 2 shows the effects of a 3-year drought, similar in severity to that of 1976, with wells that operated during 1980 but with increased pumping rates to make up for dry conditions. The computed drawdowns for plan 2 are shown in figure 20. In much of the southern half of the model area, pumping is minimal and drawdowns are less than 1.0 foot, reflecting the effects of decreased areal recharge. However, along the western boundary, the higher density of pumping centers and the relatively greater distance from the Chippewa River produce as much as 6.0 feet of drawdown in the simulation. The computed sources and discharges for plan 2 are shown in table 14. As expected for the 30-day duration of pumping, aquifer storage is the major source of water to support the pumping. However, leakage from the river is also significant. Table 14 indicates that, with pumping plan 2, the river is not gaining overall and, in fact, is losing 12.7 ft^3/s within the model area. For pumping plan 2, therefore, model-computed streamflow reduction as compared to the steady-state calibration would be 26.3 ft^3/s [13.6 ft^3/s leakage into the river, steady-state calibration (table 12) plus 12.7 ft^3/s leakage from the river, plan 2, table 14]. This reduction is less than one-third the available streamflow at Milan at the 50-percent flow duration and about two-thirds the available streamflow at the 70-percent flow duration (U.S. Geological Survey gaging-station files, District Office, St. Paul, Minn.). The effect on streamflow would, of course, be less if pumping were spread out over more than 30 days.

Table 14 also shows that with the additional lowering of the water table in plan 2, the amount of water lost to evapotranspiration is about 13.1 ft^3/s less than in plan 1. Computed flow into the aquifer through constant-head nodes is 1.5 ft^3/s greater in plan 2 than in plan 1. However, the amount of water derived from constant-head nodes is still only a small part of the total sources.

Plan 3 simulates the effects of maximum potential development (79 additional wells) with average areal recharge (4.8 inches per year) and pumping rates equal to an application rate of 8 inches of irrigation water. The simulation approached dynamic equilibrium in about 4 years. The computed drawdowns shown in figure 21 are little different in areal extent and magnitude from those of plan 2 (fig. 20). However, the west-central part of the model area shows the greatest drawdown with a maximum of about 9 feet. Table 14 indicates that for plan 3, aquifer storage is the primary source and that evapotranspiration loss is 11.2 ft^3/s less for plan 3 than for plan 1. Also, model results indicate that, overall, the river would be gaining slightly (1.2 ft^3/s) under the conditions of plan 3.

Plan 4 simulates 3 years of drought conditions and maximum potential development with 79 additional pumping wells. Areal recharge was reduced to 3.4 inches per year and pumping rates are equivalent to an application rate of 17 inches of irrigaion water to compensate for dry conditions. The pumping rate for plan 4 (360 Mgal/d) was more than double the rate for plan 3. Figure 22 shows model-computed drawdown at the end of the irrigation season after 3 years of simulation. Drawdowns are generally less than 1 foot near the Chippewa River, but are greater than 12 feet along the western boundary of the surficial aquifer. Model-computed sources and discharges for plan 4 are shown in table 14. Because of the short duration of simulated pumping (30 days),

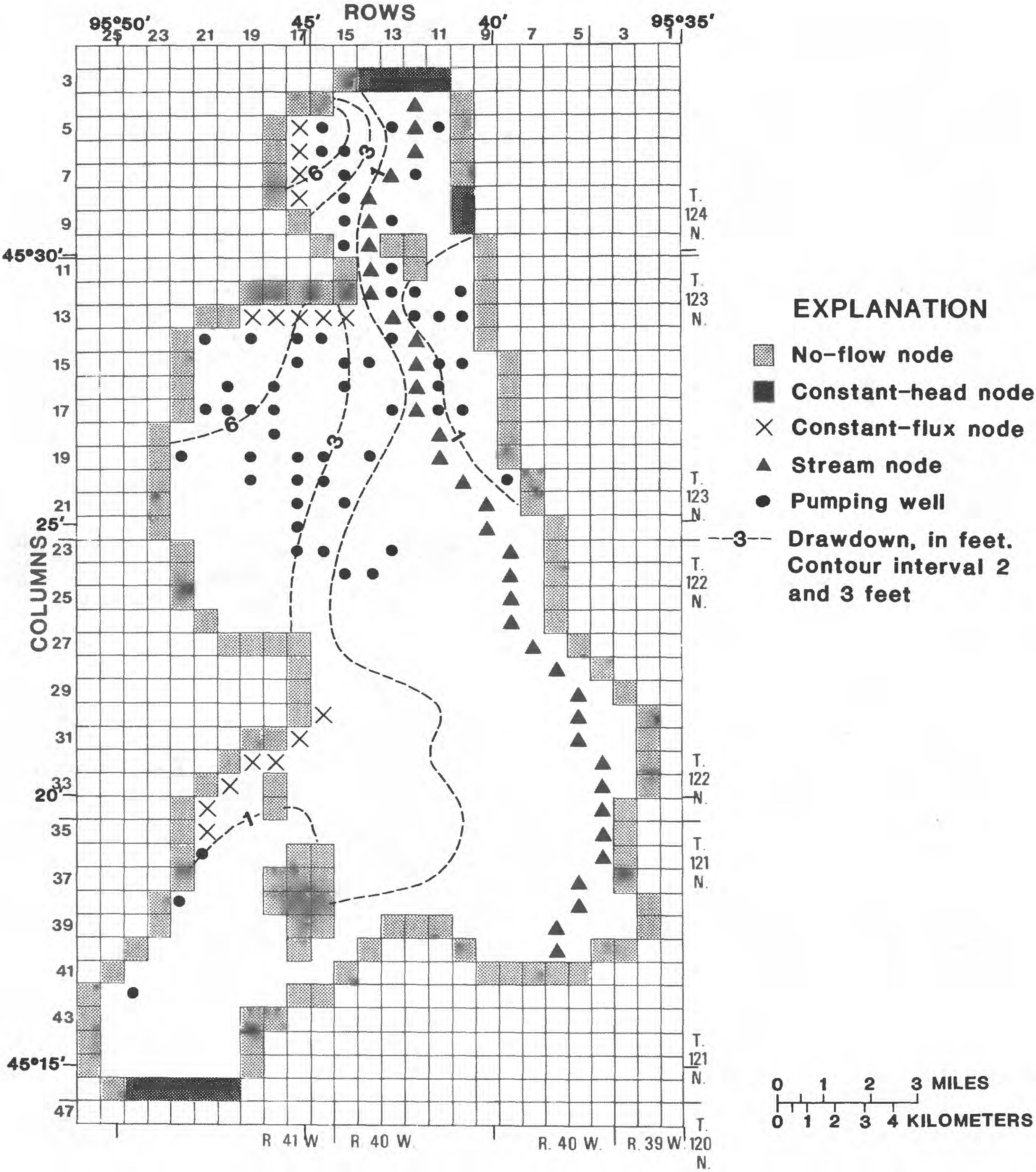


Figure 20.--Computed drawdown for simulation of Plan 2 in the Benson area model

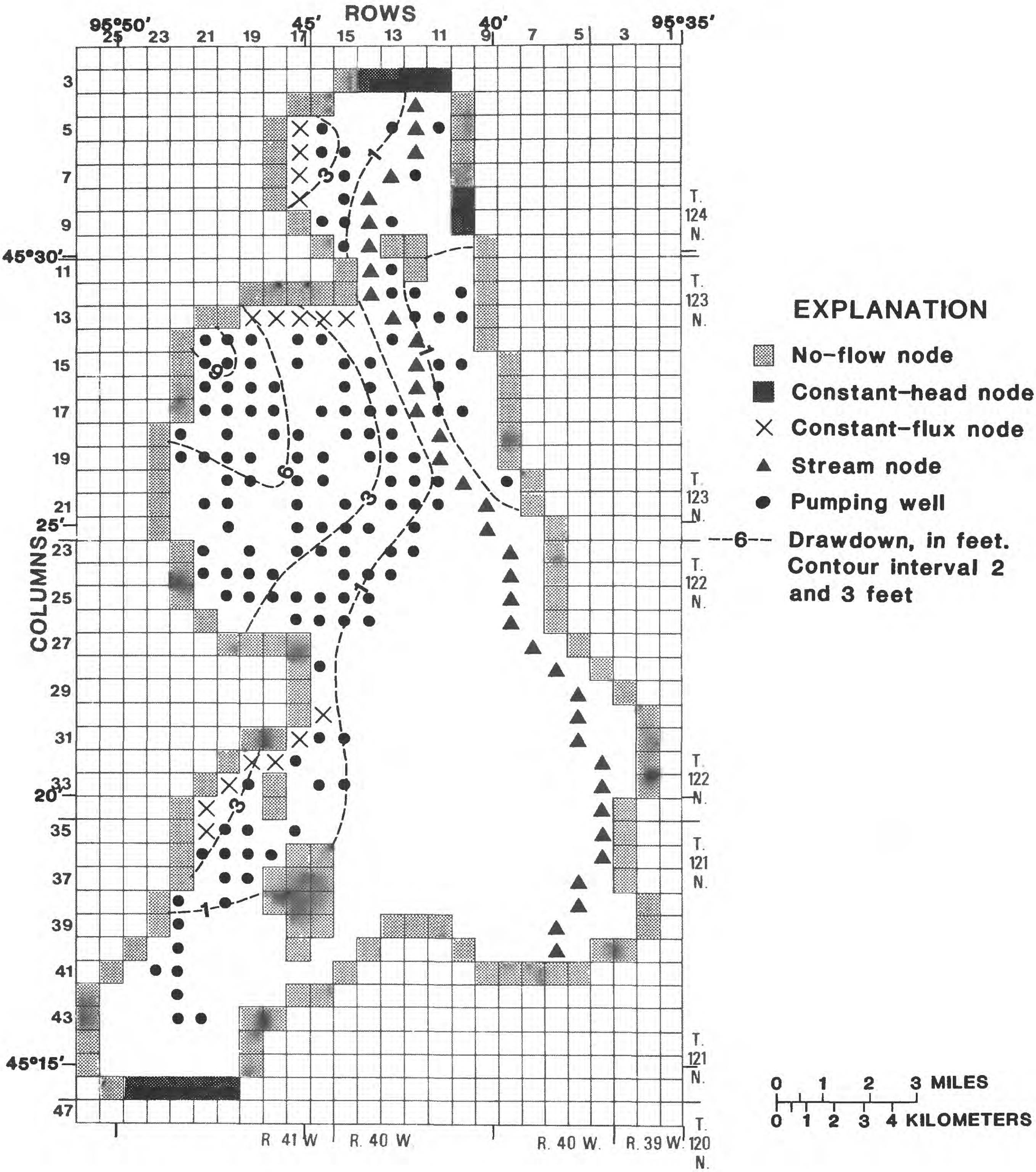


Figure 21.--Computed drawdown for simulation of Plan 3 in the Benson area model

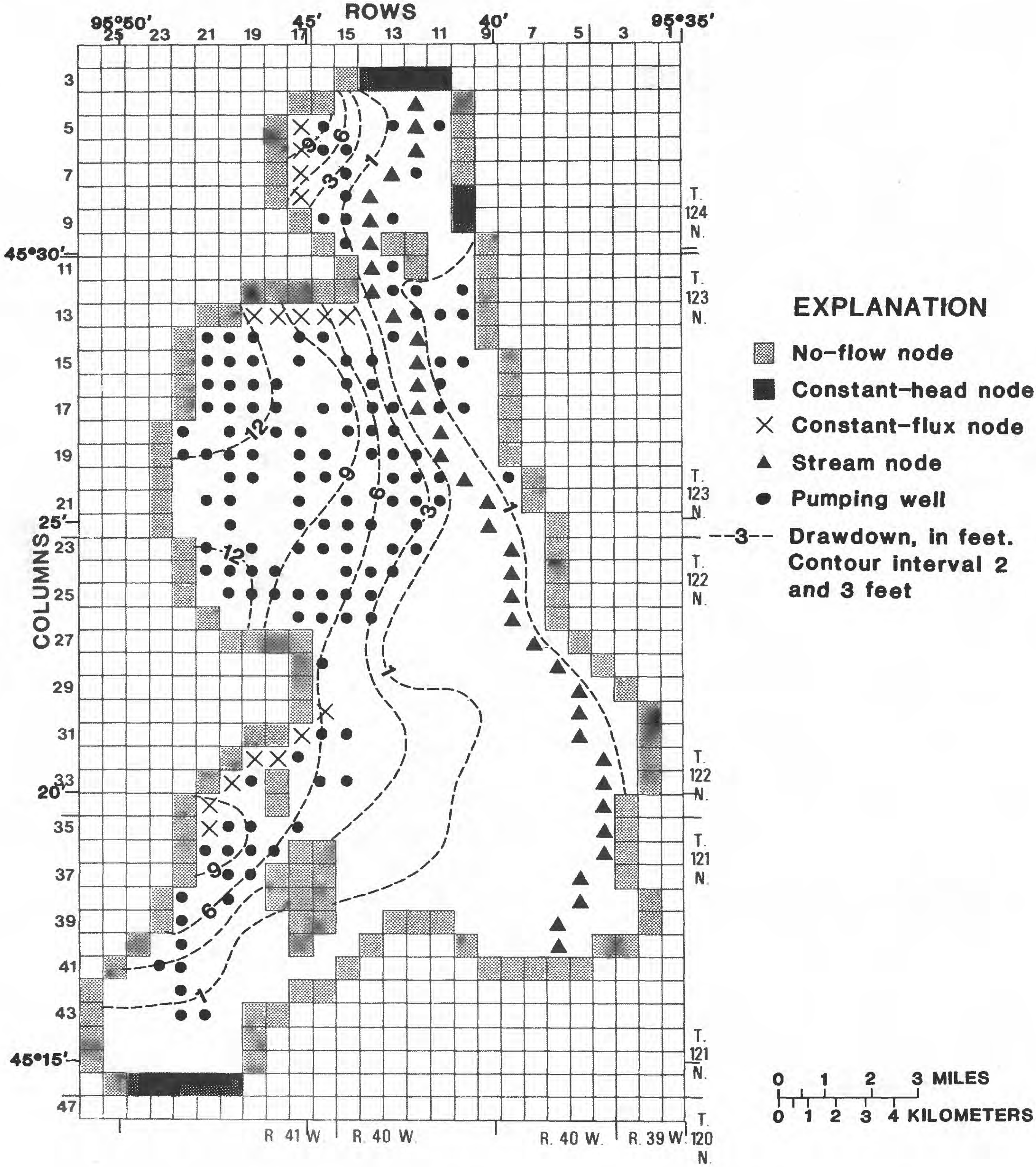


Figure 22.--Computed drawdown for simulation of Plan 4 in the Benson area model

removal of water from aquifer storage constitutes 96 percent of total sources. Leakage from the river constitutes only 3 percent of the total sources but the rate of induced leakage from the river (16.9 ft^3/s) is significant compared to streamflow. Total streamflow reduction computed by the model for plan 4 as compared to the steady-state calibration would be 30.5 ft^3/s (13.6 from the steady-state calibration, table 12 and 16.9 from results of plan 4, table 14). This reduction equals about 35 percent of flow in the Chippewa River at the 50-percent flow duration and about 75 percent of streamflow at the 70-percent flow duration (U.S. Geological Survey gaging-station files, District Office, St. Paul, Minn.). The effect on streamflow would be less if pumping were spread out over more than 30 days.

Comparison of rates of evapotranspiration for plans 1 and 4 (table 14) indicates that a significant quantity of water (about 21 ft^3/s) is recovered from evapotranspiration when water levels are lowered by increased pumpage. However, because of the short duration of pumping, the evapotranspiration recovery rate is less than 4 percent of total pumpage.

During simulation of plans 1 to 4 with the Benson area model, flow from constant-head boundaries was carefully monitored to assure that it was not a significant percentage of total sources. In all simulations, constant-head boundaries supplied less than 3 percent of total sources (table 14). Although this amount is small, model results indicate that water levels would decline slightly in the aquifer near areas where constant-head boundaries were specified in the model. However, the water-level declines probably would be only a fraction of a foot.

Table 15 is a summary of the four development plans and the corresponding model results.

SUMMARY AND CONCLUSIONS

In the northern part of the Pomme de Terre and Chippewa River valleys, glacial melt water deposited outwash consisting of coarse sand and gravel in narrow, steep-sided erosional valleys. The outwash ranges from 0 to 100 feet thick with transmissivities ranging from 0 to 35,000 ft^2/d. Potential well yields of as much as 4,000 gal/min are possible in local areas from properly constructed wells. Farther south, the deposits are fine to medium grained and range from 0 to 80 feet thick with transmissivities ranging from 0 to 25,000 ft^2/d. Potential well yields of 1,500 gal/min are possible in local areas, with the exception of the area southeast of Clontarf along the Chippewa River where potential yields are generally less than 500 gal/min. Regionally, ground-water flow is from north to south, paralleling the drainage of the Pomme de Terre and Chippewa Rivers. Locally, however, water moves from the aquifer boundaries toward the rivers or pumping wells.

Mean annual precipitation is 25 inches, of which about 5 inches enters the surficial aquifer, mostly in March and April. Precipitation accounts for 97 percent of the total inflow to the system under dynamic equilibrium conditions. Leakage from the aquifer to the stream and evapotranspiration represent the major outflows from the aquifer.

Table 15.—Summary of model results for simulation of plans 1 to 4 in the Benson area model

Development plan	Conditions of the simulation	Model results
1	1980 well development (60 wells) Average areal recharge and pumpage Run to dynamic equilibrium (4 years)	Water levels declined less than 2 feet; ground-water discharge to river is less than one-third that for the steady-state simulation. Streamflow reduced by 9.6 ft^3/s.
2	1980 well development (60 wells) Drought: reduced recharge rate; increased pumpage Three-year simulation	Water levels declined 1 to 2 feet regionally and as much as 6 feet along western boundary. River loses water; total streamflow reduction is 26.3 ft^3/s.
3	Maximum hypothetical development (139 wells) Average areal recharge and pumpage Run to dynamic equilibrium (4 years)	Water levels declined 1 to 2 feet regionally and as much as 9 feet in some areas. Streamflow reduced by 12.4 ft^3/s
4	Maximum hypothetical development (139 wells) Drought: reduced recharge rate; increased pumpage Three-year simulation	Water levels declined 1 to 3 feet regionally and as much as 12 feet in some areas. River loses water; total streamflow reduction is 30.5 ft^3/s.

Ground water in the surficial aquifer is a mixed calcium magnesium-sulfate bicarbonate type that is chemically suitable for most uses. In general, the concentration of most constituents analyzed was below limits recommended by the Minnesota Pollution Control Agency for drinking water, but, in local areas, concentrations of manganese, iron, nitrite plus nitrate, and dissolved solids exceed the recommended limits. Dissolved-solids concentrations range from 405 to 581 mg/L. Salinity hazard, as indicated by specific conductance values that range from 580 to 1,000 micromhos per centimeter, approached the high range at several locations.

An analytical model was used to estimate the effect on streamflow of pumpage from the surficial aquifer in a narrow, 50-mile reach of the Pomme de Terre River valley in Stevens and Grant Counties. The model indicates that existing wells pumping at maximum potential yields could reduce streamflow by 55 ft^3/s. Addition of 23 wells also pumping at maximum potential yields, could reduce streamflow by 77 ft^3/s and eliminate flow in the Pomme de Terre River during low base-flow conditions.

In Pope and Swift Counties, digital models were used to simulate flow in the surficial aquifer and investigate the probable regional effects of development. In the Appleton area, model analysis indicates that pumping has lowered water levels as much as 3 feet between 1973 and 1980 and reduced streamflow by about 14 ft^3/s. Additional drawdowns of 1 to 2 feet and as much as 4 feet near aquifer-till boundaries can be expected if 1980 pumping and recharge conditions continue. Simulation of a 3-year drought with increased pumping rates indicates water levels would decline as much as 9 feet near aquifer-till boundaries and streamflow would be reduced about 41 ft^3/s, which is 95 percent of available flow in the Pomme de Terre River at the 55-percent flow duration. Model results also indicate that, during the first year of a drought, the combined pumpage from wells operated during 1980 and simulated in the analytical model and in the Appleton area model, results in computed streamflow diversions that exceed available streamflow by 48 and 60 ft^3/s at the 55- and 70-percent flow duration, respectively. Under such conditions, pumping could not be sustained as simulated unless there was sufficient water in storage in the stream channel or unless streamflow was artificially augmented. In light of these results, state and local water-management groups may wish to investigate the use of upstream lakes and reservoirs to store water for release during the irrigation season when natural flow may become critically low.

In the Cyrus-Benson area, model results indicate that, under 1980 development and average areal recharge, dynamic equilibrium would be reached in less than 4 years and additional drawdown would be less than 2 feet. A 3-year drought coupled with increased pumping from irrigation wells that operated during 1980 would lower water levels as much as 6 feet and reduce flow in the Chippewa River by about 26.3 ft^3/s. At maximum hypothetical development in terms of the number of wells and normal areal recharge, water levels would be lowered as much as 9 feet and streamflow would be reduced by 12.4 ft^3/s. At maximum hypothetical development, drought conditions and increased pumping would lower water levels as much as 12 feet and reduce flow in the Chippewa River by about 30.5 ft^3/s, which equals about 75 percent of available streamflow at the 70-percent flow duration.

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