GROUND-WATER APPRAISAL OF SAND PLAINS IN BENTON, SHERBURNE, STEARNS, AND WRIGHT COUNTIES, CENTRAL MINNESOTA

By G. F. Lindholm

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CECIL D. ANDRUS, Secretary

GEOLOGICAL SURVEY

H. William Menard, Director

For additional information write to:

U.S. Geological Survey
702 Post Office Building
St. Paul, Minnesota 55101

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CONVERSION FACTORS

The following factors may be used to convert the inch-pound units published herein to the International System of units (SI).

Multiply	By	To obtain
inch (in)	25.40	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
acre	.4047	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
gallon per minute (gal/min)	.06309	liter per second (L/s)
inch per year (in/yr)	25.40	millimeter per year (m/yr)
foot per second per foot [(ft/s)/ft]	.3048	meter per second per meter [(m/s)/m]
foot per day (ft/day)	.3048	meter per day (m/day)
foot squared per day (ft^2/day)	.0929	meter squared per day (m^2/day)
cubic foot per second (ft^3/s)	.02832	cubic meter per second (m^3/s)

GLOSSARY

The geologic and hydrologic terms pertinent to this report are defined as follows:

Aquifer - A formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells or springs.

Base flow - Sustained streamflow, composed largely of ground-water discharge.

Drawdown - The vertical distance between the static (nonpumping) water level and the level caused by pumping.

Drift - All deposits resulting from glacial activity.

Evapotranspiration - Water withdrawn by evaporation from water surfaces and moist soil and by plant transpiration.

Ground water - That part of subsurface water that is in the saturated zone.

Hydraulic conductivity - The rate of flow of water transmitted through a porous medium of unit cross-sectional area under a unit hydraulic gradient at the prevailing kinematic viscosity; measured at right angles to the direction of flow.

Ice contact - Stratified drift deposited in contact with melting glacier ice, includes eskers, kames, kame terraces, and features marked by numerous kettles, some being ice-block lakes.

Outwash - Sorted, stratified drift deposited beyond the ice front by meltwater streams.

Saturated zone - Zone in which all voids are ideally filled with water. The water table is the upper limit of this zone, and the water in it is under pressure equal to or greater than atmospheric.

Sorting coefficient - The square root of the ratio of the 75-percentile grain size to the 25-percentile grain size.

Specific yield - The ratio of the volume of water that a saturated rock or soil will yield by gravity to its own volume.

Storage coefficient - The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. In an unconfined aquifer, it is virtually equal to the specific yield.

Surficial aquifer - The saturated zone between the water table and a lower confining body, synonymous with unconfined aquifer.

Till - Unsorted, unstratified drift deposited directly by and underneath glacial ice.

Transmissivity - The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of an aquifer under a unit hydraulic gradient.

Tunnel valley - A trench cut by a subglacial stream whose present surface expression is typically an esker with adjacent elongate lakes.

Water table - That surface in a ground-water body at which the water pressure is equal to or greater than atmospheric.

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ABSTRACT

Surficial-sand aquifers in 960 square miles of central Minnesota have been studied to determine the occurrence, availability, and suitability of the surficial aquifer as a source of water. The aquifer is being increasingly developed for irrigation.

During the drought of 1976, nearly 24,000 acre-feet of ground water was withdrawn for irrigation, more than double that of the previous year. The number of irrigation pumping centers more than doubled from 1975 to 1977. Nearly all water is pumped from drift aquifers, except in the eastern parts of Sherburne and Wright Counties, where Paleozoic sandstone beds are a reliable source.

Physical and hydrologic properties of the surficial aquifer were determined by test augering, pumping tests, and laboratory sieve analyses. The aquifer is predominantly medium to coarse sand with lesser amounts of gravel in much of the study area. The Sauk River valley in Stearns County is nearly 50 percent poorly sorted gravel of irregular thickness. Saturated thickness of sand in the Maine Prairie area locally exceeds 100 feet, and transmissivity exceeds 40,000 feet squared per day. Similar deposits in Sherburne County exceed 80 feet in thickness, transmissivity exceeds 30,000 feet squared per day, and wells theoretically could yield 2,000 to 3,000 gallons per minute. Theoretical well yields of less than 100 gallons per minute can be expected where saturated thickness is less than 20 feet and transmissivity is less than 5,000 feet squared per day. Pumping tests indicate horizontal to vertical ratios of hydraulic conductivity ranging from 2-27:1.

Average annual precipitation is 27 inches, about 8 of which is recharge to the surficial aquifer. Regional ground-water movement is toward the Mississippi River, which transects the area. Tributary streams and lakes act as controls for local flow systems. At extreme low flow in August 1976, mainstem gains in streamflow in the Elk, St. Francis, Sauk, and Mississippi Rivers averaged 0.4, 0.4, 0.2, and 2.5 cubic feet per second per river mile, respectively.

Ground water is of the calcium bicarbonate type and is suitable for most uses. Relatively high nitrate and chloride concentrations occur in a heavily irrigated area in Sherburne County.

Surficial aquifers in Sherburne County and the Maine Prairie area of Stearns County were simulated by two-dimensional digital ground-water-flow models. Calibration was achieved by matching calculated water-table heads and streamflow gains with observed field values. Aquifer responses to pumping stresses under present and hypothetically expanded development were determined for average and below average recharge conditions.

Irrigation withdrawals for 1977 totaling 15.6 cubic feet per second from 96 pumping centers were included in the Sherburne steady-state model. Increasing withdrawals to 52.2 cubic feet per second from 153 pumping centers would lower regional water levels as much as 8 feet within a few years at normal recharge rates.

Irrigation withdrawals in 1977, totaling 2.0 cubic feet per second from 19 pumping centers, were included in the Maine Prairie steady-state model. Increasing withdrawals to 10.8 cubic feet per second from 42 pumping centers would lower regional water levels as much as 18 feet at normal recharge rates.

Both modeled areas will support additional withdrawals, but caution must be exercised because lowering ground-water levels will also lower lake levels and reduce streamflow. In some areas, aquifer dewatering will reduce individual well yields.

INTRODUCTION

Increasing demands for ground water create concern as to the amount available and its quality. Although water use for all purposes is increasing in central Minnesota, the greatest increase is for irrigation in areas of sandy soils. Interest in irrigation is greatest during and immediately after abnormally dry growing seasons, such as that in 1976. According to Minnesota Department of Natural Resources data, the number of irrigation centers more than doubled, and the amount of water withdrawn and acres irrigated nearly doubled from 1975 to 1977. Concern about hydrologic effects of this development was expressed by groups such as the Central Minnesota Regional Development Commission and the respective County Boards. This investigation resulted because of such concern.

Purpose and Scope

The purpose of this study was to describe the occurrence, availability, and quality of ground water in four central Minnesota counties. Objectives were to (1) map the areal extent and thickness of surficial aquifers, (2) describe the occurrence of buried-drift and bedrock aquifers, (3) estimate annual recharge to surficial aquifers, (4) determine hydrologic properties of surficial aquifers, (5) determine effects of and potential for increased development of surficial aquifers, (6) determine water quality, and (7) establish observation wells to monitor effects of future development.

Emphasis is placed upon surficial-drift aquifers because they are the most easily developed and economical source of large quantities of water and are presently the main source for irrigation. Buried-drift and bedrock aquifers are briefly described.

This report summarizes findings and evaluates effects of real and hypothetical stresses placed on the ground-water system. It is intended for use by planners, developers, and water users as a guide for developing ground-water resources.

Location and Extent

The study area (fig. 1) includes 845 mi^2 of sand plain in central Minnesota distributed as follows: Benton County, 75; Sherburne County, 380; Stearns County, 335; and Wright County, 55. An additional 115 mi^2 of ice-contact deposits in Stearns and Wright Counties were also studied, but in less detail. The largest continuous sand plain in Sherburne, southern Benton, and northern Wright Counties, is the western half of the Anoka sand plain, as described by Cooper (1935, p. 39-43). Study boundaries are largely the contacts between surficial sand and till, as shown in figure 1. In western Benton and eastern Stearns Counties, the northern limit coincides with the boundary of a similar study by Helgesen (1973). Van Voast (1971) previously studied a major sand plain in west-central Minnesota that included about 60 mi^2 of southwestern Stearns County. At present, 1980, a sand-plain study is in progress in Todd County, whose southern boundary is the Stearns-Todd County line.

The study area is bisected by the Mississippi River. Part of the eastern boundary of Wright County is the Crow River. Included in Sherburne County is the 48-mi^2 Sherburne National Wildlife Refuge and the 17-mi^2 Sand Dunes State Forest.

Previous Investigations

Winchell and Upham (1888) first summarized the geology and natural history of central Minnesota, including the study area. Leverett (1932) mapped and described the glacial geology in more detail as part of a statewide study. A comprehensive study of the glacial history of east-central Minnesota was made by Cooper (1935). He deciphered a complex glacial history with emphasis on drainage development and sand-plain formation in late Wisconsin time. Farnham (1956) further discussed the origin of the Anoka sand plain. Wright, in the same volume (1956), presents a sequence of glaciation in eastern Minnesota. Schneider's (1961) study of the Pleistocene

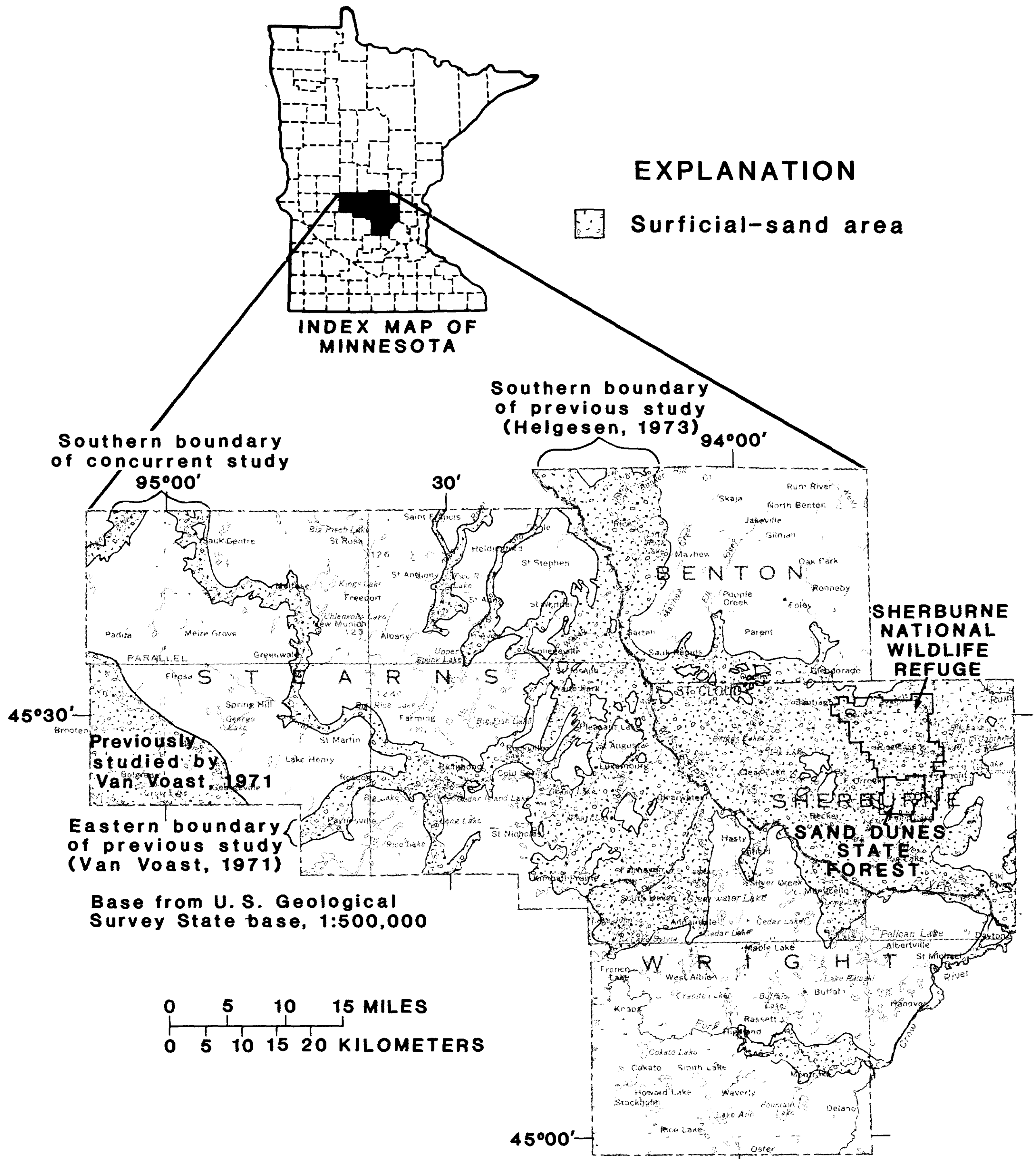


Figure 1.--Location and extent of study area

geology of the Randall region extended southward into northern Benton and Stearns Counties. The most recent summary of Minnesota's glacial history is by Wright (1972). Tunnel valleys were described by Wright (1973).

The earliest discussion of ground water in Wright County is by Hall and others (1911). Allison (1932) presents a general discussion of ground water in Stearns County, and a companion report by Thiel (1947) does the same for Benton and Sherburne Counties. Helgesen and others (1975) evaluated water resources of the Mississippi and Sauk Rivers watershed, which includes most of the study area. The remainder of the area is included in water-resource studies of the Rum River watershed (Ericson and others, 1974) and the Crow River watershed (Lindholm and others, 1974). Helgesen and Lindholm (1977) estimated the amount of water available from wells in the Anoka sand-plain aquifer, which lies partly in Sherburne County.

Methods of Investigation

The study was made over 3-years, beginning July 1, 1976. The area of study was delineated by use of topographic maps, soil survey reports, aerial photographs and field mapping. Augering of 450 test holes helped delineate the thickness of the surficial aquifers and provided information on aquifer composition. Selected aquifer samples collected during augering were sieved to determine particle size. Reported data on 2,700 privately owned wells supplemented test-hole data.

Observation wells for determining changes in water levels were completed in 49 test holes. Five of the wells were installed in 1969 as part of a regional reconnaissance. Five wells completed in surficial-sand aquifers were equipped with recorders. Water levels in other wells were measured biweekly except during December through February, when measurements were made monthly.

Water levels were measured in 240 irrigation wells in March 1978 and in most wells during May and September 1978. Concurrent with these water-level measurements, the discharge of selected streams was measured to determine ground-water contribution to streamflow. A more complete set of discharge measurements was made throughout the study area in August 1976, during extreme drought. Comparative discharge data were collected in 1969 and 1970 during a regional reconnaissance. More than 40 years of continuous discharge data are available for stations on the Mississippi, Sauk, and Elk Rivers.

Staff gages were installed in five lakes to compare lake-level changes with water-level changes in nearby observation wells.

Aquifer tests were made at nine sites to determine local hydraulic properties. Irrigation wells were pumped at four sites, and small-diameter wells installed by the U.S. Geological Survey were pumped at the others.

Chemical analyses were made of 35 ground-water and 18 surface-water samples. Three samples were analyzed for heavy metals and pesticides to determine if land-use practices are affecting water quality. These data will provide a baseline to which future water quality can be compared.

Well and Test-Hole Numbering System

The system of numbering wells and test holes is based on the U.S. Bureau of Land Management's system of subdivision of public lands. That part of the study area east of the Mississippi River is in the fourth principal meridian and base-line system; that part west is in the fifth principal meridian and base-line system. The first segment of a well or test-hole number indicates the township north of the base line; the second, the range west of the principal meridian; and the third, the section in which the well or test hole is located. The uppercase letters, A, B, C, and D, following the section number, locate the well within the section. The first letter denotes the 160-acre tract, the second the 40-acre tract, and the third, the 10-acre tract as shown in figure 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 35.30.10CCB1 indicates the first well or test hole located in the NW$^1/4$ SW$^1/4$ SW$^1/4$ sec.10, T.35 N., R.30 W.

Acknowledgments

The author is grateful to well owners, well drillers, and State agencies for data used in this report. Special thanks are given to irrigators who permitted pumping tests of their wells, to landowners who permitted the drilling of test holes and the installation of observation wells, and to well owners who permitted sampling of their wells. Without the cooperation of many people, the study could not have been made.

GEOLOGY

Rocks are containers of ground water. To understand the occurrence, distribution, and movement of water, the container must be defined. In a broad sense, two contrasting rock types are considered in this report -- bedrock and drift.

Bedrock

Precambrian igneous and metamorphic rocks directly underlie the drift in much of the study area (Sims, 1970), (fig. 3). In the St. Cloud area, granitic outcrops are numerous. Elsewhere, in Benton, Stearns, and in western Wright Counties, gneiss, schist, or argillite underlie the drift. These rocks are typically dense and have low porosity and permeability.

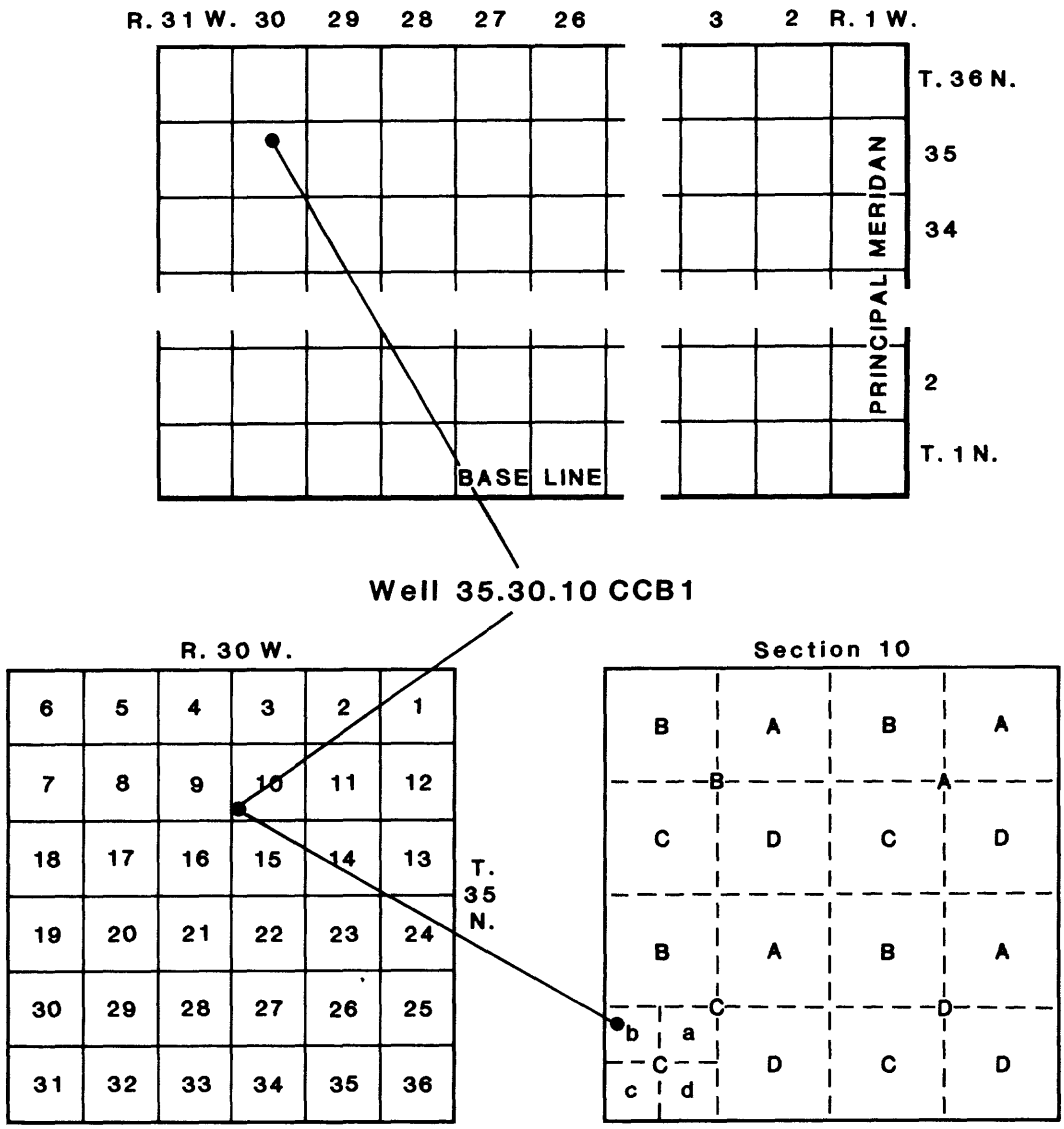


Figure 2.--System of numbering wells and test holes

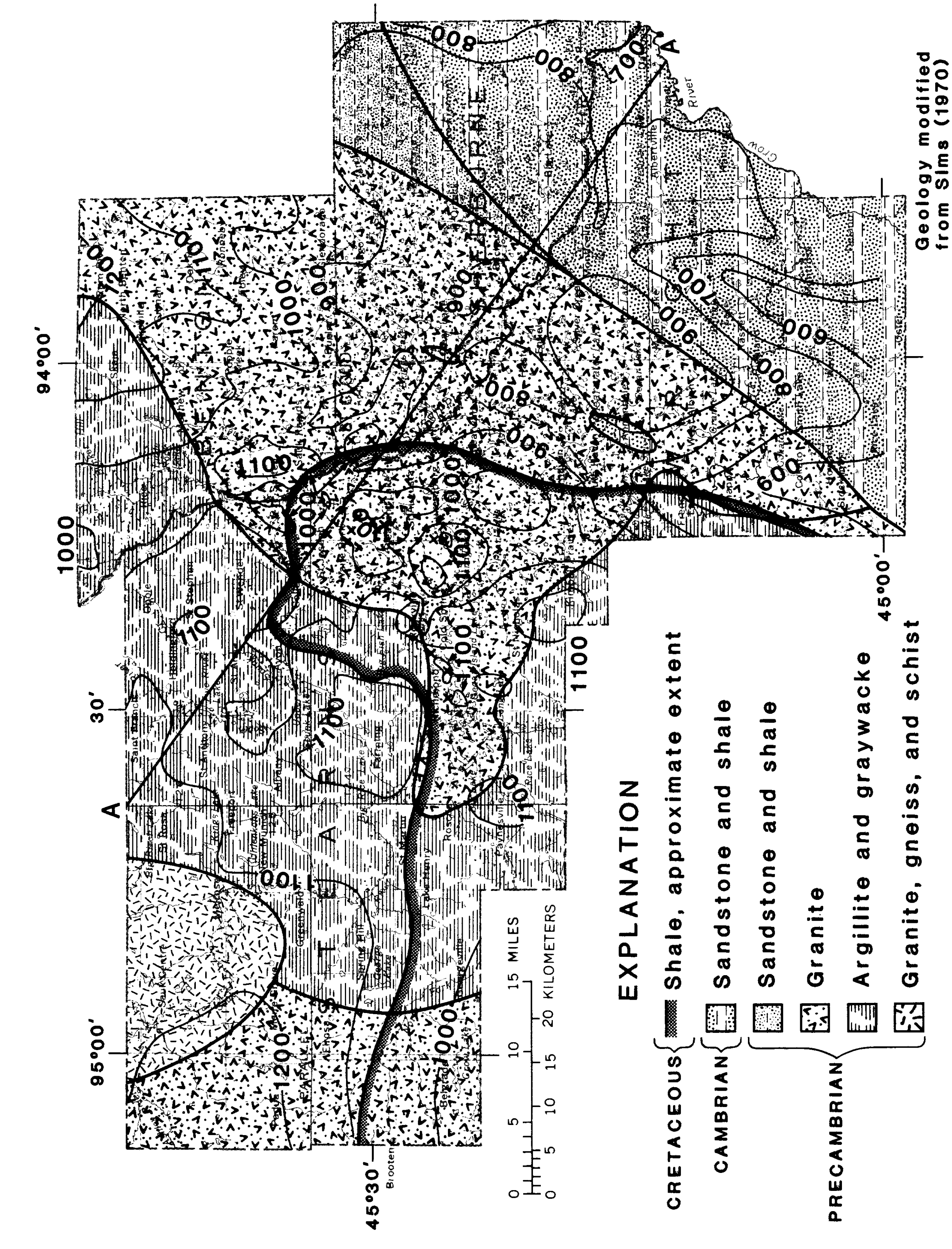
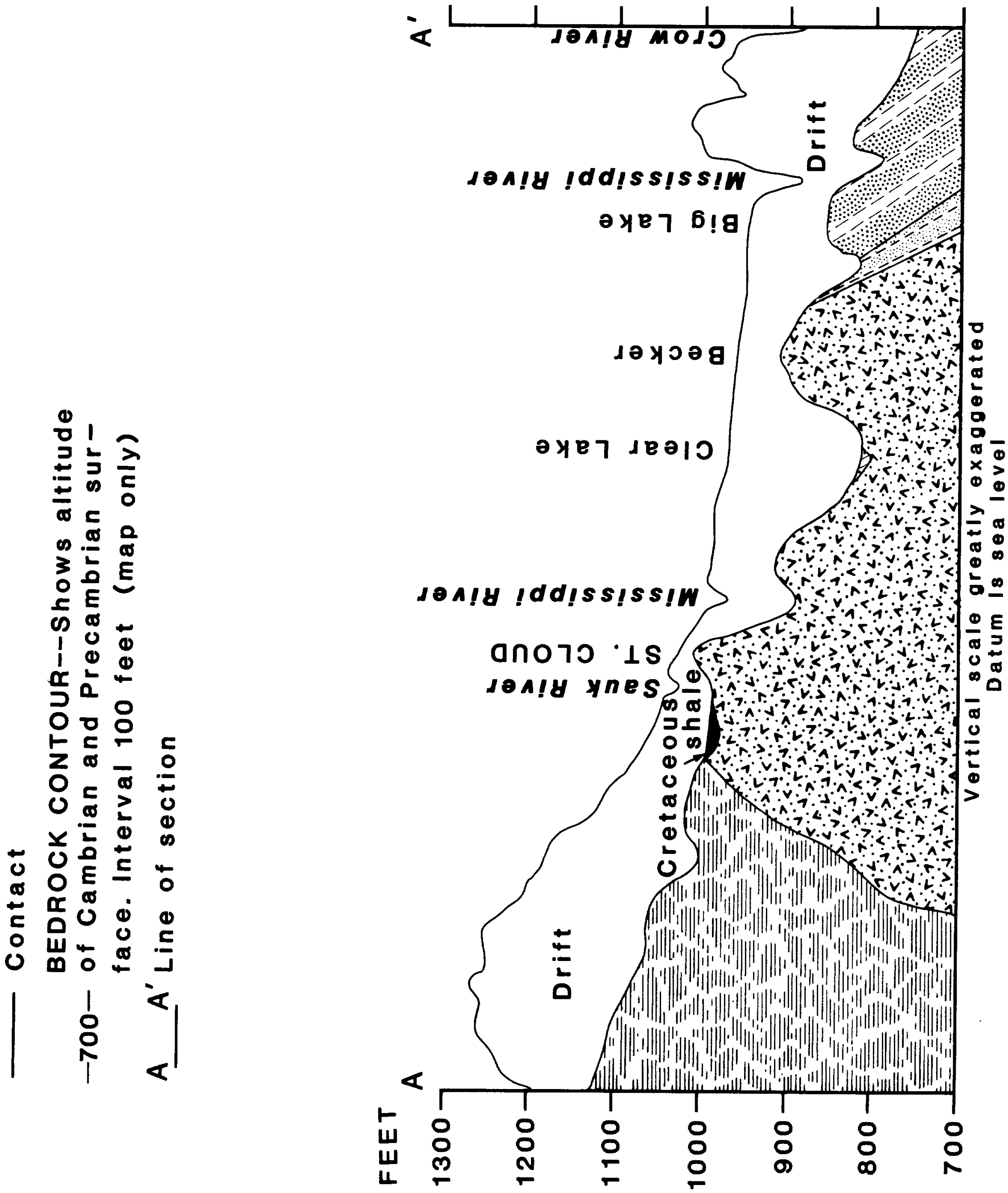


Figure 3.--Map and geologic section



showing bedrock geology

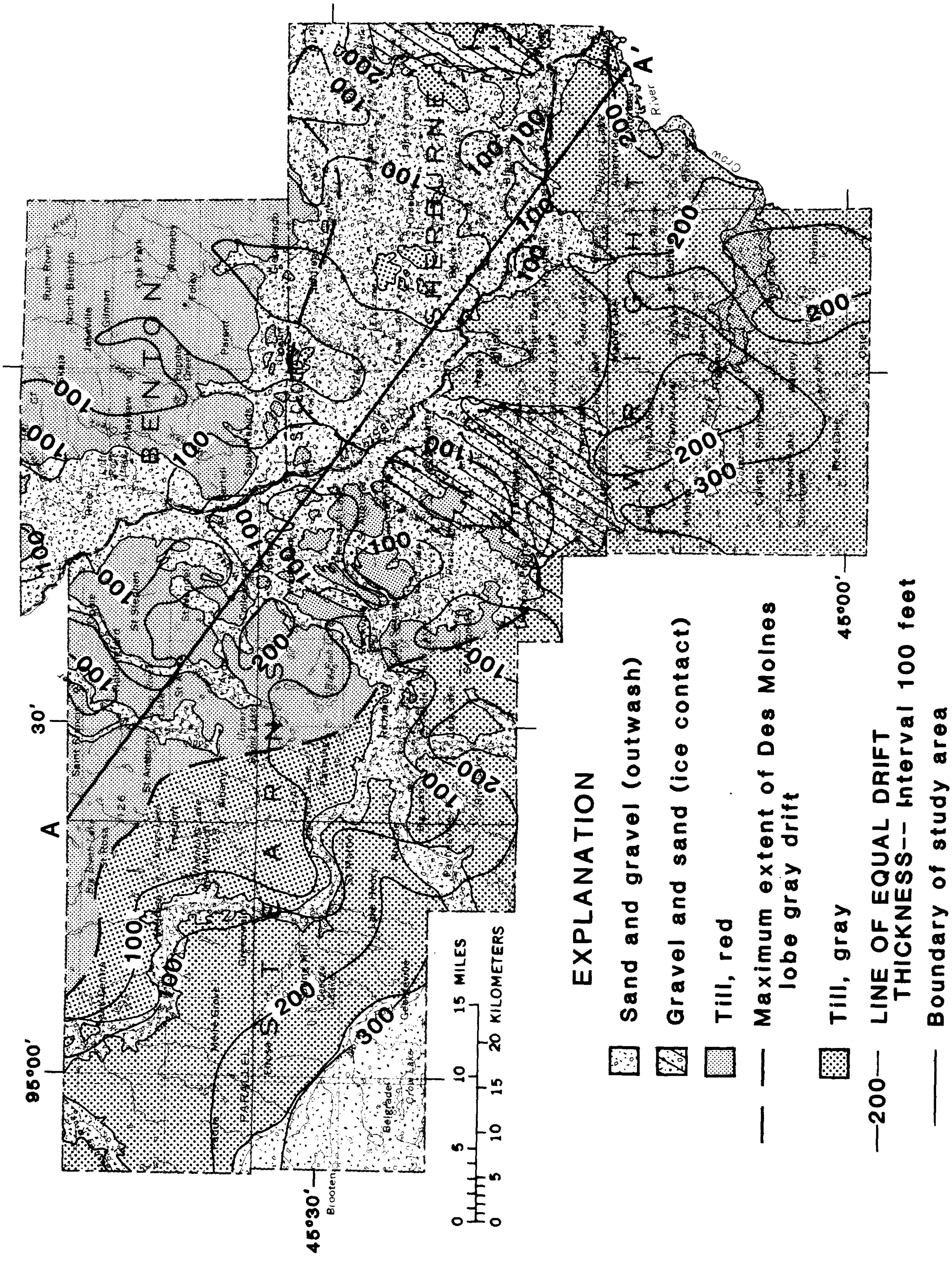
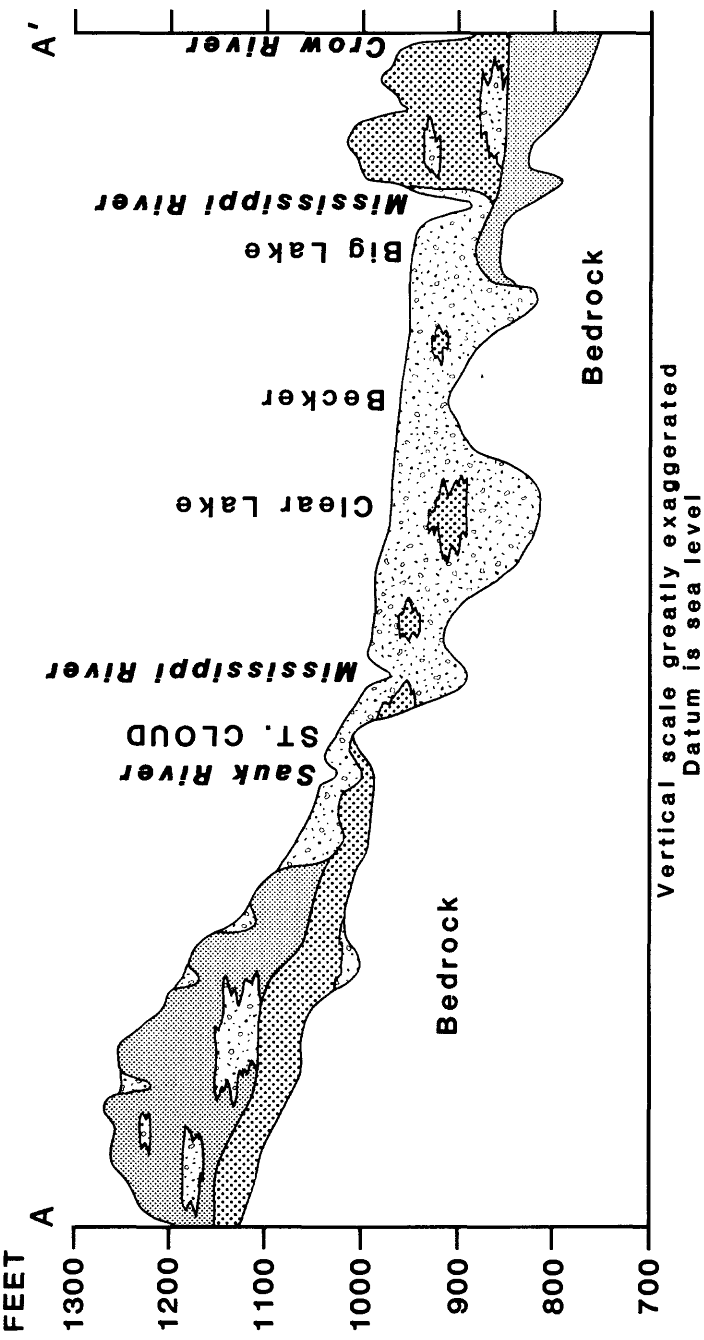


Figure 4.--Map and geologic section



showing surficial geology

Water is available only from fractures, which are generally discontinuous. Wells several hundred feet into the rock may be needed for even a domestic supply of less than 10 gal/min.

Precambrian sandstone and shale directly underlie drift in a small part of northeastern Sherburne County. In eastern Sherburne and Wright Counties, the Precambrian sandstone and shale is overlain by a southeastward-dipping sequence of Cambrian sandstone and shale. Thickness of the Cambrian sandstone and shale wedge ranges from a featheredge on the west to 350 feet in the extreme southeast corner of the study area. In this area, the Cambrian rocks are about 50 percent sandstone. Thickness of the underlying Precambrian rocks is unknown. Outliers of probable Cambrian sandstone are found in a bedrock valley that extends from Annandale northeastward through Clear Lake. Till generally separates overlying drift aquifers from sandstone, although locally they are in direct contact.

Cretaceous deposits, predominantly shale, separate drift from underlying igneous and metamorphic rocks in southern Stearns and western Wright Counties. Thin (less than 1 foot) lignite beds and small amounts of sand occur within the shale sequence. In the subsurface, it is often difficult to differentiate Cretaceous rocks from till. The Cretaceous rocks are discontinuous having a maximum reported thickness of about 70 feet, and are not considered to be an aquifer.

The pre-Cretaceous bedrock surface is irregular, having as much as 180 feet of relief within a mile. A series of southwest-trending erosional valleys are the predominant feature. The valleys acted as controls for Pleistocene drainage and deposition. Wright (1973) mapped tunnel valleys in Sherburne and Wright Counties that coincide with the position of the two largest bedrock valleys.

Drift

Glacial deposits overlie the bedrock in virtually the entire area (fig. 4). Drift exceeds 300 feet in thickness in southern Wright County, where it fills bedrock valleys. Drift in the study area reflects a complex late Wisconsin glacial history. Evidence of pre-Wisconsin Glaciation has not been identified.

Topography of the sand plains is nearly flat to gently rolling in contrast to that of surrounding till areas, where the surface is more irregular. The plain is disrupted in many places by pits that are now lakes or peat-covered wetlands. Streams are entrenched on the sand plains. The Mississippi River, the largest stream, has cut embankments 40 to 50 feet below the upland surface.

Till

Gray sandy, calcareous till deposited by the Wadena Lobe during the Hewitt phase is the lowermost drift unit and is everywhere buried. Its coarse fraction is predominantly dolomite whose source was the carbonate terrane of Manitoba, Canada (Wright and Ruhe, 1965). Overlying Wadena till north and east of a line from Buffalo in Wright County to Albany and the northern Stearns County line is red-brown drift attributable to an advance of ice from the northeast. The till's red color is imparted by oxidized fine-grained metamorphic rocks and pebbles of red sandstone, rocks native to northeastern Minnesota.

The St. Croix terminal moraine, which crosses the study area in a northwesterly direction, was deposited by the Superior Lobe. Between Albany and the eastern Wright County line, the St. Croix moraine is buried by younger gray drift deposited by the Des Moines Lobe that entered the area from the west. The Grantsburg sublobe, an offshoot of the Des Moines Lobe, extended over Wright County, southeastern Stearns County and most of Sherburne County. Drift deposited by the Grantsburg sublobe and the Des Moines Lobe is typically gray calcareous silty till containing fragments of Cretaceous shale from northwestern Minnesota.

Outwash

Outwash deposits (sand and gravel) are associated with the retreat of each ice lobe. Surficial outwash can be readily mapped, but subsurface deposits are generally difficult to delineate. Within the limits of the Superior Lobe (St. Croix moraine), the lowermost part of the surficial outwash is a discontinuous red sand bed. It is most prevalent in the eastern two-thirds of Sherburne County, where it occurs as valley fill. Helgesen and Lindholm (1977), in their study of the Anoka sand-plain aquifer, report that the red outwash is mostly medium sand as thick as 50 feet. The distribution of materials directly underlying surficial outwash is shown in figure 5. In several areas, red lake clay and silt are found in the deepest parts of drift-filled valleys. Gray lake deposits occupy a similar position in Stearns and western Benton Counties. In several apparently isolated spots in eastern Sherburne County, outwash directly overlies Cambrian sandstone. Therefore, locally, the bedrock aquifer is in direct hydrologic connection with the outwash. Such areas are small, so, for practical purposes, the surficial and bedrock aquifers can be considered to be separate units.

Surficial outwash associated with the Des Moines Lobe occurs throughout the area. It is commonly from 20 to 60 feet thick and laterally continuous. Below the water table, the outwash is predominantly gray, turning yellow-brown when oxidized. Helgesen and Lindholm (1977) report that gray outwash of the Anoka sand plain is predominantly medium to very coarse sand.

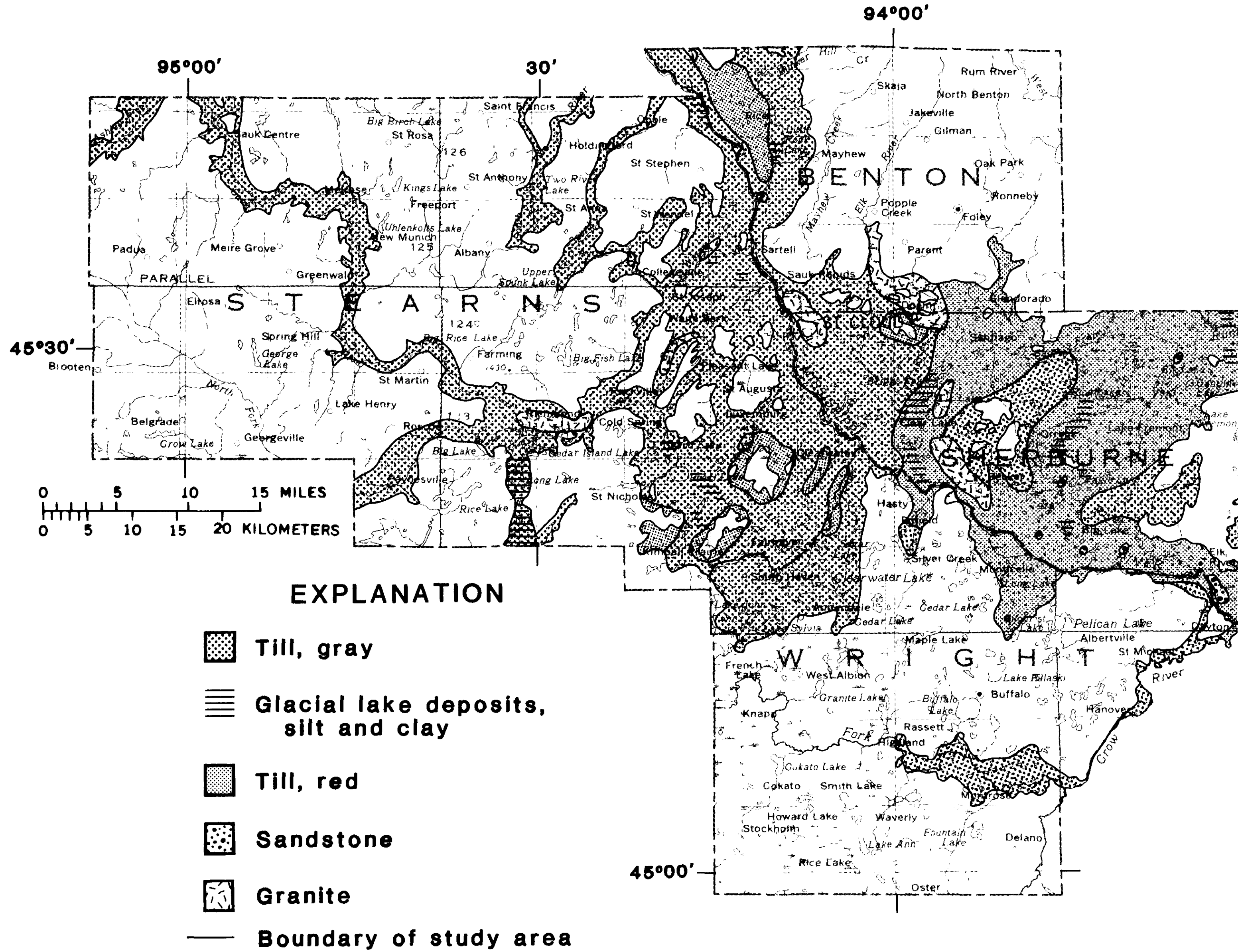


Figure 5.--Distribution of materials directly underlying the surficial outwash

Coarsest materials are in Mississippi valley-train deposits. Where both red and gray outwash are present, the red directly underlies the gray and collectively they constitute a single hydrologic unit.

Buried outwash may occur within or between till sheets. It is commonly the main source of water where surficial outwash is absent. The delineation of buried outwash aquifers is difficult, requiring extensive subsurface information. Generally, the thicker the drift, the greater the probability of penetrating a buried-outwash aquifer. Areas or points of known buried outwash are shown in plate 2.

Generalized stratigraphic relationships of the various drift units are shown in figures 6 and 7.

Ice contact

Gravel and sand of variable thickness, including bodies of till, constitute ice-contact deposits in eastern Sherburne County and parts of Stearns and Wright Counties. Ice-contact areas are characterized by irregular topography including numerous depressions formed by melting ice blocks. As such, their physiography contrasts sharply with that of outwash plains. Because of the general unpredictability of ice-contact deposits and, hence, their water-yielding characteristics, they were studied in less detail than the outwash deposits.

HYDROLOGY

Operating upon and through the geologic framework is a dynamic hydrologic system. Major gain to the system is precipitation, which averaged 27.1 inches during 1949-78. Water loss is about 4.5 inches to streamflow and about 22.6 inches to evaporation and transpiration. Within the total system is a special but inseparable ground-water system. That part of the ground-water system operating within the surficial outwash received emphasis in this study because it is the most readily available source of large quantities of water.

Surficial Aquifer

The top of the surficial aquifer is the water table (pl. 1). Its configuration approximates a subdued replica of the land surface. Depth to the water table is greatest near deeply entrenched surface-water features such as the Mississippi River and the chain of lakes along the Stearns-Wright County line (fig. 8). Water is at or near land surface in wetlands, which are most extensive in northern Sherburne County. The Sherburne National Wildlife Refuge contains a large wetland.

The bottom of the surficial aquifer is the first relatively impermeable unit (till, clay, or bedrock) thicker than 10 feet and of sufficient areal

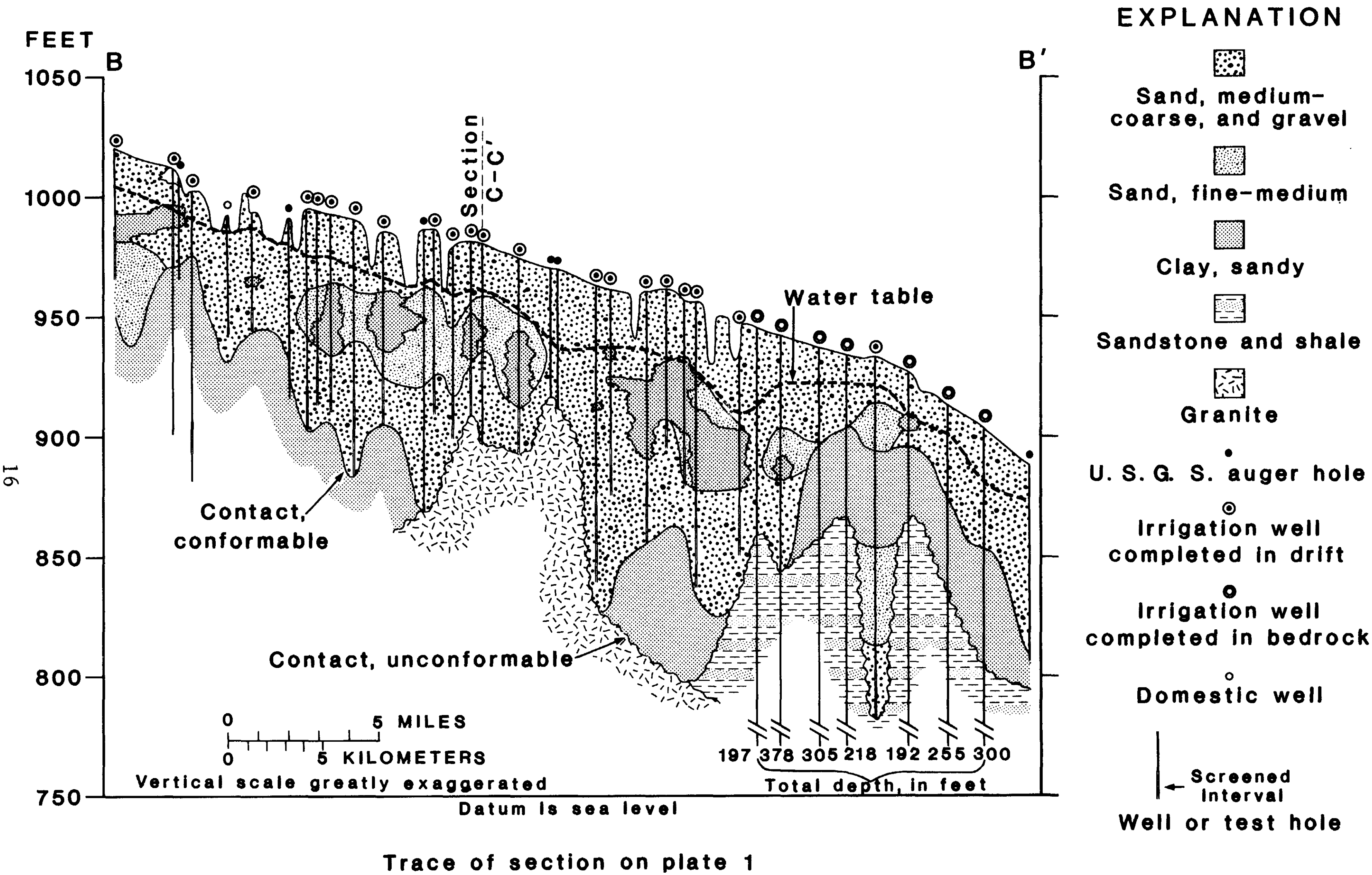


Figure 6.--Stratigraphic relationships of drift deposits, section B-B'

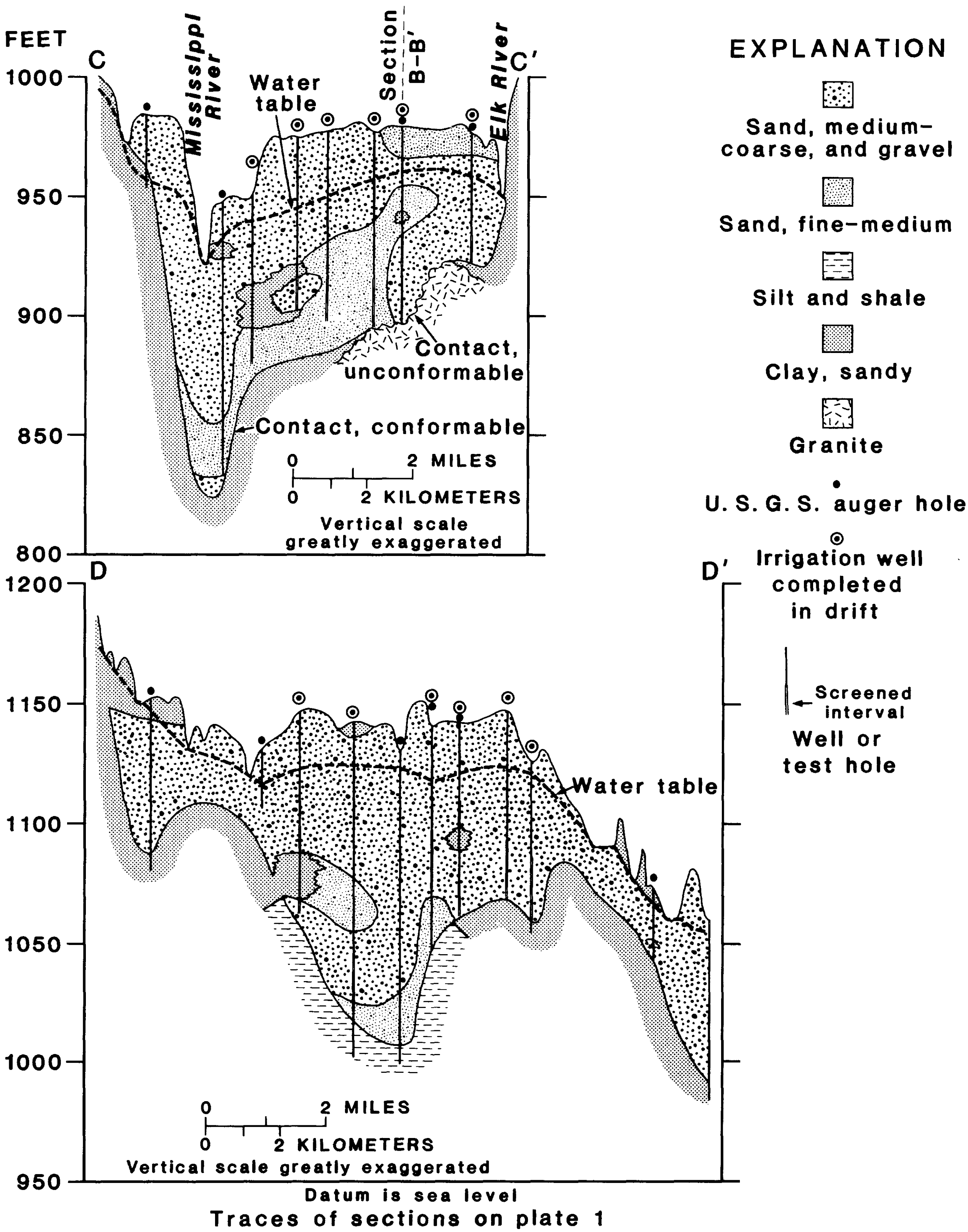


Figure 7.--Stratigraphic relationships of drift deposits, sections C-C' and D-D'

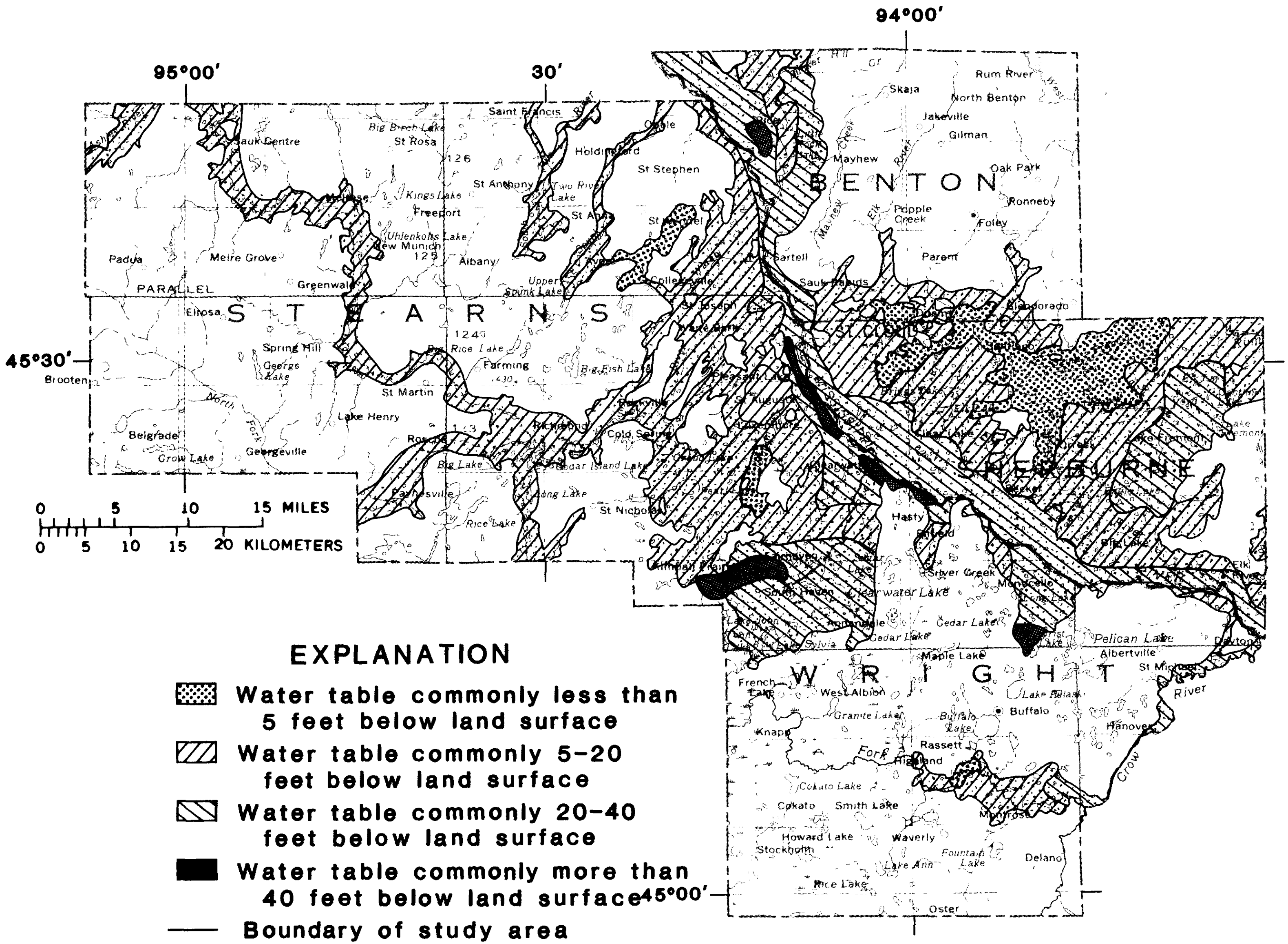


Figure 8.--Depth to water table

extent that regionally it restricts vertical water movement. Aquifer thickness was determined by test augering supplemented by drillers' logs of wells and test holes. Thickness ranges from a featheredge along aquifer boundaries to more than 80 feet in filled valleys in Sherburne County and 100 feet in Stearns County (pl. 2). Where subsurface control is concentrated, clay lenses thicker than 10 feet were delineated within the surficial outwash. Although locally they affect ground-water movement and limit its availability, the regional effect of the lenses is relatively insignificant.

Texture and hydraulic properties

Texture of the outwash was determined by examining test-hole samples and by sieve analysis of selected samples. The coarsest and most poorly sorted aquifer materials are found in the Sauk River valley (fig. 9) where gravel constitutes nearly 50 percent of some samples. The surficial aquifer in the Maine Prairie area of Stearns County is typically coarse to very-coarse well-sorted sand with considerable gravel. It is coarsest near the top, grading to fine sand near the bottom. This fact supports an observation made by Cooper (1935, p. 21) that the aquifer materials "become progressively coarser upward; at the crest pebbles and cobbles predominate." In the Rice area of Benton County, the surficial aquifer is predominantly medium well-sorted sand. Particle-size curves for the Sherburne County part of the Anoka sand plain show considerable variation in aquifer materials, ranging from fine well-sorted sand to very coarse relatively poorly sorted sand containing up to 50 percent gravel. The coarsest materials are Mississippi River valley-train deposits. Typically, they are well-sorted coarse sand, slightly coarser with depth. Aquifer materials are typically clean, less than 10 percent being finer than sand size (silt or clay), most less than 5 percent.

Hydraulic conductivity and transmissivity are indicators of an aquifer's ability to yield water to wells. Transmissivity is the product of hydraulic conductivity and saturated thickness. Variations in transmissivity reflect differences in aquifer thickness, texture, sorting, and quantity of materials finer than sand size. Storage coefficient is an indicator of an aquifer's ability to store or release water. Aquifer tests were done to determine hydraulic properties. Four tests were made at the sites of irrigation wells (12 to 16-inch diameter) having yields of several hundred gallons per minute and periods of pumping as long as 66 hours. Five additional tests were made at the sites of small-diameter ($1^1/4$-inch diameter) wells having yields less than 50 gal/min, and periods of pumping less than 6 hours long. Small-yield tests were made in areas where irrigation wells were not available and in areas where the aquifer is thin and (or) fine-grained. Tests were analyzed by the type-curve method of Boulton (1963) and by distance-drawdown methods (Lohman, 1972). Test-site locations are shown on plate 3, and results are tabulated in table 1.

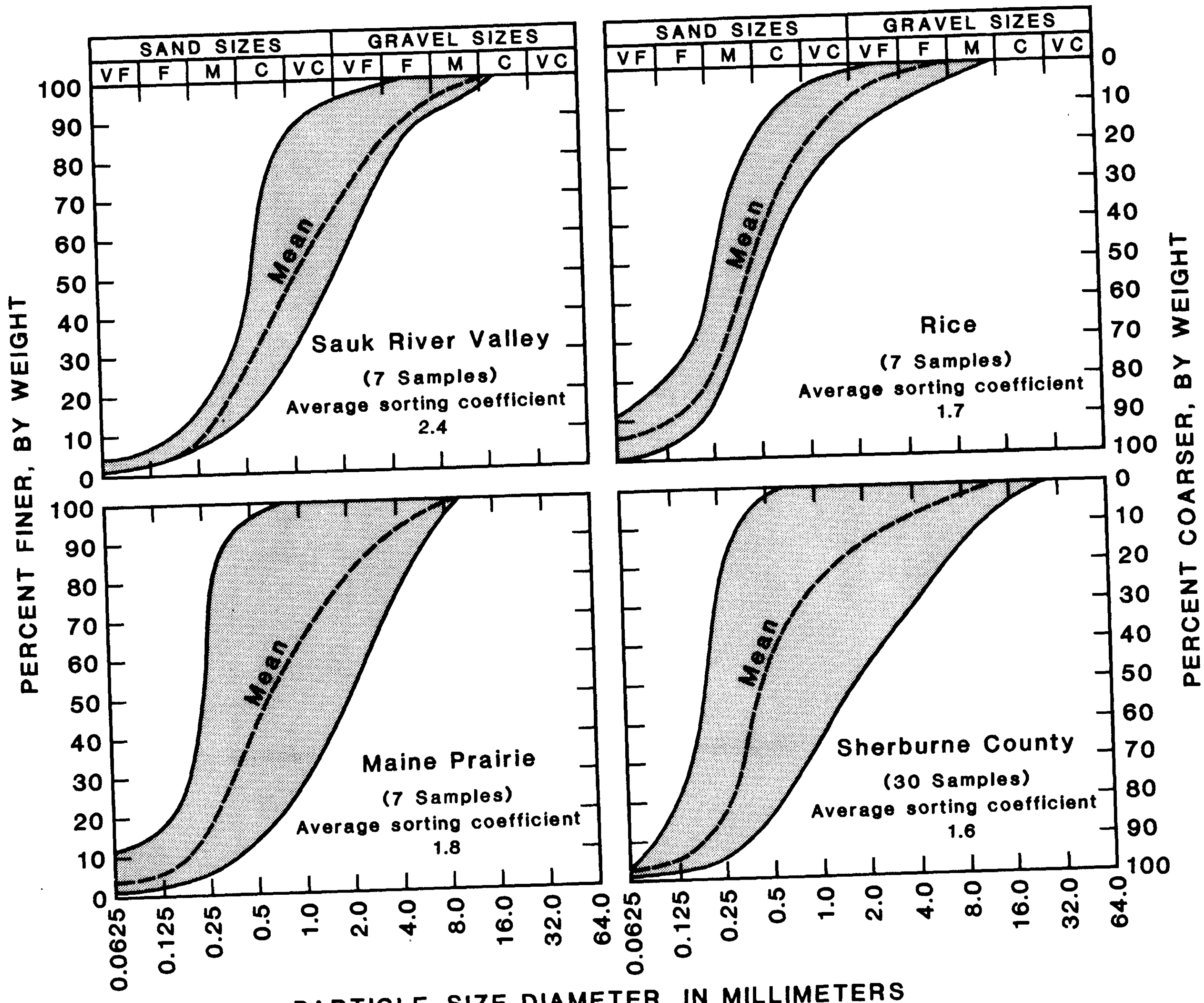


Figure 9.--Range in particle-size distribution of surficial outwash materials

Table 1.--Hydrologic properties of the surficial aquifer determined by aquifer tests

Location	Lithology	Saturated thickness (ft)	Pumping rate (gal/min)	Length of test (hrs)	Trans-missivity (ft^2/day)	Average hydraulic conductivity (ft/day)	K_h/K_z*	Storage coefficient
34.29.23ADA	Sd, m-vcs, well sorted, clean	42	830	66.6	17,000	400	2-3:1	0.32
34.29.36DCC	Sd, m-vcs, well sorted, clean	25	410	48	10,500	420	5-18:1	.29
35.26.15DBB	Sd, f-m, well sorted, clean	55	45	4.5	7300	130	-	.01
35.27.29DBB	Sd, m-vcs, poorly sorted, dirty	15	18	5	3200	210	-	-
35.19.12AAA	Sd, vf-f, well sorted, clean	30	20	4.5	900	30	-	-
38.31.17CDD	Sd, m, well sorted, clean	44	745	36.5	7600	170	21-27:1	.21
122.28.18BCC	Sd, m-vcs, well sorted, clean	68	550	11	44,000	650	2-6:1	.12
123.31.13AAC	Sd, m-vcs, and gvl; fair sorting, clean	28	53	6	16,000	570	-	.14
124.32.25DAC	Sd, cs-vcs, and gvl; poorly sorted, dirty	21	41	5	10,000	480	-	.13

* Ratio of horizontal to vertical hydraulic conductivity (Lohman, 1972)

Only horizontal hydraulic conductivity, the primary direction of ground-water movement, was determined in the field. Average conductivity, as determined by pumping tests, ranged from 30 ft/day for well-sorted fine-grained sand to 650 ft/day for well-sorted very coarse sand. Poor sorting and an increase in the clay-size fraction reduce hydraulic conductivity. The ratio of horizontal to vertical hydraulic conductivity was determined by Lohman's method (1972). Although stratification is to be expected in outwash deposits, in some areas it is relatively insignificant hydraulically as suggested by the small horizontal to vertical conductivity ratios. Higher values obtained are comparable to those for outwash deposits in Wisconsin, as determined by Weeks and others (1965). Estimates of transmissivity made from specific-capacity data (Theis and others, 1963) for irrigation wells were from 50 to 60 percent of the values obtained from pumping tests. Calculated well efficiencies from 60 to 80 percent account for a large part of the discrepancy.

Values for storage coefficient are within the expected range of 0.05 to 0.30 for water-table aquifers. Those for short tests are probably minimum values that would become higher if the period of pumping were extended.

Test holes drilled at pumping-test sites provided site-specific information on thickness and texture of various aquifer units. On the basis of information from aquifer tests and from analysis of samples collected during test drilling, hydraulic-conductivity values were assigned to different aquifer materials. Estimates of hydraulic conductivity were made for each textural unit in each test hole. Ranges of hydraulic conductivity for various size fractions are listed in table 2. Well-sorted, clean samples were assigned values at the upper end of each range. Conversely, poorly sorted samples containing silt and clay were assigned values at the lower end. Values used are in accordance with those used by Larson (1976) and Helgesen (1977) for similar studies in other parts of Minnesota. For each test hole, a summation of estimated hydraulic conductivity multiplied by the saturated thickness of each textural unit gave an estimated value of transmissivity. Areal variations in transmissivity of the surficial aquifer are shown in plate 3.

Theoretical well yields

Knowing saturated thickness and transmissivity, it is possible, making certain assumptions, to calculate theoretical optimum well yields. Assumptions made are:

1. The aquifer is homogeneous and of infinite areal extent.

2. The well is open to the full saturated thickness of the aquifer, is 100-percent efficient, and has a diameter of 12 inches (most irrigation wells in the study area are 12 inches in diameter).

Table 2.--Hydraulic conductivity of surficial-outwash materials

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

3. Drawdown after 30 days of continuous pumping is equal to two-thirds of the original saturated thickness of the aquifer. For unconfined aquifers, this drawdown results in optimum operating efficiency (Johnson, 1966, p. 107-108).

4. Storage coefficient of the aquifer is 0.20.

Theoretical well yields were determined by the nonequilibrium equation of Theis (1935). Adjustments were made for dewatering of the aquifer by the method of Jacob (1944).

Theoretical well yields (pl. 4) are relative and not absolute unless all stated assumptions are met. Local differences can be expected because seldom, if ever, are all the assumptions met. Proximity of a well to a stream, lake, or impermeable boundary may significantly affect yield. Plate 4 should, therefore, be used only as a regional guide for approximate well yields.

Largest yields can be expected where sand- and gravel-filled valleys cut into the underlying till or bedrock. In much of the Maine Prairie area of southeastern Stearns County, 3,000 gal/min or more is theoretically possible from individual wells. The surficial outwash aquifer in the Sauk River valley is typically coarse grained, but less than 30 feet thick. Although local thicknesses may be twice that amount, aquifer extent and, therefore, yield estimates would require detailed local test drilling. In the St. Cloud area, where the highly irregular granite surface is at or near land surface in many places, the surficial aquifer is generally less than 20 feet thick. Theoretical well yields are correspondingly low, less than 100 gal/min. Exceptions occur where outwash-filled valleys cut into the granite surface. Individual wells in one such valley north of St. Joseph, defined on the basis of domestic wells, can be expected to yield 2,000 gal/min or more. That valley can be traced northeastward into Benton County, where it passes under Little Rock Lake. Largest yields in northern Benton County are from outwash-filled valleys that are southern extensions of valleys mapped in Morrison County by Helgesen (1973).

Largest theoretical well yields in Sherburne County are from a series of northeastward-trending outwash-filled valleys. The easternmost valley underlies the Sherburne National Wildlife Refuge and Sand Dunes State Forest. Although not included in present development plans, large quantities of ground water are available in parts of these areas. At present, water is being impounded on the Refuge, and concern is being expressed about effects of raising water levels rather than lowering them. The valleys extend south of the Mississippi River into Wright County. The two largest valleys are separated by a granite high, centered near Becker, that limits outwash thickness and, therefore, well yields.

The surficial aquifer in the area of ice-contact deposits, along the Stearns-Wright County line, is discontinuous and poorly defined. At least locally, yields of 1,000 gal/min are theoretically possible.

Surficial-Aquifer System

The water-table map on plate 1 indicates the general direction of water movement at that surface in May 1978. The map is based on water-level measurements in 240 irrigation wells and the observation well network plus information obtained during project test drilling. The vertical component of ground-water flow is defined by head differences in wells completed at different depths. As shown on plate 1 and figure 10, the Mississippi River is the major regional control on ground-water movement. Ground water moves both horizontally and vertically to the Mississippi and, to a lesser degree, the Elk River; vertical components are strongest near the rivers. Other tributary streams, lakes, and wetlands are controls for smaller, local flow systems. In sand plain areas, many streams and lakes are in direct hydraulic connection with the surficial aquifer; that is, they are a local expression of the water table. The degree of connection is a function of the hydraulic conductivity of the aquifer, hydraulic conductivity of the stream or lake bottom sediments, and thickness of the bottom sediments. The amount of water leaving the aquifer and entering streams was determined by streamflow measurements during base flow.

Over a period of many years, inflow to and outflow from the system are approximately equal. Differences may occur during any one year, depending upon climatic variations and applied stresses. Discussion of inflow and outflow items follows.

Precipitation and recharge

Precipitation and recharge to the surficial aquifer are closely related. Average annual precipitation at the National Weather Service St. Cloud Airport Station during 1949-78 was 27.1 inches, of which about 17.9 inches, or 66 percent fell during the May-September growing season. The precipitation frequency curve (fig. 11) shows the recurrence interval of annual precipitation at St. Cloud. Variations in amount of precipitation during successive years were demonstrated during the study. In 1976 and the first half of 1977, a drought occurred. Annual precipitation in 1976 (14.3 inches) plots below the described normal line, indicating that its recurrence is greater than the 50-year recurrence interval. To determine the 1976 recurrence, data plots must be extrapolated from figure 11. Recovery from the drought was rapid because precipitation in 1977 was well above normal, and in 1978 it was just above normal.

In areas of sandy soils, snowmelt and rainfall readily infiltrate the unsaturated zone surface and recharge the ground-water system, sustaining or raising ground-water levels. Conversely, levels decline when recharge

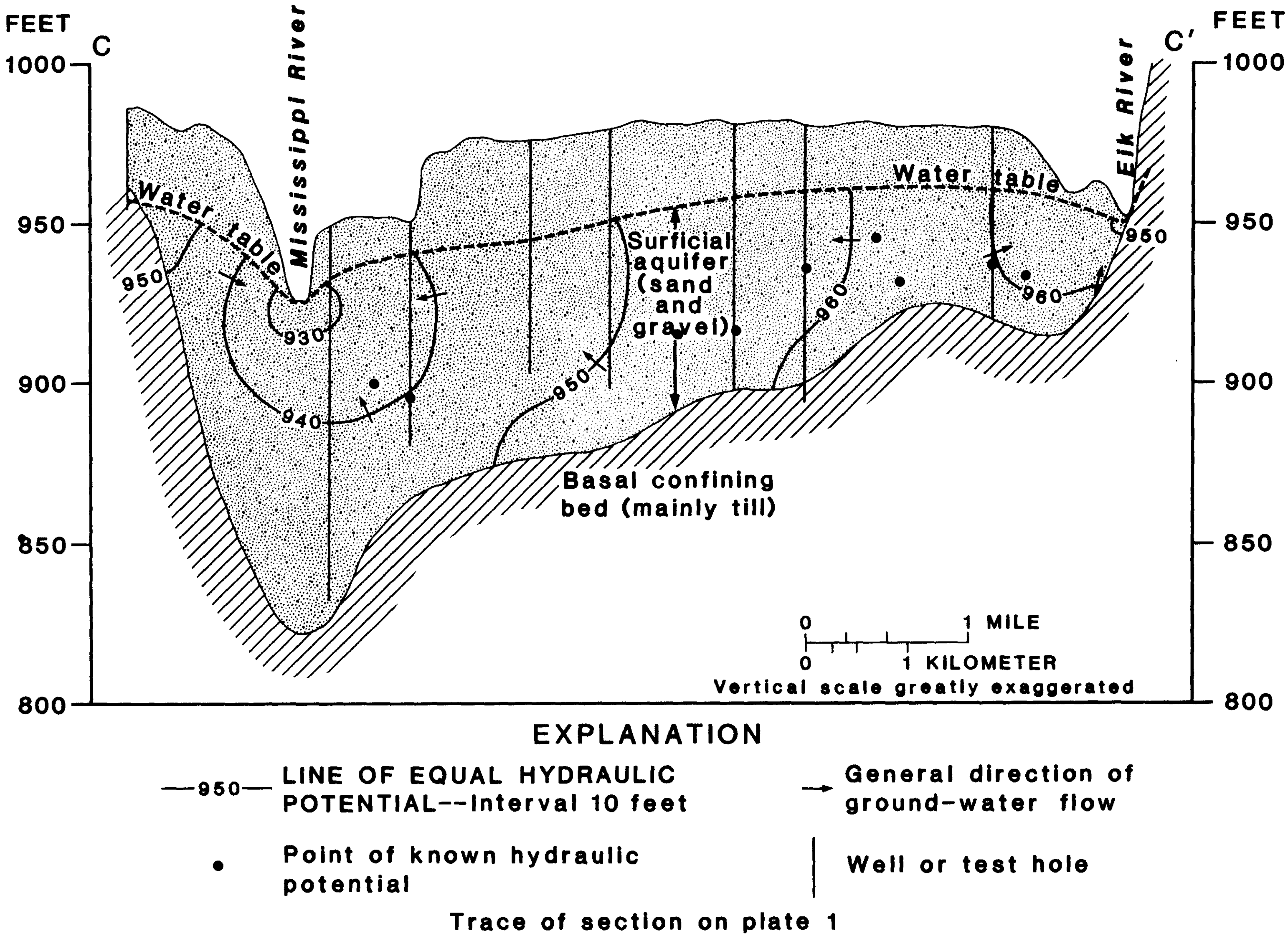


Figure 10.--Section illustrating flow through surficial aquifer

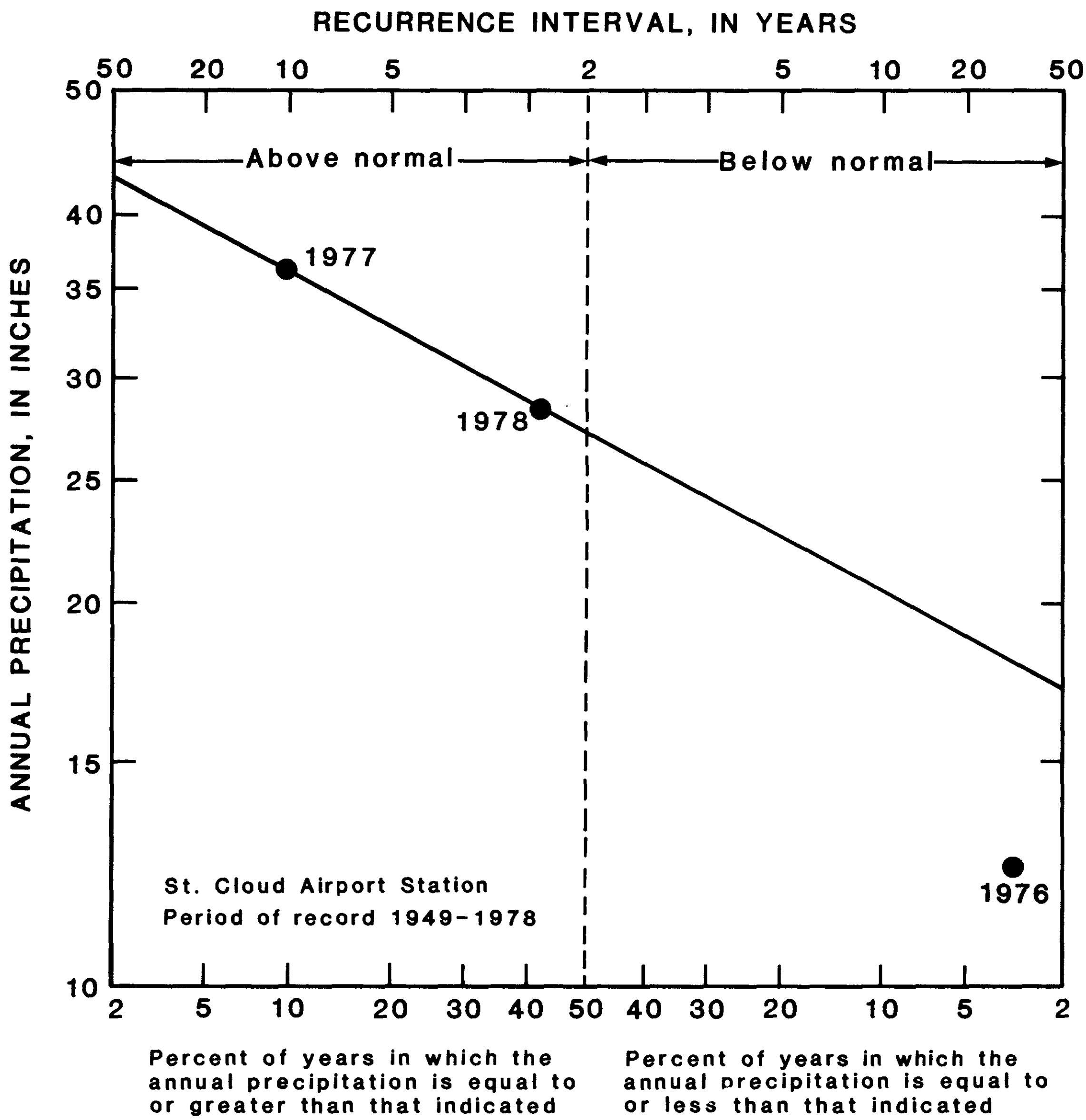


Figure 11.--Precipitation-frequency curve based on data from the National Weather Service St. Cloud Airport Station

is insufficient to offset losses. The method of determining recharge is shown in figure 12. Recharge is usually greatest in the spring as a result of snowmelt and spring rain. During the summer, most precipitation is lost as evaporation or as transpiration by plants and little or no recharge takes place. After frost in the fall, transpiration demands are greatly reduced, and, if precipitation is sufficient, a second recharge period occurs. Time and amount of precipitation are important factors in determining time and amount of recharge. Change in ground-water storage during a 1-year period is demonstrated in figure 12. Over a long period of time, such losses or gains tend to equalize.

Precipitation relates to recharge of the surficial aquifer, as shown in figure 13. Recharge is considered to be the average for observation wells 33.27.21CAA near Big Lake, 35.26.15DBB near Princeton, 35.29.28ABC near Clear Lake, and 124.28.21CDA near St. Cloud. Over the 9-year period, 1970-78, mean annual precipitation was 26.5 inches and mean annual recharge was about 8 inches (fig. 13A). The correlation between precipitation and recharge (fig. 13B) can be used to estimate the amount of recharge before 1970 from precipitation data. From this relationship, it was determined that mean annual recharge for the 30-year period, 1949-78, was also about 8 inches.

The relationship of precipitation to ground-water levels was used to determine how water levels measured in May 1978 compared to long-term average water levels. The water-table map is based on May 1978 measurements. A cumulative-departure curve of precipitation was constructed for 1949-78 (fig. 14). The curve's shape for 1969-78 is similar to the shape of ground-water hydrographs (fig. 15) for the same period. The long-term mean ground-water level for each well was estimated by visual correlation of the precipitation cumulative-departure curve and the hydrograph. The comparisons indicate that water levels in May 1978 were within a foot of the mean for 1949-78.

Streamflow

Most surface water drains to the Mississippi River; major tributaries are the Platte, Sauk, and Elk Rivers. A small area in northeastern Sherburne County is drained by the Rum River. The difference between streamflow entering and streamflow leaving the study area during extended dry periods and the winter is largely ground-water discharge to the streams. Values for selected stations listed in figure 16 are for summer base-flow periods in August 1969, 1970, and 1976. At times of measurement, stresses were at a maximum, as evapotranspiration demands were high and withdrawals for irrigation were being made from both ground-water and surface-water sources. Flow in the Elk River near Big Lake was at 78, 88, and greater than 99 percent, respectively, on the flow-duration curve (fig. 17). Discharges listed, therefore, represent very low flows that might be expected less than 25 percent of the time. Uniform discharges at station 05270500, Sauk River near St. Cloud, are due to regulations at a dam just above the station.

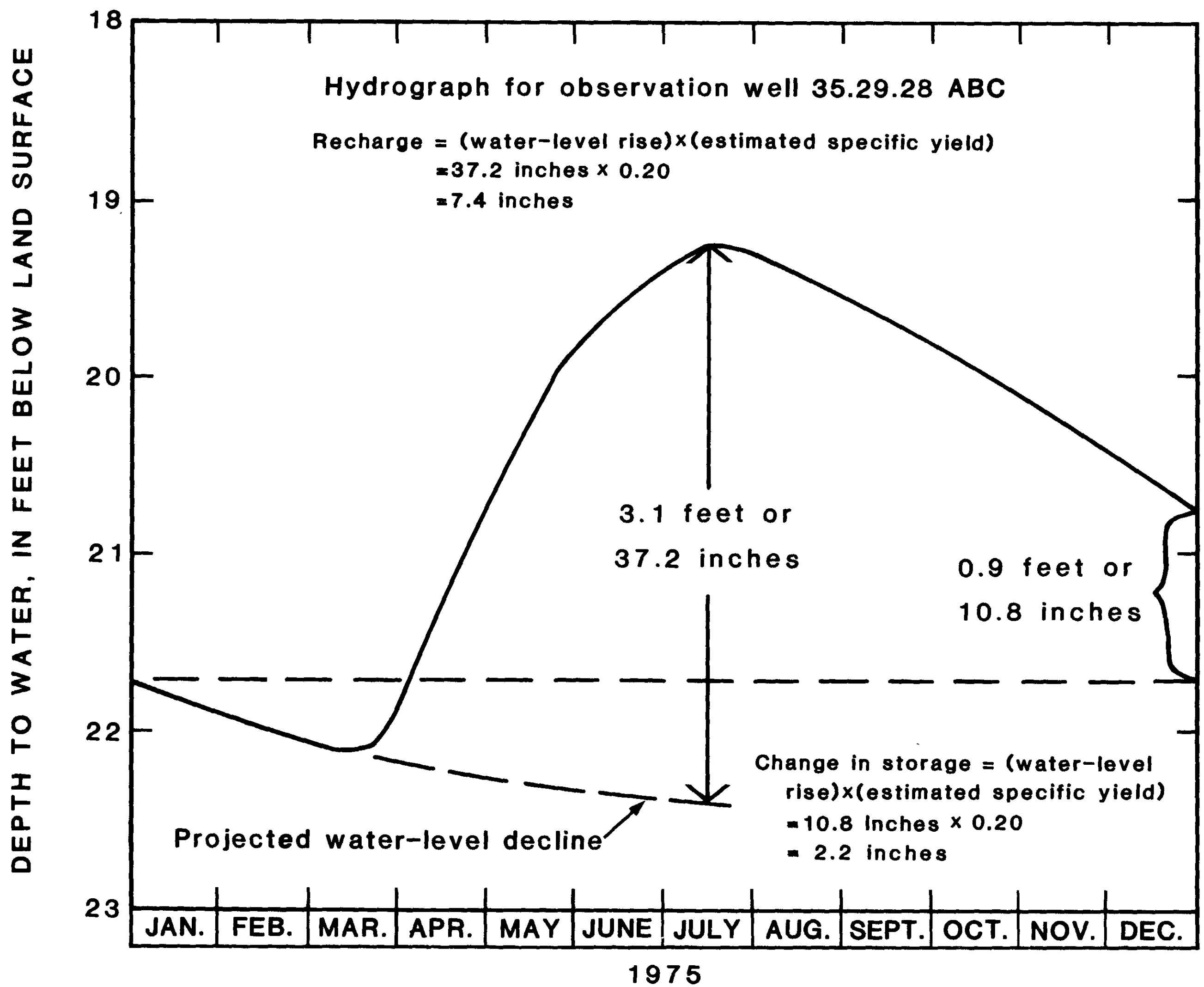


Figure 12.--Method of estimating recharge to the surficial aquifer

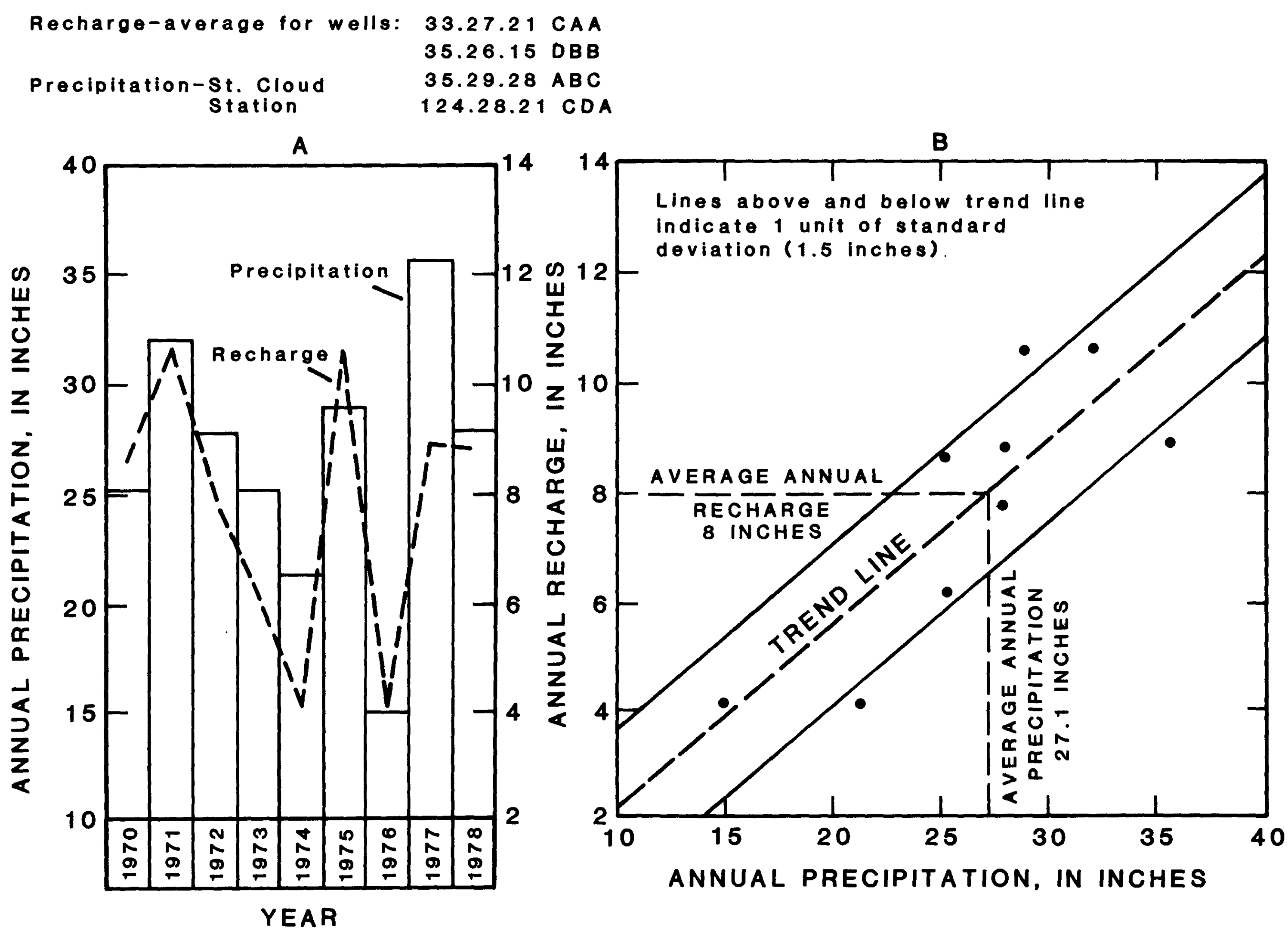


Figure 13.--Relationship between precipitation and recharge to the surficial aquifer

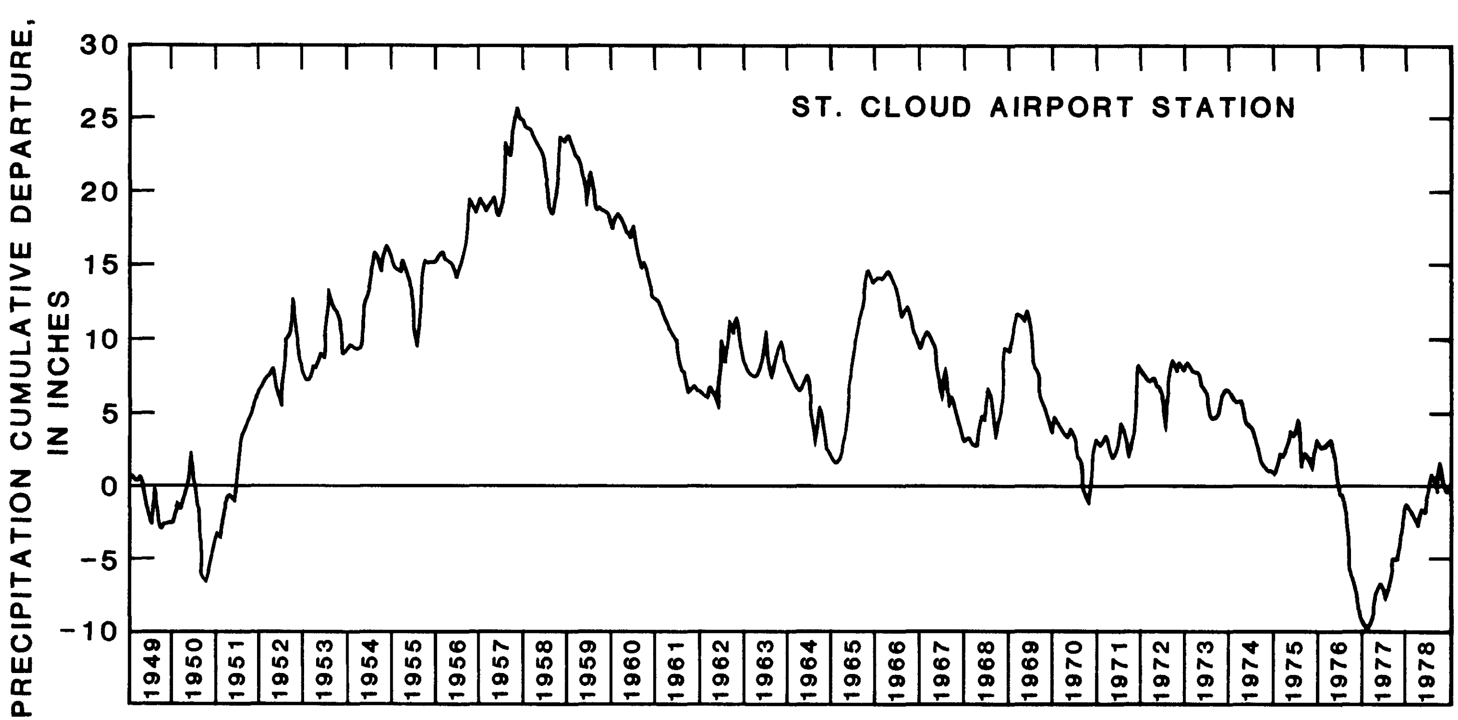


Figure 14.--Precipitation cumulative departure for 1949-78

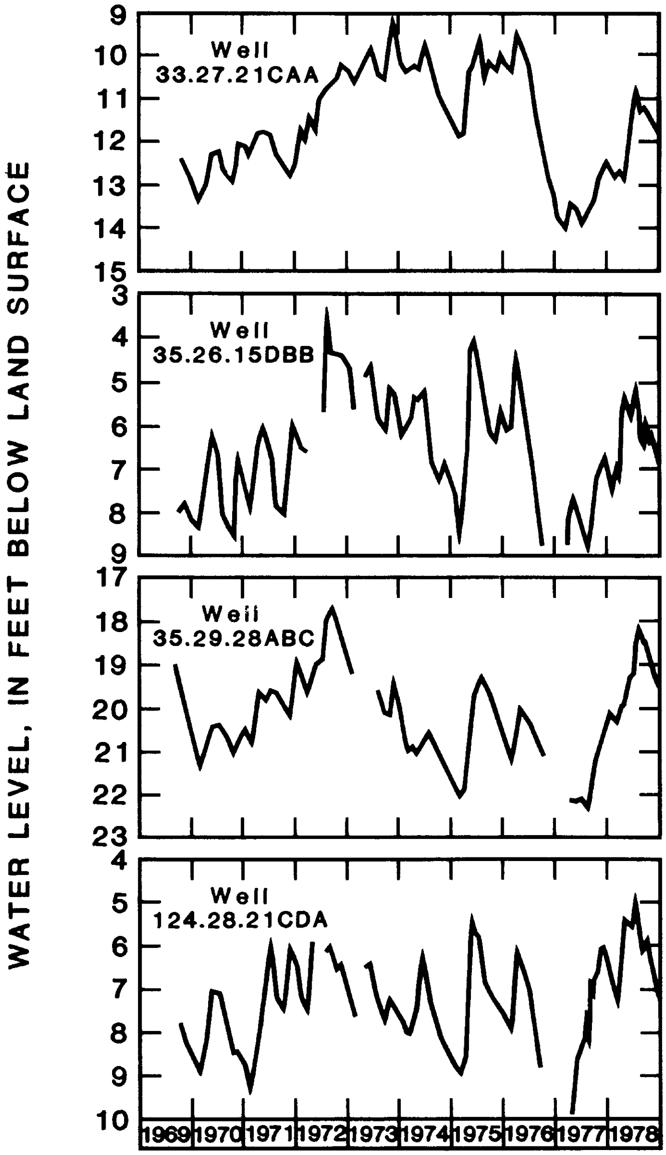


Figure 15.--Hydrographs of ground-water levels for 1969-78

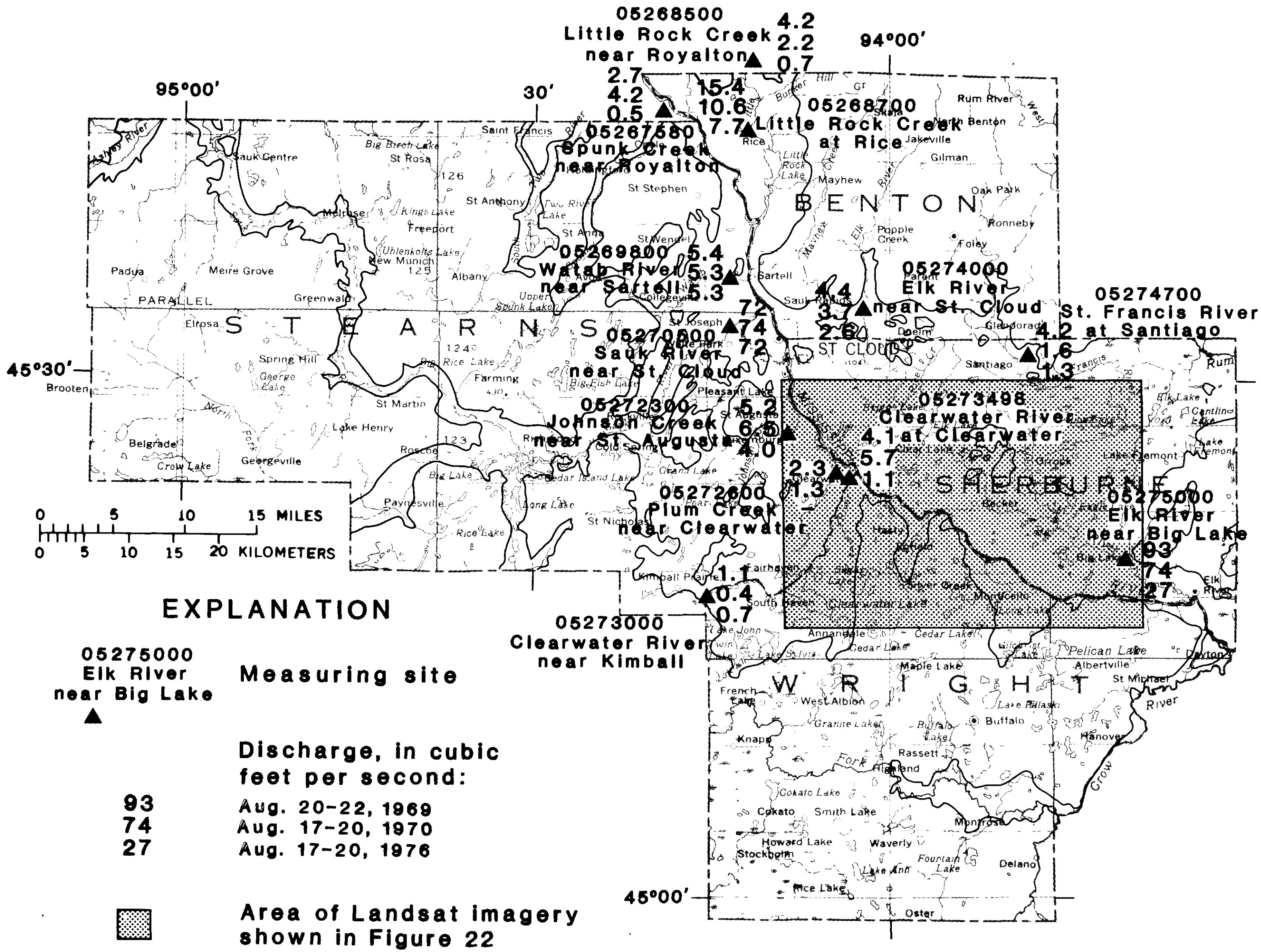


Figure 16.--Streamflow during summer low-flow periods in 1969, 1970, and 1976

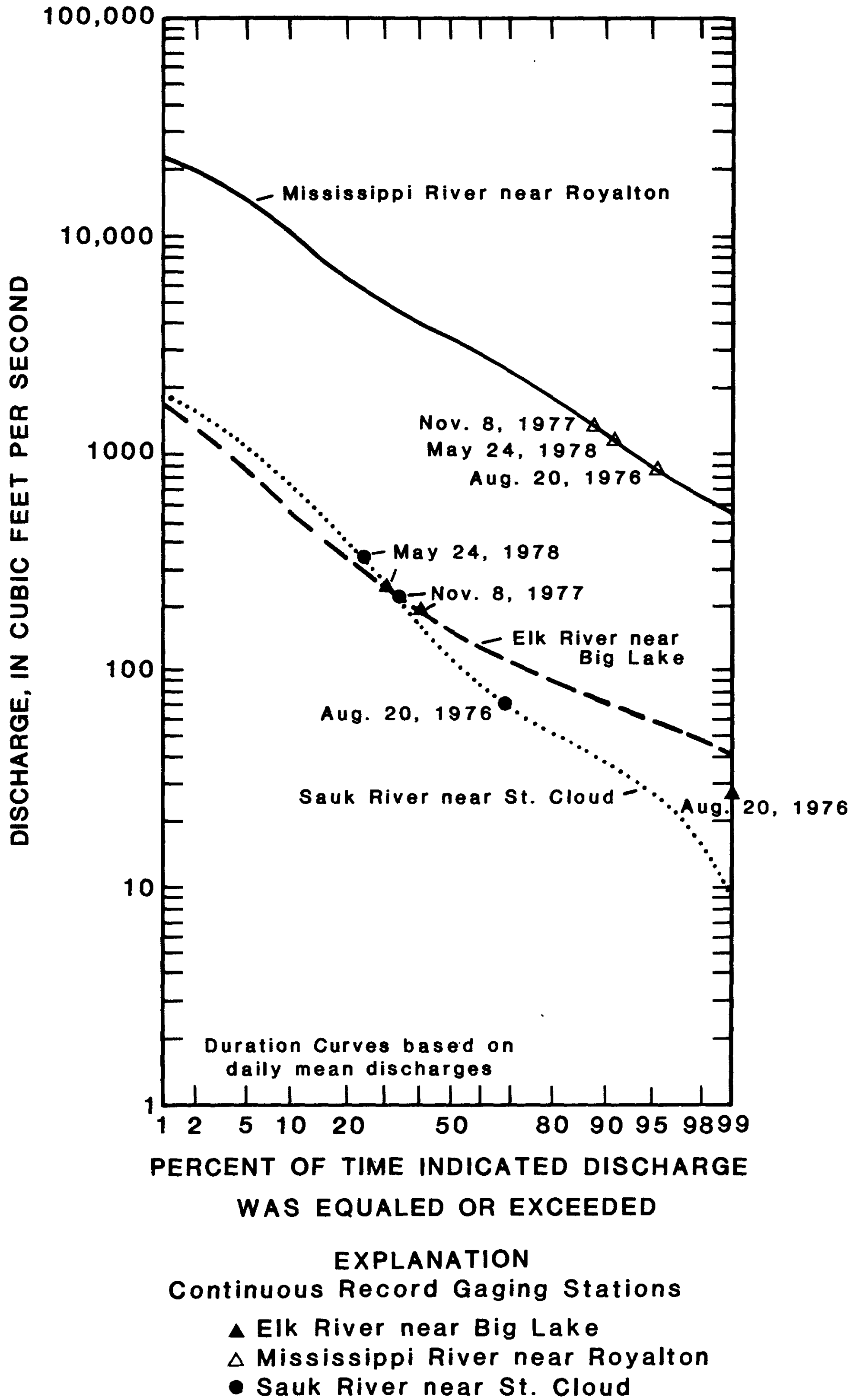


Figure 17.--Flow-duration curves for water years 1935-77

The distribution of flow throughout the year is important to water users. Figure 18 shows that streamflow is greatest in April, caused by snowmelt and spring rains. Discharge decreases steadily during the growing season, when large quantities of water are removed by evaporation and transpiration. For stations shown in figure 18, 45 to 50 percent of annual runoff occurs from May to September, even though two-thirds of the annual precipitation is received during that period. Discharge is usually lowest in September or during December to February. Monthly discharge percentages for May 1976 to February 1977, reflect the drought.

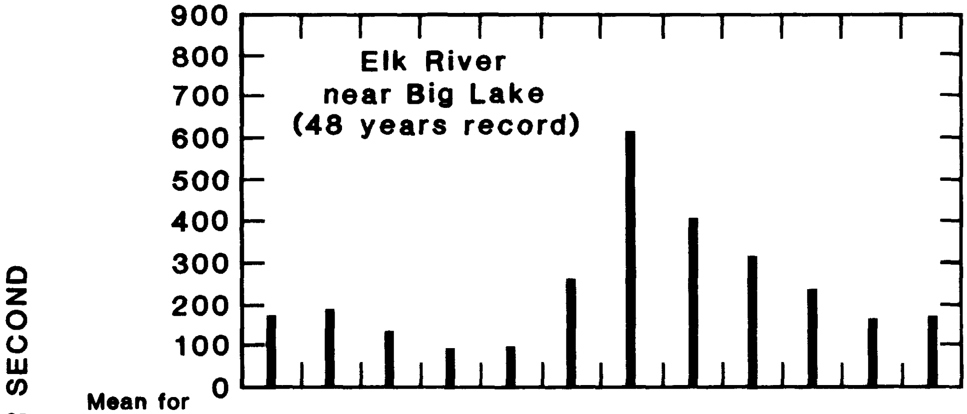
Streamflow gains per river mile of main stem were determined from base-flow measurements (table 3). Values listed are for unregulated stream reaches, except for the Mississippi River. Pickup was lowest during extreme low flow in 1976. At that time, evapotranspiration demands were at a maximum and ground-water gradients were reduced. In November 1977 and May 1978, evapotranspiration demands were less and ground-water gradients were greater. Approximate pickup of the Mississippi River was determined from data at gaging stations above and below the study area minus tributary inflow between. It is less reliable than streamflow gain-loss determinations for smaller streams because of the large quantity of water involved and regulation of flow. Values obtained compare with model-derived values of 0.3 to 2.8 ft^3/s per river mile obtained by Helgesen (1973, p. 24) in Morrison County.

Variations in streamflow pickup reflect geologic differences. Pickup is higher in the Elk River than in the St. Francis River because aquifer materials are coarser and have higher hydraulic conductivity. Although aquifer materials are coarse in the Sauk River valley, pickup is low because the aquifer is narrow and bounded by till. Streams tributary to and south of the Mississippi River (Plum Creek, Clearwater River, Silver Creek, and Otter Creek) become losing streams as they cross the coarse-textured valley-train deposits. Several series of discharge measurements verify that the Clearwater River loses substantial quantities of water to the surficial aquifer within 5 miles of its mouth.

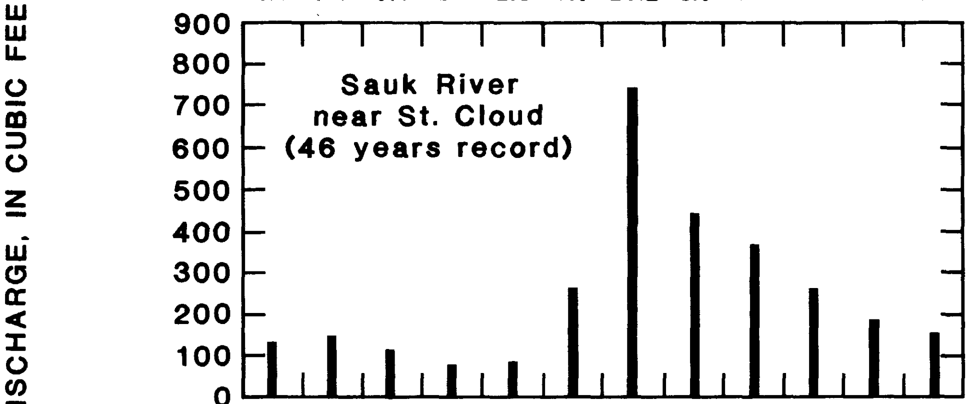
The relationship of precipitation to runoff and ground-water levels, during and preceding the period of study, is shown in figure 19. Each relationship seems to be anomalous during the drought of 1976-77, an extreme hydrologic event.

Evapotranspiration

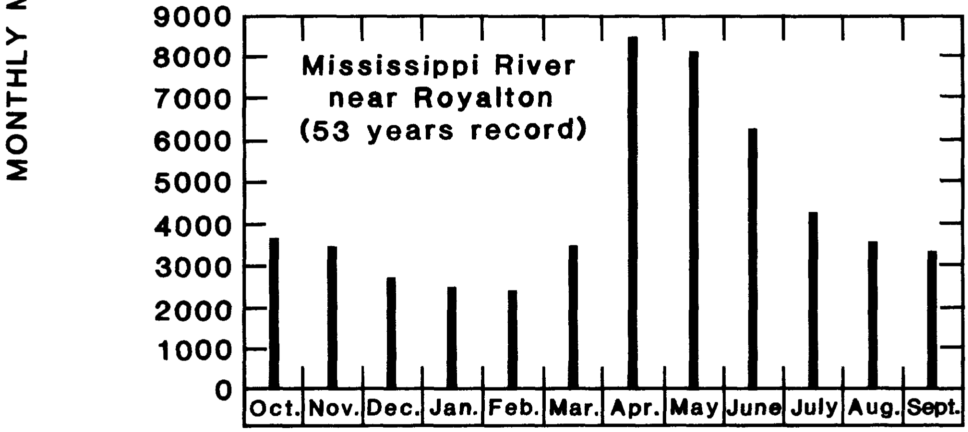
Where the water table is at land surface (wetlands) or near it, water is lost from the aquifer by evaporation and transpiration. During the growing season, plants, whose roots reach the aquifer, act as pumps, removing water from the aquifer. Some native vegetation and crops grown in the area have roots that extend to depths of 5 feet. It is, therefore, assumed that evapotranspiration from the surficial aquifer is active where the water table is less than that depth (fig. 8). Data from the National Weather



	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
Mean for period of record	6.1	6.7	4.5	3.3	3.4	9.1	21.7	14.2	11.0	8.3	5.8	5.9
1976 W.Y.	4.9	7.6	7.1	5.2	7.0	19.7	23.1	6.9	5.3	3.3	1.4	1.5
1977 W.Y.	4.1	5.5	4.8	4.2	4.2	17.6	17.3	9.7	7.9	6.6	5.3	13.6
1978 W.Y.	4.8	7.8	5.1	2.9	2.3	6.0	20.2	8.5	7.2	23.2	4.8	7.7



	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
Mean for period of record	4.4	4.9	3.8	2.7	3.0	8.9	24.9	15.0	12.3	8.7	6.2	5.2
1976 W.Y.	4.5	5.1	5.3	4.8	4.9	20.9	36.1	7.6	3.3	2.9	2.7	1.9
1977 W.Y.	2.2	2.3	2.5	2.0	1.9	7.9	20.5	11.8	8.6	9.1	8.6	22.6
1978 W.Y.	4.2	7.9	5.8	2.8	1.6	7.4	21.0	10.2	9.8	20.7	3.9	8.0



	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
Mean for period of record	7.0	6.6	5.1	4.7	4.5	6.7	16.3	15.7	12.0	8.2	6.8	6.4
1976 W.Y.	10.1	10.5	8.9	8.1	8.7	11.8	23.9	6.7	3.8	3.7	2.1	1.7
1977 W.Y.	3.9	4.0	3.9	4.0	4.5	9.4	13.8	8.8	10.9	10.3	8.4	21.1
1978 W.Y.	7.9	8.8	7.2	4.4	3.3	4.7	17.0	7.3	9.8	10.4	8.5	10.2

Figure 18.--Monthly mean discharge for Elk, Sauk, and Mississippi Rivers. Numbers below graphs are percent of flow

Table 3.--Streamflow pickup per river mile of main stem at base flow

Stream	Date	Percent duration Elk River near Big Lake	Pickup in $(ft^3/s)/mi$ Range	Mean
St. Francis River	Aug. 17-20, 1976	99+	0 - 0.9	0.4
	Nov. 7-10, 1977	40	0.7 - 1.8	1.4
	May 22-24, 1978	30	1.0 - 3.1	1.8
Elk River	Aug. 17-20, 1976	99+	.3 - .9	.4
	Nov. 7-10, 1977	40	.3 - 3.8	2.2
	May 22-24, 1978	30	1.5 - 3.3	2.2
Sauk River	Aug. 17-20, 1976	99+	.1 - .4	.2
		Percent duration Mississippi River near Royalton		
Mississippi River	Aug. 20-22, 1969	70	-	4.9
	Aug. 17-20, 1970	93	-	4.3
	Aug. 17-20, 1976	95	-	2.5

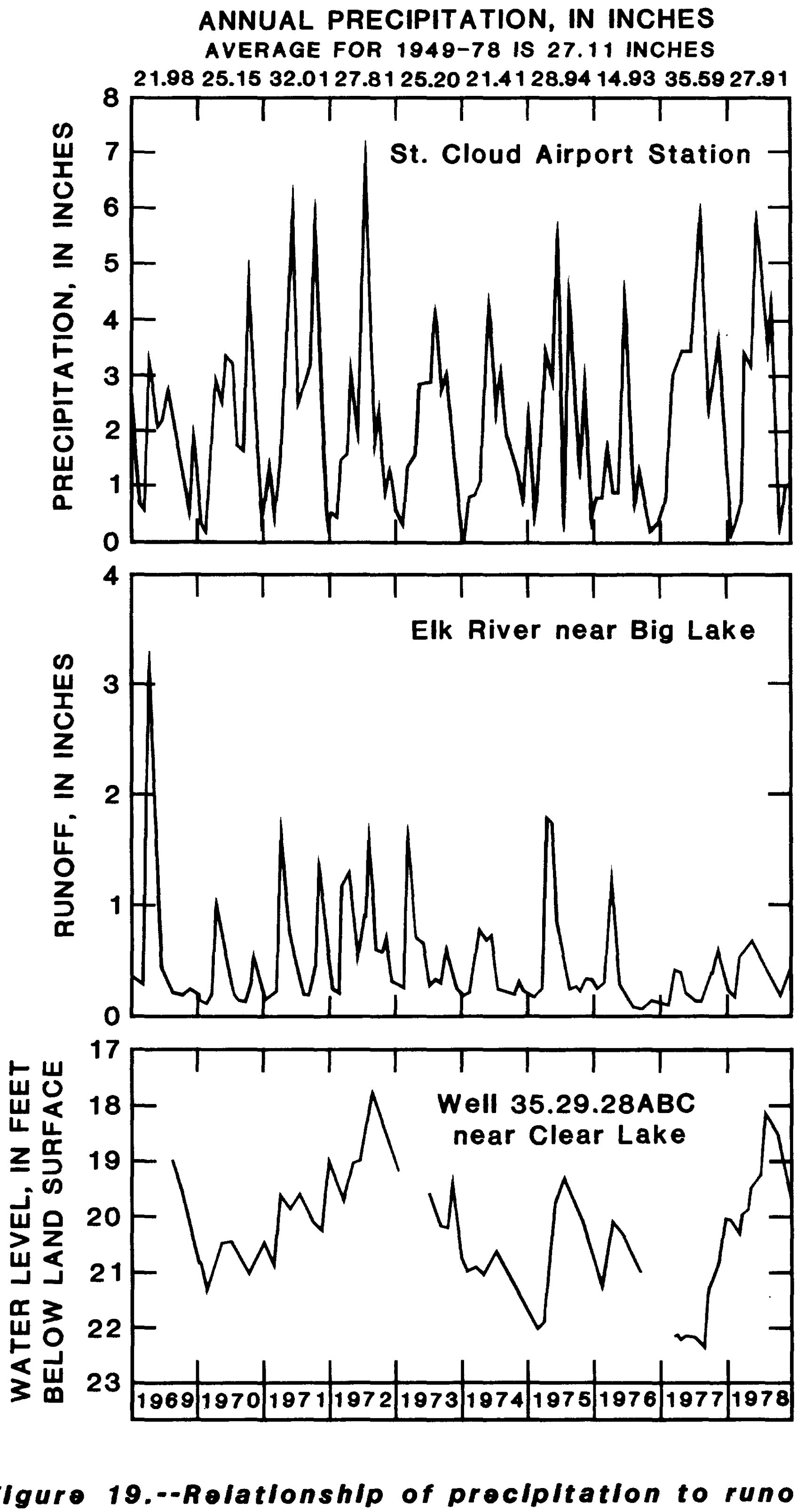


Figure 19.--Relationship of precipitation to runoff and ground-water levels

Service, St. Cloud Airport Station indicate that potential evapotranspiration from May through October averaged about 22.2 inches during 1949-78, as calculated by the method of Thornthwaite and Mather (1957). Precipitation for that period averaged 19.8 inches; the difference, about 2.4 inches, is the average annual water loss from the aquifer by evapotranspiration. Evapotranspiration is greatest in June, July, and August.

Underflow

Ground water moves into and out of the study area as underflow where the aquifer extends beyond county boundaries. Perennial streams, more or less perpendicular to bounding county lines, flow in each such area. Ground water moves into the streams, as determined by stream base-flow measurements; the primary direction of flow is semiparallel to bounding county lines. The quantity of underflow moving into and out of the study area is consequently small. Calculated amounts are negligible considering the total amount of water in the ground-water system.

Most study boundaries are the contact between topographically higher till areas and sand plains. Till is relatively impermeable, allowing only slow movement of small amounts of water. For study purposes, the amount of water moving into and out of the study area through till is assumed to be negligible.

Water in sandstone aquifers, underlying the drift in eastern Sherburne and northern Wright Counties, moves regionally southeastward, with components toward the Mississippi River (Helgesen and others, 1975). Heads are such that near the city of Elk River some wells in sandstone aquifers flow. In most areas, the sandstone is separated from the surficial aquifer by a relatively impermeable till. It is, therefore, assumed that a small but unknown amount of interchange occurs between the drift and the sandstone.

Irrigation is the greatest single use of ground water in the area. The first withdrawals were in the early fifties. Although the irrigation season lasts from 90 to 100 days, wells are pumped for a third or less of that time, thereby imposing a cyclical stress on the hydrologic system. Increases in the number of pumping centers, and irrigation pumpage during 1958-77, are shown in figure 20. Reported data are not 100 percent complete, and their accuracy is subject to question, but they are probably fairly close to being correct. Until about 1967, near equal amounts of ground water and surface water were used for irrigation. Since then, more ground water has been used. Although most pumping centers consist of only one well, some consist of two or more wells, where needed to obtain an adequate supply.

Irrigation first developed in eastern Sherburne County where sandstone aquifers underlying the drift provide a reliable source of water. However, since 1972, drift aquifers have been the main source of water for irrigation wells. Increased interest in irrigation resulted from the drought of 1976, as shown by the large increase in the number of pumping centers in 1977.

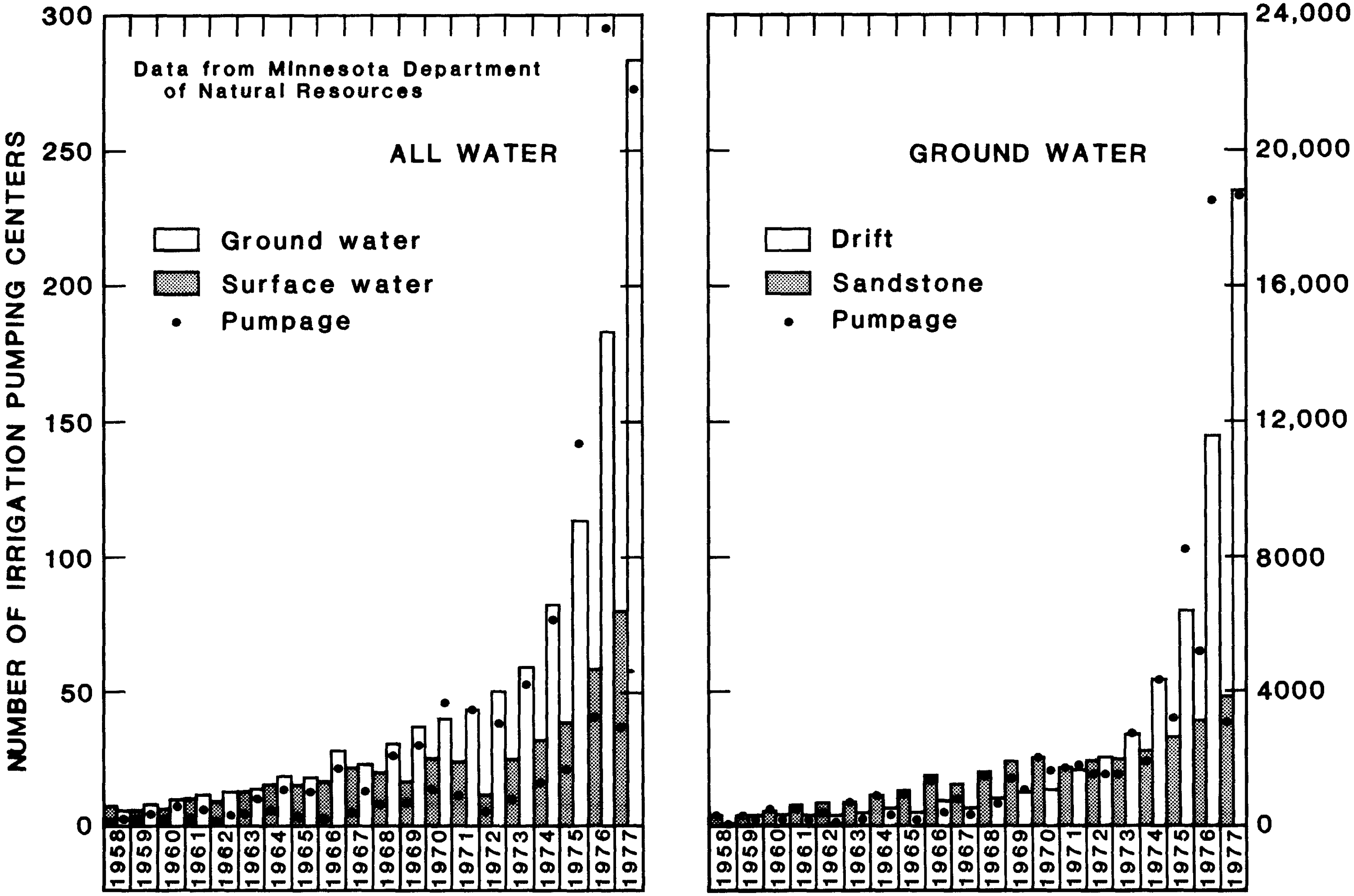


Figure 20.--Number of irrigation pumping centers and amount of water withdrawn from sand-plain areas

History of irrigation development in each county is shown in figure 21 and table 4. Irrigation-well locations are shown in plate 2. Sherburne County has the largest sand-plain area and the greatest number of ground-water and surface-water pumping centers. Development of irrigation in part of Sherburne County from 1973-77 is documented by Landsat imagery (fig. 22).

Ground-water use for irrigation in Sherburne County has increased steadily over the past 20 years with a rapid increase starting in 1974. Development was slower in the other counties until the drought in 1976. Data for 1978 were not available at the time of writing.

The Northern States Power Company's Sherco plant at Becker, Minn., continuously withdraws a total of 350 gal/min from 3 wells completed in the surficial aquifer. Expansion plans call for four additional wells, each capable of pumping 250 gal/min (Hanson, 1977).

Throughout the study area, most water for rural domestic, stock, and light industrial use is from drift sources. Cities underlain by sandstone obtain their municipal supply from that source. Other cities obtain water from the drift, most from buried aquifers. St. Cloud's municipal supply is from the Mississippi River. Ground-water withdrawals for domestic use are particularly concentrated in the urban St. Cloud area. It was beyond the scope of this study to account for all water withdrawn. Except in urbanized areas, domestic use is scattered. In rural areas, water use for irrigation far exceeds all other uses.

Effects of Development

Pumping stresses superimpose changes upon the natural hydrologic system. The type and degree of change is dependent upon location of applied stress and its intensity. Changes can be considered to be either local, around the well site, or regional, affecting a large area due to the combined effects of many pumping centers.

Local

Water-level changes due to pumping are greatest at the well site, becoming smaller with increasing distance from the pumped well. They define a cone of depression, centered at the pumped well, according to distance-drawdown relationships expressed in figure 23. The nonequilibrium equation of Theis (1935) defining these curves is for confined aquifers. Decreasing saturated thickness due to dewatering of unconfined aquifers makes it necessary to adjust the above curves by use of figure 24. Because well yield is theoretically proportional to unadjusted drawdown, curves in figures 23 and 24, based on a pumping rate of 300 gal/min, can be used for any pumping rate assuming aquifer storage coefficient and period of pumping are as stated. Storage coefficient used is typical for unconfined drift aquifers and period of pumping is maximum for an irrigation season in the study area. Estimates of drawdown thus made are considered to be maximum. Knowing the

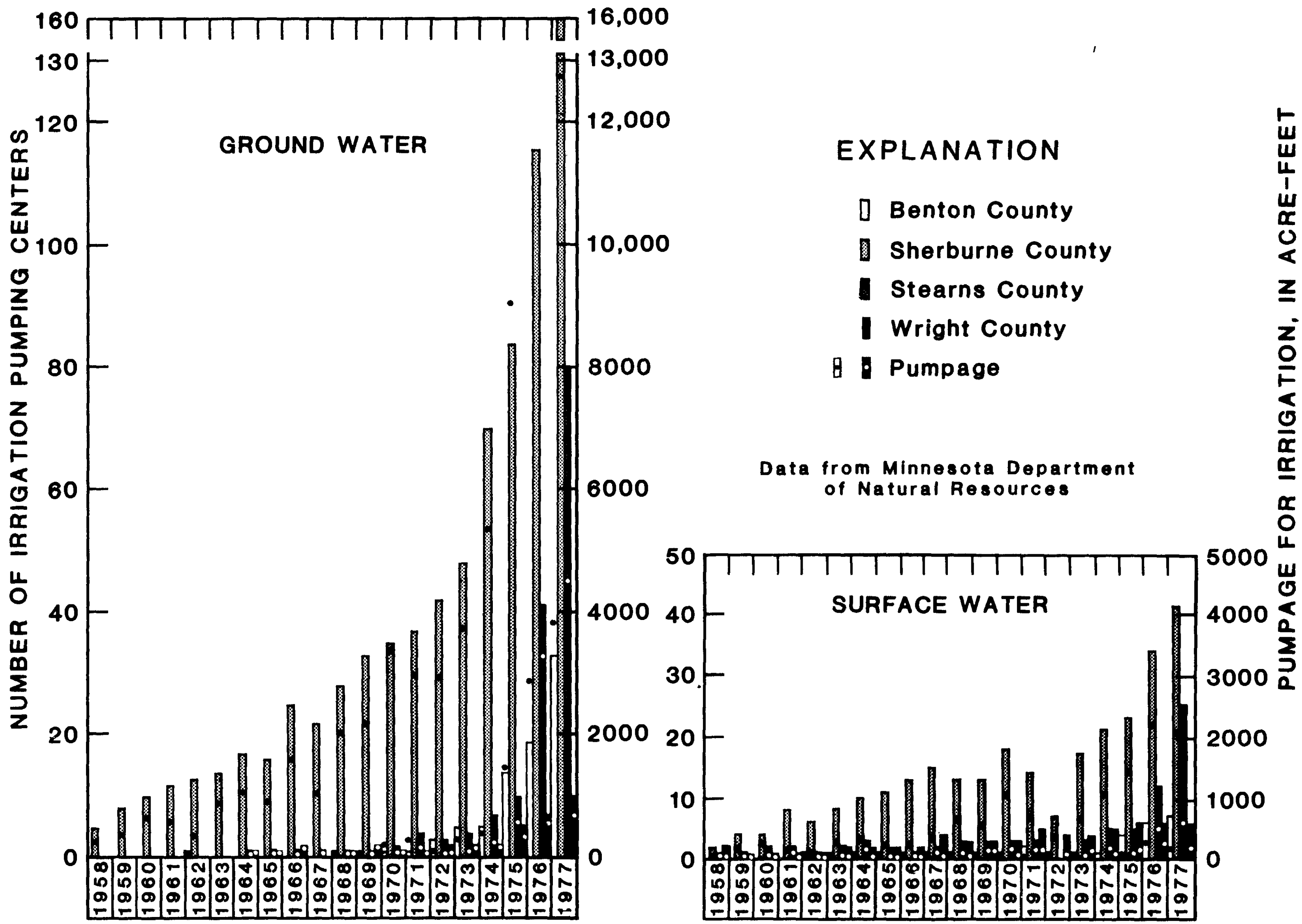
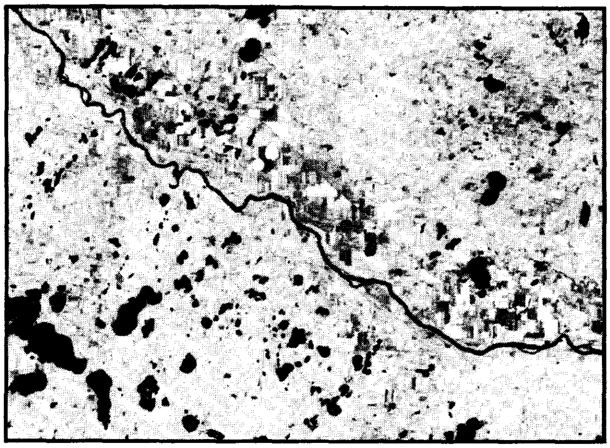


Figure 21.--Number of irrigation pumping centers and amount of water withdrawn from sand-plain areas in each county

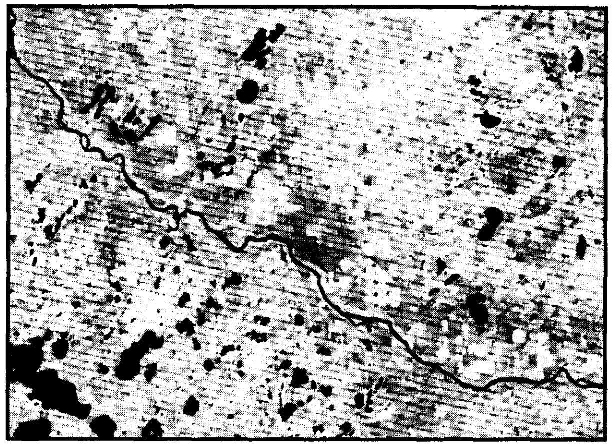
Table 4.--Pumpage for irrigation within study area as reported to Minnesota Department of Natural Resources. Top number is acre-feet of water pumped, bottom number is number of pumping centers.

[SW = surface water; GW = ground water]

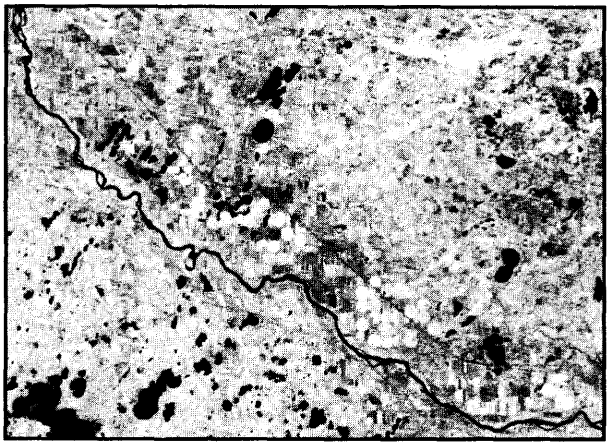
County	1960		1965		1970		1975		1976		1977	
	SW	GW	SW	GW	SW	GW	SW	GW	SW	GW	SW	GW
Benton	-	-	17	-	<1	194	39	1474	264	2882	183	3864
	-	-	(1)	-	(1)	(1)	(4)	(14)	(6)	(19)	(7)	(33)
Sherburne	70	633	217	938	1024	3341	1144	9024	2197	16,897	2066	12,782
	(4)	(10)	(11)	(16)	(18)	(35)	(23)	(84)	(34)	(116)	(41)	(160)
Stearns	73	-	36	13	119	63	95	558	478	3274	593	4495
	(2)	-	(2)	(1)	(3)	(2)	(5)	(10)	(12)	(41)	(25)	(80)
Wright	<1	-	<1	69	39	84	158	332	282	598	120	708
	(1)	-	(2)	(1)	(3)	(1)	(6)	(5)	(6)	(7)	(6)	(10)
TOTAL	143	633	270	1020	1182	3682	1736	11,388	3221	23,651	2962	21,849
	(7)	(10)	(16)	(18)	(25)	(39)	(38)	(113)	(58)	(183)	(79)	(283)



August 29, 1973
No. 1400-16378



July 17, 1974
No. 1724-16292



August 8, 1975
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August 2, 1976
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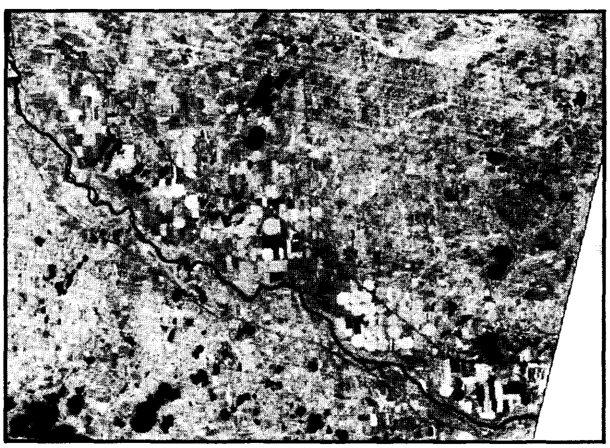
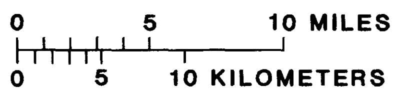


August 3, 1977
No. 5837-15152



Lightest color circles and parallel—ograms are irrigated areas. Dark line is the Mississippi River. Area shown is outlined in figure 16

Figure 22.--Landsat imagery showing development of irrigation from 1973-77 in part of Sherburne County

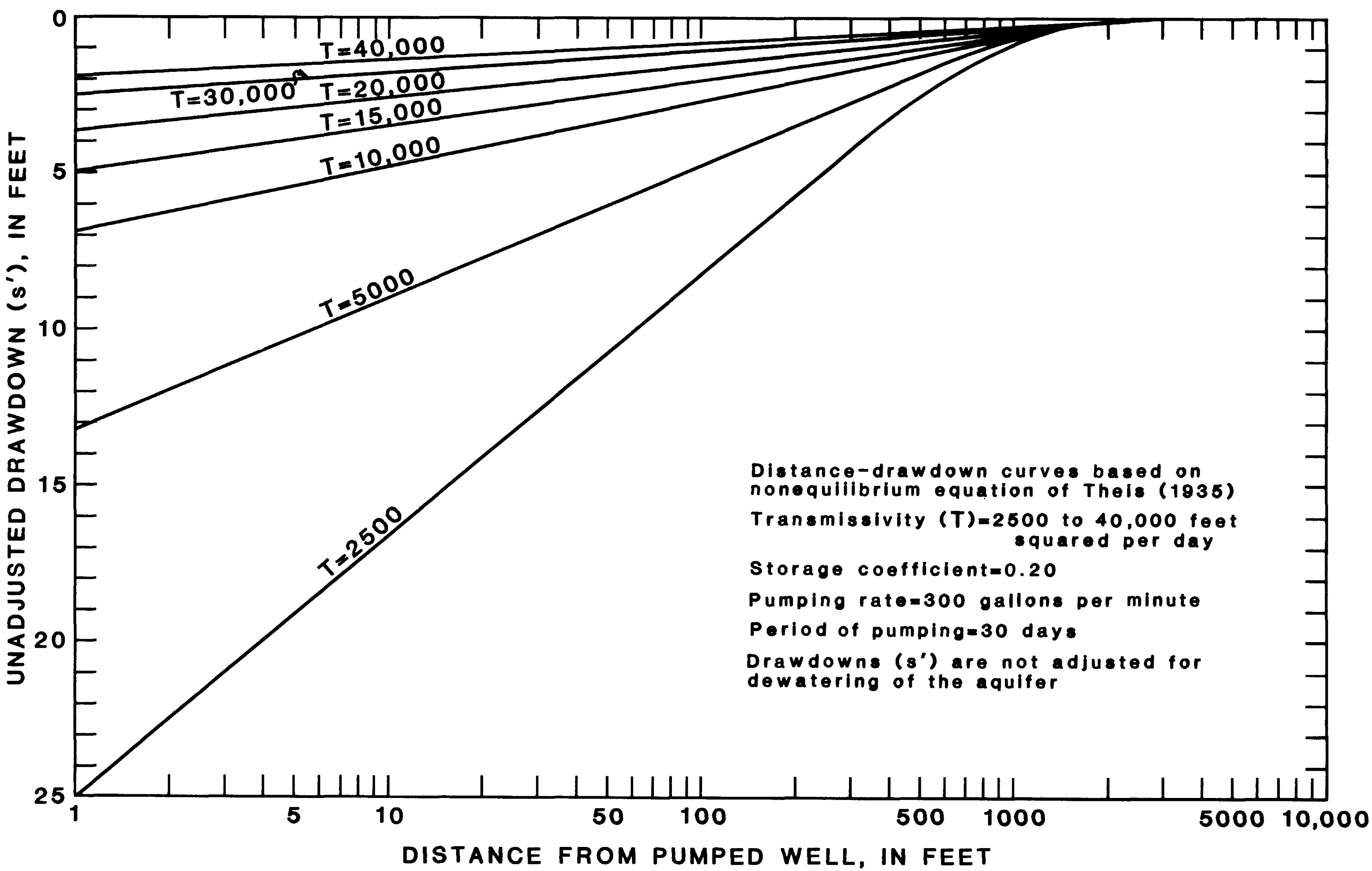


Figure 23.--Theoretical relation of drawdown to distance from a well

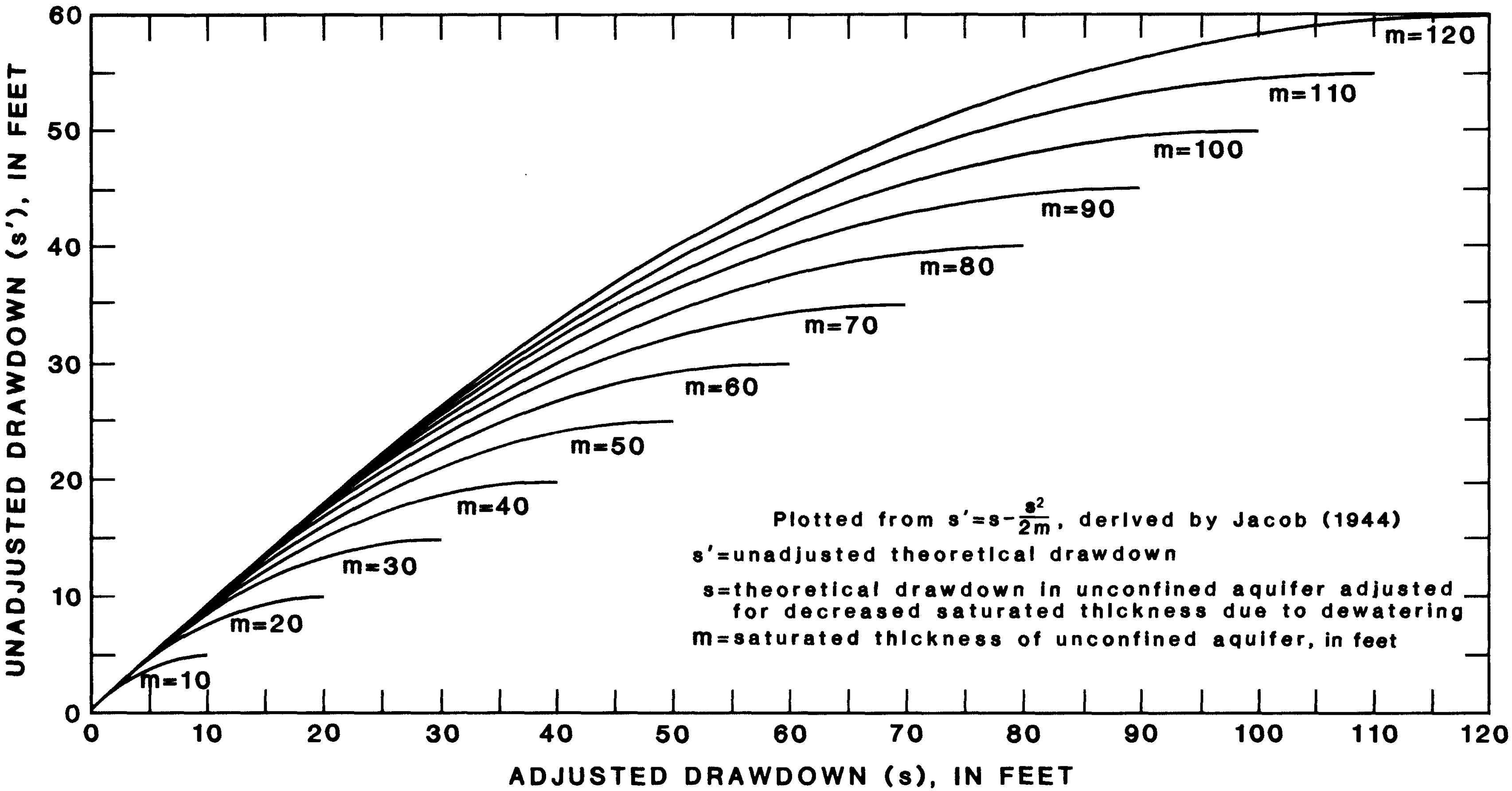


Figure 24.--Theoretical curves for adjustment of drawdown in unconfined aquifers

saturated thickness and transmissivity, estimates of which can be made from plates 2 and 3, it is possible to estimate drawdown at any distance from the pumped well if criteria listed on figure 23 are met. To illustrate, hypothetical examples follow:

Example 1.--In an area where saturated thickness is 40 feet and transmissivity is 10,000 ft^2/day, a yield of 600 gal/min is needed. How many wells will be required and how should they be spaced to obtain the desired yield? It is assumed that the wells will be open to the full saturated thickness of the aquifer, 100-percent efficient, and maximum allowable drawdown midway between any 2 wells is 4 feet.

A. From figure 23, distance-drawdown relationships for a transmissivity of 10,000 ft^2/day are defined. At distances of 1, 10, and 100 feet from a well, pumping 300 gal/min, drawdowns of 6.8, 4.8, and 2.8 feet, respectively, can be expected. Beyond 700 feet, drawdown should be less than 1 foot.

B. Because unadjusted drawdown is theoretically proportional to yield, pumping at 600 gal/min would double the drawdowns listed in A above. Expectable unadjusted drawdown 1 foot from the pumped well would, therefore, be 13.6 feet.

C. From figure 24, adjusted drawdown 1 foot from the pumped well is 17 feet. Because this drawdown is within the optimum operating range of two-thirds the original saturated thickness (40 x 0.67 = 26.8) a single well should supply the needed amount.

Example 2. The same criteria stated in example 1 apply except a yield of 1,200 gal/min is needed.

A. Drawdowns at 300 gal/min as listed in example 1-A apply.

B. To obtain 1,200 gal/min, unadjusted drawdowns would be four times those listed in example 1-A. One foot from the pumped well, unadjusted drawdown would be 4 x 6.8 or 27.2 feet.

C. Unadjusted drawdown 1 foot from the pumped well exceeds two-thirds of the original saturated thickness (40 x 0.67 = 26.8). A second well should be considered to help supply the needed amount.

D. Assume two 600 gal/min wells will be drilled. Drawdown at any point between two wells is equal to the sum of the drawdowns for each well; therefore, maximum allowable adjusted drawdown for each well midway between the two is 2 feet.

E. From figure 24, 2 feet of unadjusted drawdown equals 2 feet of adjusted drawdown.

F. Because a 300 gal/min well causes 1 foot of drawdown 600 feet from the pumped well (fig. 23), a 600 gal/min well would cause 2 feet of drawdown. Therefore, two wells each pumping 600 gal/min should be spaced 1,200 feet apart if drawdown midway between the two is limited to 4 feet.

Knowing saturated thickness and transmissivity of an unconfined aquifer, figures 23 and 24 can be used in a variety of ways to estimate pumping effects. However, actual effects will differ from the theoretical estimates because wells are never 100-percent efficient, periods of pumping differ, hydraulic properties of the aquifer vary from place to place, and aquifer boundaries commonly are intercepted. Effects of cones of depression reaching various types of boundaries are illustrated in figure 25.

Regional

The combined effects of withdrawing large quantities of water from many pumping centers may create regional water-level declines. To estimate declines it is necessary to consider all items of recharge and discharge and their effects on ground-water levels. Such an analysis is possible by use of digital-computer models of the ground-water system. Models of the unconfined ground-water system in Sherburne County and the Maine Prairie area of Stearns County are discussed in the following sections of this report.

AQUIFER MODELS

Two-dimensional finite-difference steady-state ground-water-flow models of the surficial-aquifer system were constructed of Sherburne County and of the Maine Prairie area of Stearns County (pl. 1). Areas modeled are presently undergoing extensive ground-water development for irrigiation, and development likely will continue (G. Ertel, F. Januska, and W. Peterson, oral commun., 1978). The models provide a useful tool for planners, managers, and water users in evaluating the potential effects of increased use on the ground-water system.

The two-dimensional flow model of Trescott and others (1976) was used to simulate the surficial-aquifer systems. The model was designed to solve the partial differential equation:

$$\frac{\partial}{\partial x}\left(T\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T\frac{\partial h}{\partial y}\right) = W(x, y)$$

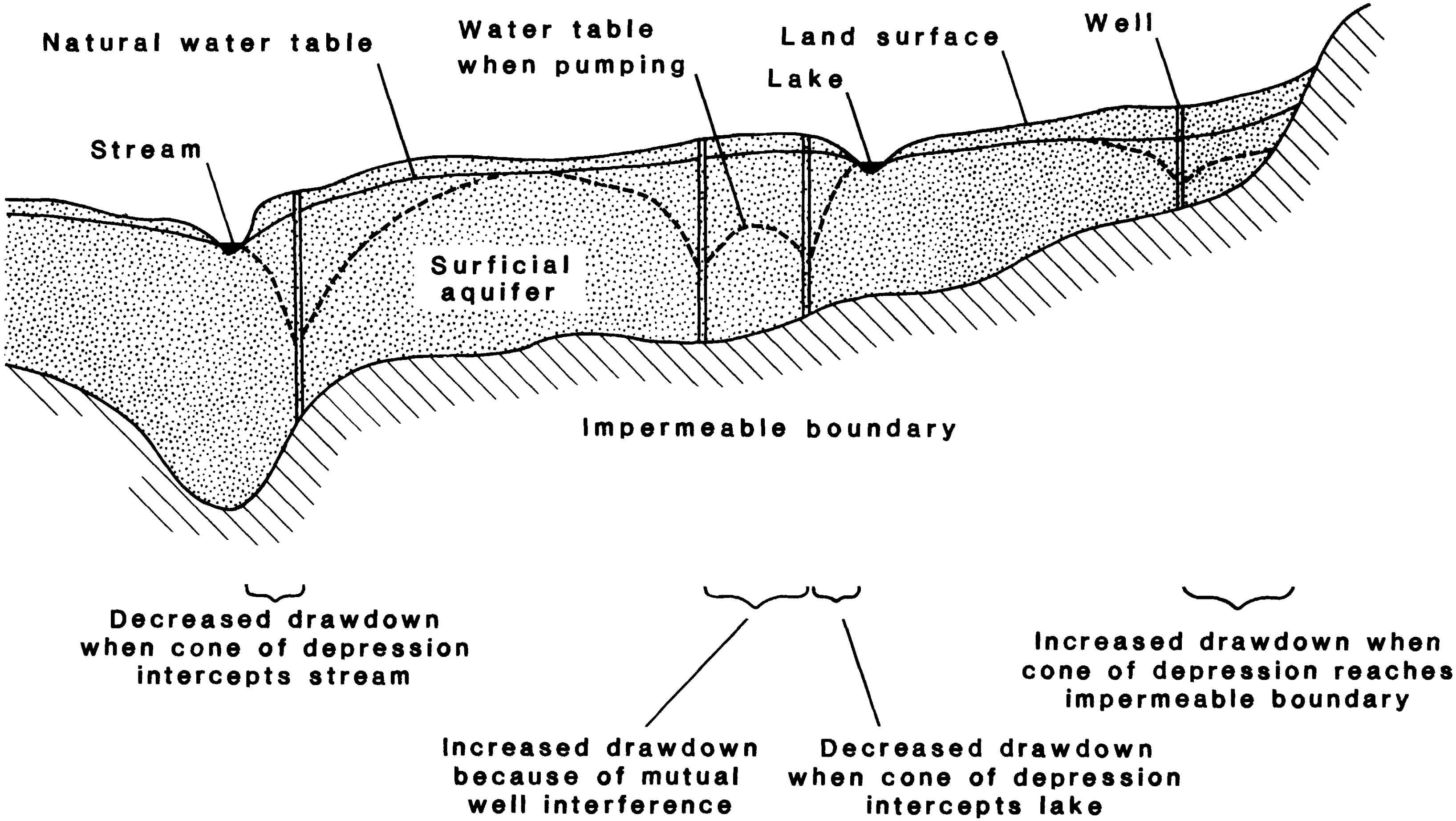


Figure 25.--Diagrammatic hydrogeologic section showing boundary effects on water levels when pumping

that describes the steady flow of water in a two-dimensional isotropic aquifer where:

	Unit
T is transmissivity,	(L^2/T)
h is hydraulic head,	(L)

W(x, y) is a function that defines average rates of aquifer recharge and discharge from time-dependent sources.

Bottom altitudes and hydraulic conductivities of the aquifer are used with model-calculated heads to calculate model transmissivities.

The modeled areas were subdivided into discrete blocks within which all aquifer properties were assumed to be uniform (fig. 26). Smaller blocks were used in areas of concentrated hydrologic stress and near irregular-shaped aquifer boundaries. Model grids were oriented so that their axes are parallel to estimated principle directions of ground-water flow.

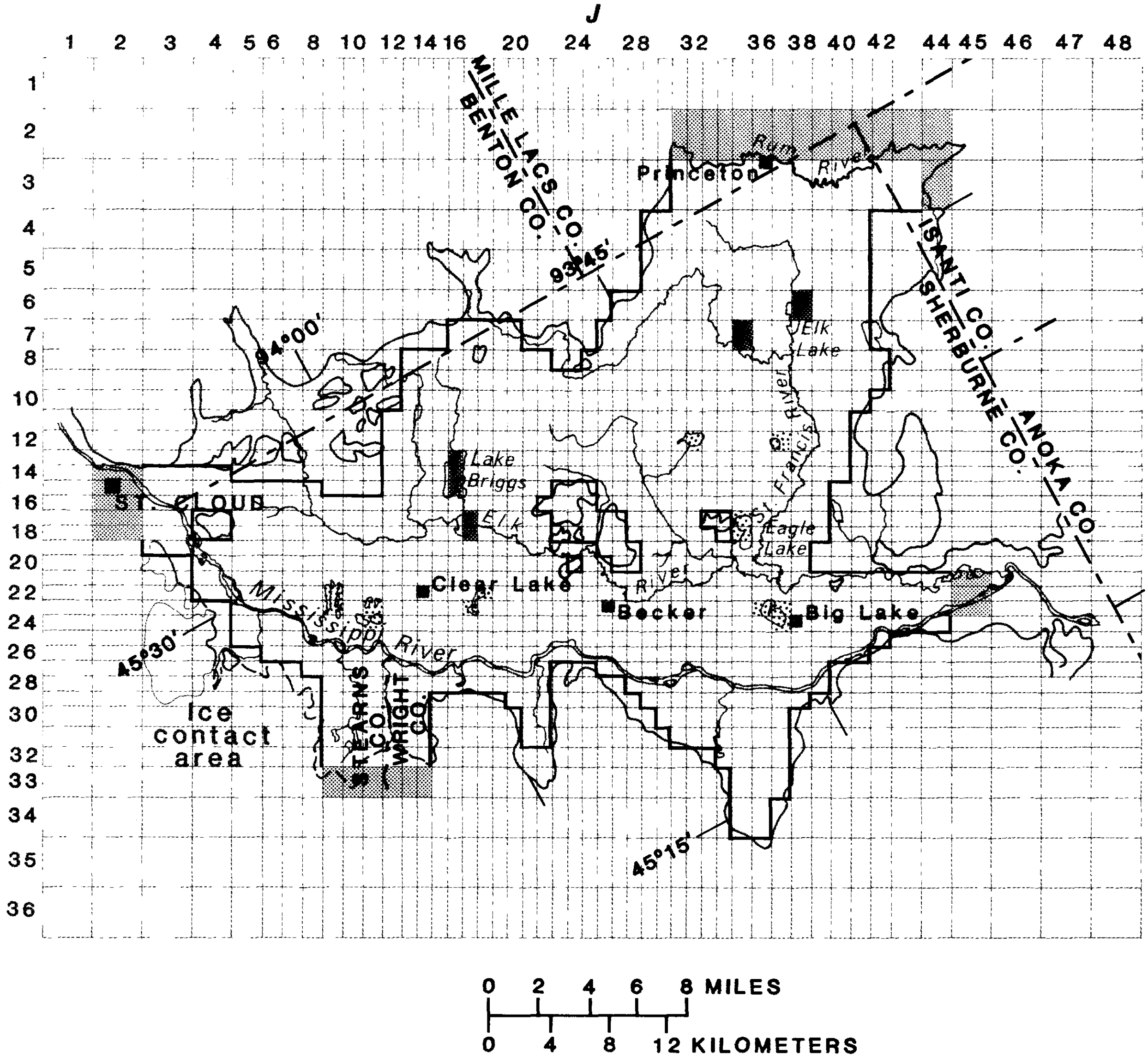
By convention, each block, the center of which is referred to as a node, is referenced by a unique row (I) and column (J) designation. For example, in the Sherburne County model, the city of Big Lake is located in block 24, 38, that is row 24, column 38 (fig. 26). Finite-difference approximations of the partial-differential equation are written for each block and the subsequent series of algebraic equations is solved simultaneously using a digital computer. Details of aquifer-simulation techniques can be obtained from Trescott and others (1976).

The models were calibrated for steady-state conditions by comparing model-calculated values of head and streamflow gain to estimated average field conditions. There were not sufficient data available to calibrate the models for transient conditions.

Model analyses are regional in scope and cannot provide detailed information on hydraulic effects at individual well sites. Hydraulic effects at specific sites are considered in the section "Effects of Development."

Conceptual Model

Water moving into, through, and out of the surficial outwash constitutes the surficial-aquifer system. Precipitation is the major source of recharge to the aquifer. Locally, small amounts of water are gained by seepage from streams. Some water enters and leaves the surficial aquifer as underflow; quantities involved are relatively small and in about equal amounts.



EXPLANATION

- Boundary of study area
- Boundary of model, no flow
- Constant head node representing model boundary
- Constant head node representing flow-through lake
- Evaporation node representing no outflow lake

Figure 26.--Finite-difference grid and boundary conditions for the Sherburne County model

Large quantities of water are discharged from the surficial aquifer to streams and lakes. A lesser amount is discharged by evapotranspiration from wetlands where the water table is at or near the land surface. Pumping, largely for irrigation, accounts for a small but increasing amount of discharge.

Quantities of water involved in the water budget for each modeled area are presented in following sections.

Model Representation

Following are methods used to represent geohydrologic features and components of the hydrologic system that are common to both modeled areas.

The contact between aquifer materials and the relatively impermeable till was modeled as a no-flow boundary. Where the aquifer thickens gradually from the till-aquifer contact, the no-flow boundary was moved to the 10-foot saturated-thickness line to ease computational problems. Where the aquifer extends beyond modeled boundaries, and ground-water development is far enough away so that effects of simulated stresses are negligible, the aquifer boundary was modeled as constant head.

Hydrograph analyses indicate that recharge to surficial aquifers is variable but averages about 8 inches per year. Recharge, as used in the models, represents a net amount that is the sum of recharge from precipitation and of any other sources or sinks of water that are not explicitly a part of the model. These sources and sinks might include vertical leakage from underlying drift or bedrock, return water from irrigation, and discharge from wetlands other than lakes. It has been estimated that from 15 to 20 percent of irrigation water applied on sand plains is returned to the aquifer (E. Weeks, oral commun., 1978).

All streams and lakes in the modeled areas are in hydraulic connection with the surficial aquifer; the degree of connection being dependent upon hydraulic conductivity and thickness of bottom materials. Perennial streams were modeled to define aquifer losses and gains along designated reaches dependent upon water-table gradients and hydraulic conductivities of streambed materials.

Models were used to estimate hydraulic conductivity of streambed materials because no field data were available. Lakes, where surface inflow exceeds open-water evaporation, have a relatively constant altitude and hence were modeled as constant head. Lakes having no natural outlets were modeled as though evaporation rates always were a maximum unless water levels dropped below lake bottoms.

Evapotranspiration of ground water was incorporated into the model by specifying that the maximum rate of 2.4 in/yr applies where the water table was at land surface and that the rate decreases linearly to zero at a depth of 5 feet.

Irrigation pumping was represented by average withdrawal rates estimated from total reported pumpage for 1977 (the most recent complete data available). Pumping centers were distributed areally to represent actual and hypothetically expanded development.

Sherburne County

The area herein referred to as Sherburne County represents 500 mi^2 of surficial outwash. Included is most of Sherburne County plus extreme southern Benton County and parts of Stearns and Wright Counties bordering the Mississippi River. A variable grid with 36 rows and 48 columns was used. The grid was oriented in a northeast-southwest direction (fig. 26). Grid blocks range in size from 0.36 to 1.2 mi^2 (230 to 770 acres). Smallest blocks were assigned to the area between the Elk and Mississippi Rivers, where ground-water development for irrigation is extensive, and to areas where definition of stream and boundary locations was needed.

The northwestern and southwestern extremities of the modeled area were treated as constant head to simulate underflow into the area. The Rum River, which forms the northeastern boundary, was also modeled as constant head.

Aquifer hydraulic conductivities were determined at several sites by aquifer tests (table 1) and were estimated at several hundred test-hole sites. Logs of wells and test holes were used to define the base of the aquifer.

Hydraulic conductivities of streambed materials in the Mississippi River main stem were determined by model analysis to be 1×10^{-7} and 1×10^{-3} (ft/s)/ft of streambed material. The higher value is for the reach between Clear Lake and Big Lake where the coarseness and cleanness of aquifer materials was assumed to be reflected in streambed materials also. Streams tributary to the Mississippi River were estimated to have a bed-material hydraulic conductivity of 1×10^{-6} (ft/s)/ft of streambed thickness. This value is comparable to the 2.9×10^{-6} (ft/s)/ft obtained by Helgesen (1977) in the Pineland Sands area of central Minnesota, and to values of 6.7×10^{-6} and 5.9×10^{-7} (ft/s)/ft obtained by Larson (1976) in the Appleton area of west-central Minnesota.

In eastern Sherburne County, water from underlying bedrock aquifers is used for irrigation. Some of the irrigation water returns to the surficial-aquifer system as recharge. To approximate steady-state ground-water levels, 12 inches of recharge was applied to the heavily irrigated area of coarse-textured valley-train deposits along the Mississippi River.

A third of the total might be attributed to return flow from irrigation and (or) vertical leakage from underlying drift or bedrock. Four inches of recharge was applied in the north-central part of Sherburne County, an area dominated by wetlands, where net recharge is decreased by large evapotranspiration losses. The distribution of recharge used in the model is shown in figure 27.

Model analysis using rates and parameters stated above produced an acceptable steady-state simulation as described in the calibration section.

Calibration

The model was calibrated by comparing estimated average aquifer heads and streambed leakage, as determined from measured values, with corresponding values obtained from the model. Heads measured in May 1978, 8 months after the last irrigation season, approximate long-term average water levels. Measured heads are used to estimate water levels at the centers of grid blocks that contain observation wells (fig. 27) for comparison with model-calculated values.

Model-calculated and estimated heads at selected observation wells are compared in table 5, and a regional comparison of the configuration of the water table based on measured and calculated heads is shown in figure 28.

Another check on model calibration is calculated versus measured values for base-flow gains or losses in streams. Data obtained in May 1978, at 30 percent on the flow-duration curve for Elk River near Big Lake, were adjusted to 50-percent duration to approximate average conditions. A comparison of measured and calculated values along selected reaches of the Elk and St. Francis Rivers also indicates that the model is a reasonable approximation of the hydrologic system (fig. 29).

The model was tested to determine its sensitivity to changes in aquifer hydraulic conductivity, recharge, and leakage to streams. Varying aquifer hydraulic conductivity and recharge within "reasonable" ranges resulted in relatively small changes in aquifer head; whereas, varying hydraulic conductivity of streambed materials resulted in relatively large changes in head.

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

INFLOW

	ft^3/s
Recharge from precipitation	277
Leakage from streams......................	3
Total.....	280

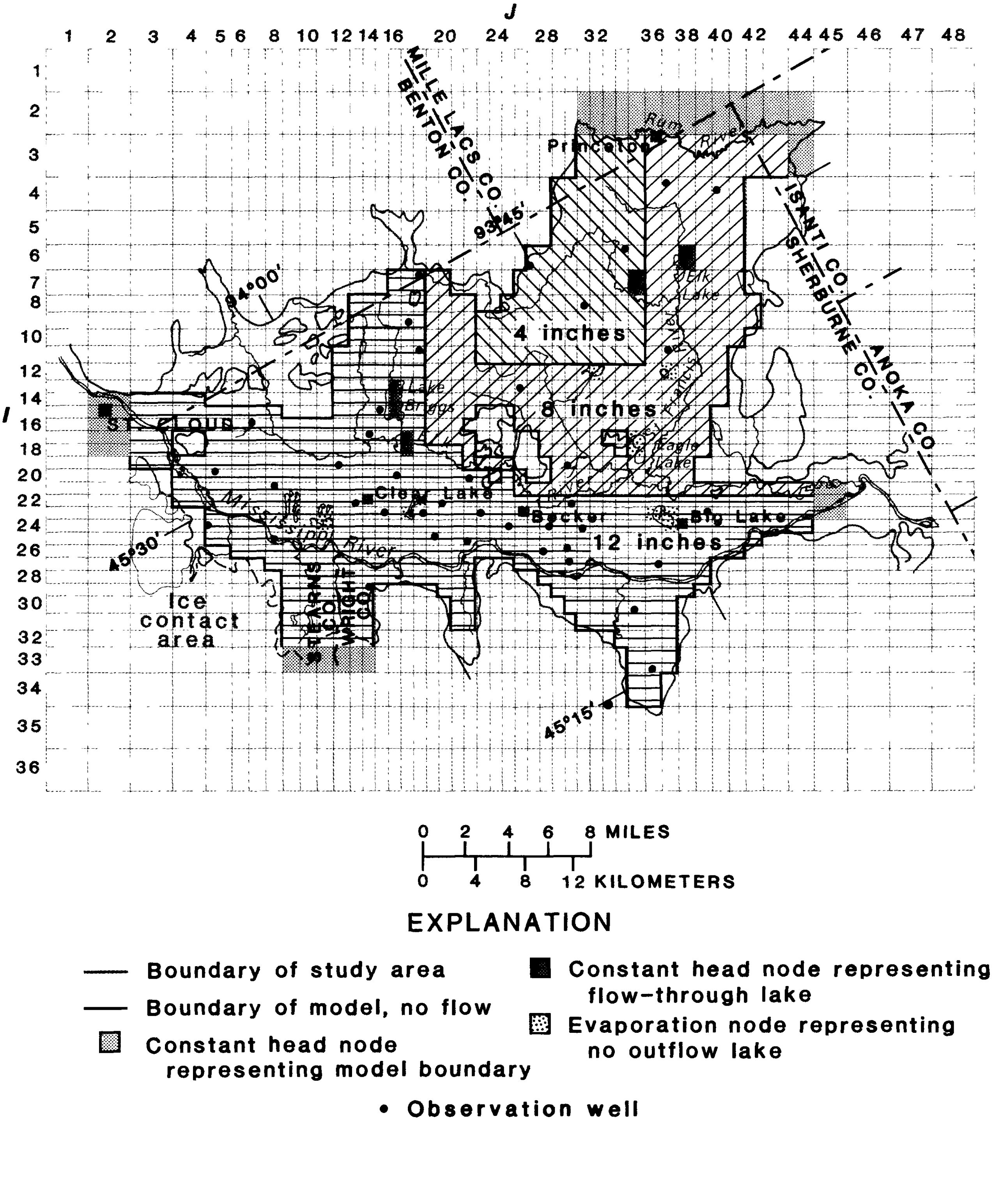
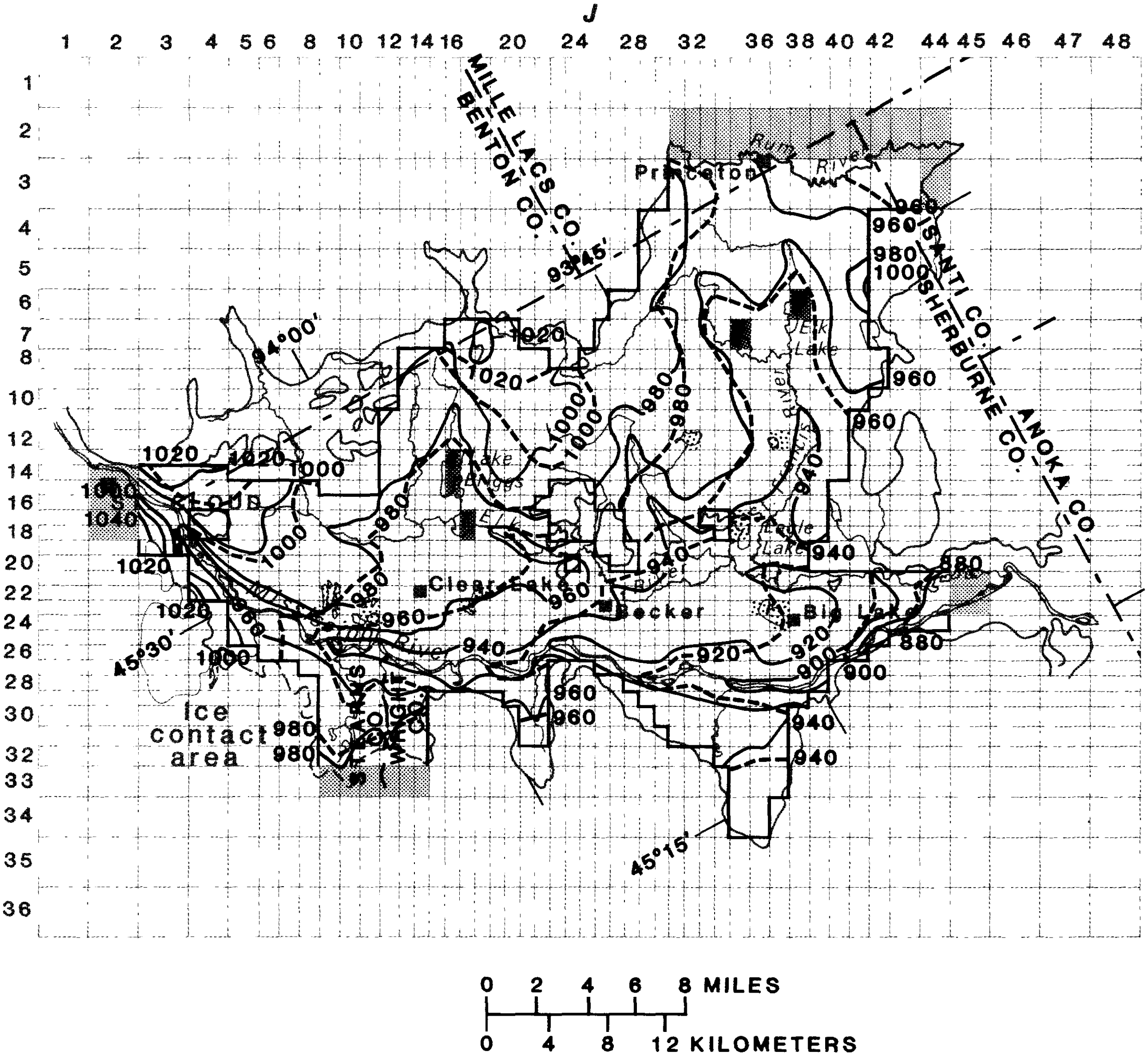


Figure 27.--Distribution of modeled recharge to the surficial aquifer

Table 5.--Sherburne County model-calculated heads compared with measured heads in selected wells, May 1978

Node		Head, datum is mean sea level	
I	J	Estimated, May 1978[b]	Model calculated
[a] 4	37	962	970
4	40	962	971
6	34	954	958
[a] 7	18	1015	1018
8	31	982	976
9	17	1011	1005
[a] 11	18	1000	995
11	37	951	955
13	26	991	992
15	15	971	970
16	7	998	1003
[a] 17	14	971	970
[a] 19	12	978	978
[a] 19	30	947	946
[a] 20	5	999	1000
[a] 20	16	969	968
[a] 20	22	960	958
[a] 21	8	991	990
[a] 22	13	977	971
22	18	963	962
[a] 22	20	953	950
[a] 22	30	936	933
[a] 23	15	961	963
[a] 23	18	960	958
[a] 23	23	952	946
23	26	946	938
23	39	922	914
24	5	978	981
[a] 24	25	936	936
[a] 24	28	935	931
[a] 24	31	928	926
[a] 25	19	945	948
[a] 25	22	941	938
[a] 26	28	929	925
[a] 26	30	920	922
[a] 27	30	914	921
27	36	916	916
29	14	974	968
30	35	928	926
[a] 33	36	941	946

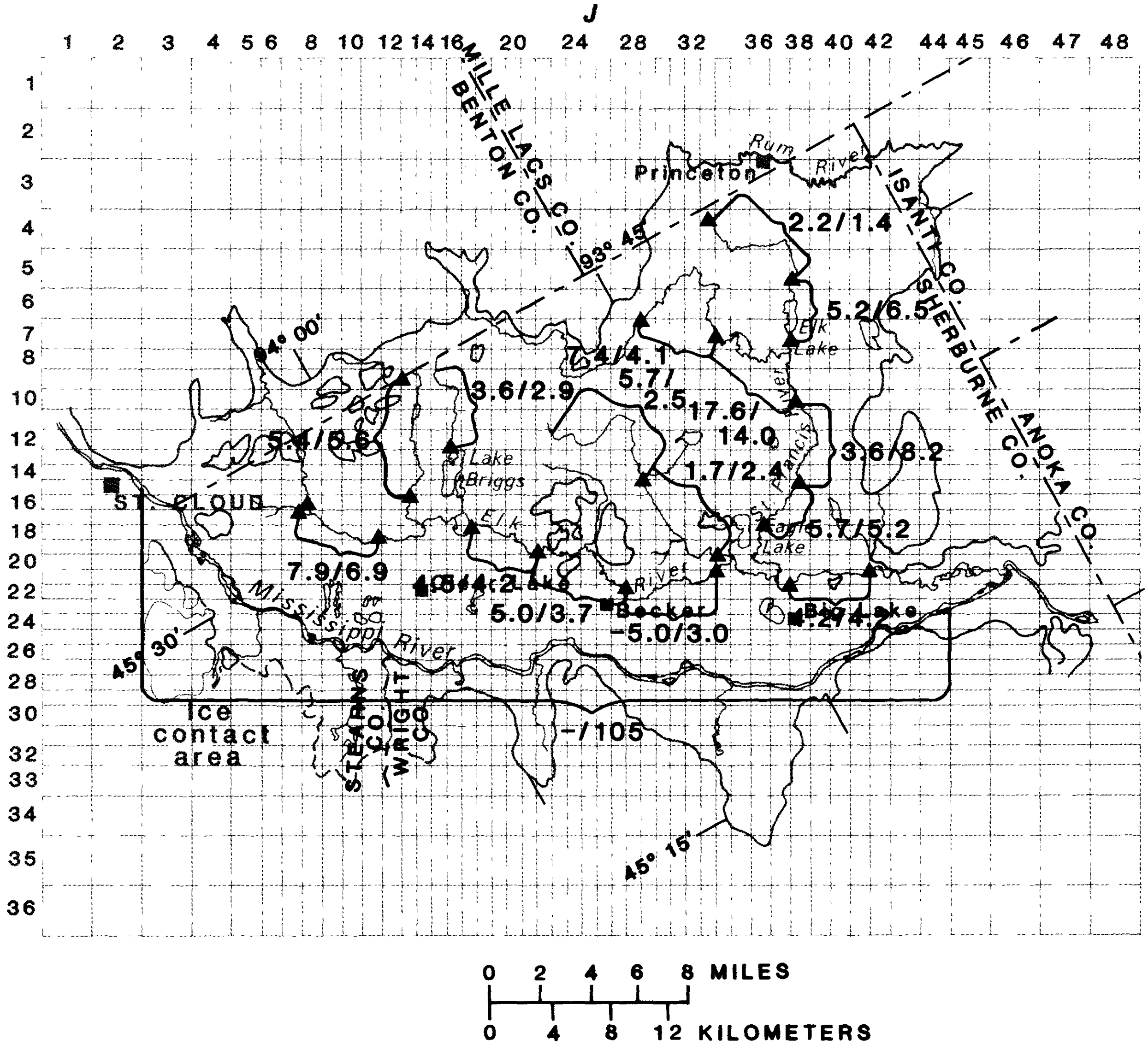
[a]Irrigation well, head may be affected by residual drawdown.
[b]Measured head was adjusted to estimated head at center of node. See figure 27 for position.



EXPLANATION

- Boundary of study area
- Boundary of model, no flow
- Constant head node representing model boundary
- Constant head node representing flow-through lake
- Evaporation node representing no outflow lake
- —960— Water-table contour based on heads measured in May 1978. Contour interval 20 feet. Datum is mean sea level
- --960-- Water-table contour based on model calculated heads. Contour interval 20 feet. Datum is mean sea level

Figure 28.--Configuration of the water table based on measured heads compared with configuration based on model calculated heads



EXPLANATION

—— Boundary of study area ▲ Streamflow measuring site (May 1978)

5.7/5.2 Top number indicates measured streamflow pickup or loss along indicated reach, in cubic feet per second, adjusted to 50 percent duration. Bottom number indicates model calculated streamflow pickup or loss, in cubic feet per second

Figure 29.--Comparison of streamflow pickup or loss measured in May 1978, to model calculated pickup or loss

OUTFLOW

	ft^3/s
Leakage to streams........................	211
Leakage to lakes..........................	29
Pumping...................................	16
Leakage to bounding streams...............	13
Evapotranspiration........................	11
Total.....	280

Stress

The steady-state model simulates "average" hydrologic conditions. Because ground-water withdrawals for irrigation are a significant part of the total water budget, they are included in the steady-state simulation. To help evaluate the potential effects of hypothetical increases in development and in withdrawals during periods of below-normal precipitation (drought), the model was stressed as follows:

Plan

A. Use withdrawal rates as determined from the reported pumpage for 1977 from known pumping centers; average recharge equal to 4, 8, and 12 in/yr as shown in figure 27.

B. Use a 50-percent increase in withdrawal rates from known pumping centers; average recharge equal to 3, 6, and 9 in/yr, representing a 25-percent reduction from that shown in figure 27 owing to a hypothetical drought of several years duration.

C. Use withdrawal rates determined from 1977 reported pumpage from known pumping centers plus 0.15 ft^3/s (equivalent to 8 inches of water distributed over 160 acres) from hypothetical centers (G. Ertel, F. Januska, and W. Peterson, oral commun., 1978); average recharge equal to 4, 8, and 12 in/yr.

D. Use a 50-percent increase in withdrawal rates from both known and hypothetical pumping centers; average recharge equal to 3, 6, and 9 in/yr, representing a drought of several-years duration.

E. Use double the withdrawal rates (equivalent to about 16 inches of water distributed over 160 acres) from both known and hypothetical pumping centers; average recharge equal to 4, 8, and 12 in/yr.

F. Use a 50-percent increase in withdrawal rates used in plan E (triple rate used in plan C) from both known and hypothetical pumping centers; average recharge equal to 3, 6, and 9 in/yr, representing a drought of several-years duration.

Pumping-center locations are shown in figure 30. Hypothetical centers are located where individual wells might yield at least 500 gal/min and where county extension directors believe that irrigation might increase. Withdrawal rates applied for each plan are listed in table 6. The rates represent the total volume of water withdrawn annually from the entire block and are not necessarily obtainable from a single well. All simulated pumpage is for irrigation except as indicated.

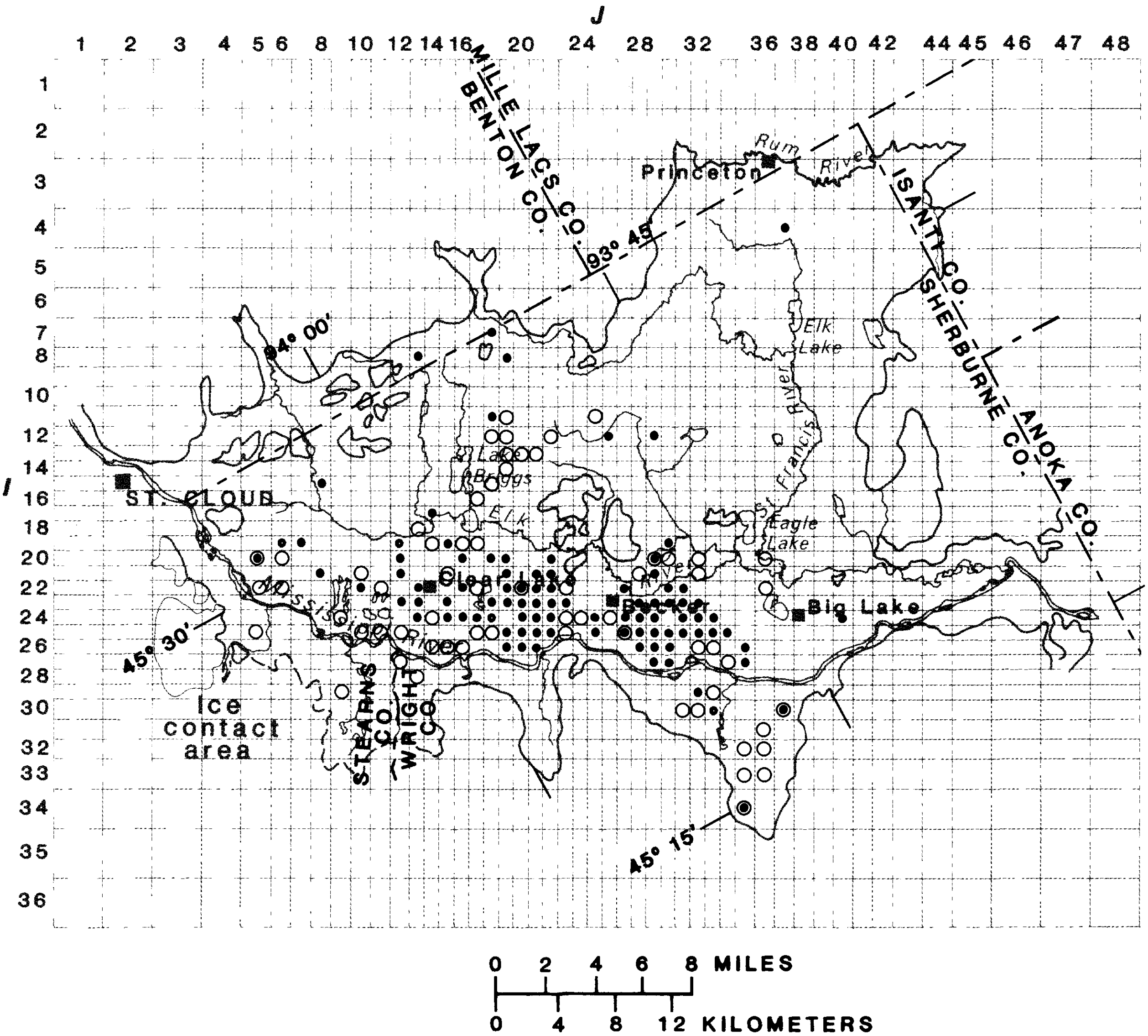
Below-normal precipitation in 1976 and early 1977 resulted in below-normal recharge and a consequent 50-percent increase in irrigation pumping. The combination imposed a severe short-term stress on the hydrologic system. The potential effects of drought conditions with various levels of development were simulated by plans B, D, and F.

Results

Departure of any inflow or outflow value from the long-term average will change other items in the water budget. Expansion of irrigated area and increased pumping to compensate for precipitation deficiencies during drought periods were analyzed. The results obtained are considered to be a reasonable approximation of aquifer response to selected stresses. Table 7 is a summary of the modeling plans and aquifer responses.

Plan A, steady-state simulation, assumes that hydraulic head in aquifer recovers after every irrigation season. Model-calculated heads compare favorably with measured heads as shown in figure 28 and table 5. Water-level measurements obtained during May 1978 suggest that, at least locally, the head does not fully recover from one irrigation season to another. Between Big Lake and Clear Lake, where irrigation wells are concentrated, residual cones of depression are suggested on the water-table map on plate 1. Residual drawdown is less than 5 feet and, therefore, not shown by closed contours. Block size and accuracy of input data do not permit model definition of residual cones.

Modeled 1977 pumpage from the surficial aquifer totaled nearly 3.7 billion gallons distributed as shown in figure 30 and listed in table 6. A steady-state simulation with no pumpage results in water-level rises of as much as 4 feet as shown in figure 31. Therefore, the effect of present withdrawals for irrigation is to lower the water table by as much as 4 feet below the estimated level with no pumping.



EXPLANATION

— Boundary of study area

• Present pumping center

◉ Hypothetical pumping center or addition to present center

Figure 30.--Pumping center locations for Sherburne County model

Table 6.--Nodal withdrawal
[in cubic

NODE I	J	PLAN A	B	C	D	E	F	I	J	PLAN A	B	C
4	37	0.015	0.022	0.015	0.022	0.030	0.038	22	5	-	-	0.150
7	18	.139	.208	.139	.208	.278	.348	22	6	-	-	.150
8	13	.086	.129	.086	.129	.172	.215	22	10	0.197	0.296	.197
8	19	.106	.159	.106	.159	.212	.265	22	11	-	-	.150
11	18	.070	.105	.070	.105	.140	.175	22	13	.080	.120	.080
11	19	-	-	.150	.225	.300	.375	22	16	.145	.218	.145
11	25	-	-	.150	.225	.300	.375	22	17	-	-	.150
12	18	-	-	.150	.225	.300	.375	22	19	.125	.188	.125
12	19	-	-	.150	.225	.300	.375	22	20	.445	.668	.595
12	22	-	-	.150	.225	.300	.375	22	21	.140	.210	.140
12	26	.061	.092	.061	.092	.122	.152	22	22	.080	.120	.080
12	19	.006	.009	.006	.009	.012	.015	22	23	-	-	.150
13	19	-	-	.150	.225	.300	.375	[a]22	27	.139	.208	.139
13	20	-	-	.150	.225	.300	.375	22	30	.084	.126	.084
13	21	-	-	.150	.225	.300	.375	22	31	.089	.134	.089
14	19	-	-	.150	.225	.300	.375	22	36	-	-	.150
15	8	.183	.274	.183	.274	.366	.458	23	9	.080	.120	.080
15	18	-	-	.150	.225	.300	.375	23	12	.240	.360	.240
16	17	-	-	.150	.225	.300	.375	23	13	.372	.558	.372
17	14	.095	.142	.095	.142	.190	.238	23	15	.276	.414	.276
18	13	-	-	.150	.225	.300	.375	23	18	.127	.190	.127
19	6	.153	.230	.153	.230	.306	.382	23	19	.206	.309	.206
19	7	.178	.417	.278	.417	.556	.695	23	20	.085	.128	.085
19	12	.117	.176	.117	.176	.234	.292	23	21	.085	.128	.085
19	14	-	-	.150	.225	.300	.375	23	22	.249	.374	.249
19	15	.039	.058	.039	.058	.078	.098	23	23	.053	.080	.053
19	16	-	-	.150	.225	.300	.375	23	28	.139	.208	.139
19	17	-	-	.150	.225	.300	.375	23	29	.266	.399	.266
19	30	.060	.090	.060	.090	.120	.150	23	30	.120	.180	.120
20	5	.288	.432	.438	.657	.876	1.10	23	31	.250	.375	.250
20	6	-	-	.300	.450	.600	.750	23	32	.230	.345	.230
20	12	.275	.412	.275	.412	.550	.688	24	9	-	-	.150
20	16	.160	.240	.160	.240	.320	.400	24	13	.080	.120	.080
20	18	.178	.267	.178	.267	.356	.445	24	14	-	-	.150
20	19	.188	.282	.188	.282	.376	.470	24	15	.176	.264	.176

rates, Sherburne County model
feet per second]

D	E	F	I	J	PLAN A	PLAN B	PLAN C	PLAN D	PLAN E	PLAN F
0.225	0.300	0.375	24	33	0.089	0.034	0.089	0.134	0.178	0.222
.225	.300	.375	24	40	.168	.252	.168	.252	.336	.420
.296	.394	.492	25	5	-	-	.300	.450	.600	.750
.225	.300	.375	25	10	-	-	.150	.225	.300	.375
.120	.160	.200	25	11	-	-	.150	.225	.300	.375
.218	.290	.362	25	12	-	-	.150	.225	.300	.375
.225	.300	.375	25	17	-	-	.150	.225	.300	.375
.188	.250	.312	25	18	-	-	.150	.225	.300	.375
.892	1.19	1.49	25	19	.150	.225	.150	.225	.300	.375
.210	.280	.350	25	20	.089	.134	.089	.134	.178	.222
.120	.160	.200	25	21	.127	.190	.127	.190	.254	.318
.225	.30	.300[b]	25	22	.045	.068	.045	.068	.090	.112
.208	.278	.348	25	23	-	-	.150	.225	.300	.375
.126	.168	.210	[c]25	25	.780	1.17	.780	1.17	1.56	1.56[b]
.134	.178	.222	25	27	.230	.345	.380	.570	.760	.950
.225	.300	.375	25	28	.150	.225	.150	.225	.300	.375
.120	.160	.200	25	29	.150	.225	.150	.225	.300	.375
.360	.480	.600	25	30	.320	.480	.320	.480	.640	.800
.558	.744	.930	25	31	.199	.298	.199	.298	.398	.498
.414	.552	.690	25	32	.089	.134	.089	.134	.178	.222
.190	.254	.318	25	33	.300	.450	.300	.450	.600	.750
.309	.412	.515	25	34	.033	.050	.033	.050	.066	.082
.128	.170	.212	26	14	-	-	.150	.225	.300	.375
.128	.170	.212	26	15	-	-	.150	.225	.300	.375
.374	.498	.622	26	16	-	-	.150	.225	.300	.375
.080	.106	.132	26	19	.080	.120	.080	.120	.160	.200
.208	.278	.348	26	20	.185	.278	.185	.278	.370	.462
.399	.532	.665	26	21	.089	.134	.089	.134	.178	.222
.180	.240	.300	26	28	.231	.346	.231	.346	.462	.578
.375	.500	.625	26	19	.166	.249	.166	.249	.332	.415
.345	.460	.575	26	30	.082	.123	.082	.123	.164	.205
.225	.300	.375	26	32	.325	.488	.475	.712	.950	1.19
.120	.160	.200	26	33	-	-	.150	.225	.300	.375
.225	.300	.375	26	35	.184	.276	.184	.276	.368	.460
.264	.352	.440	27	23	-	-	.150	.225	.300	.375

Table 6.--Nodal withdrawal rates,

NODE I	J	PLAN A	B	C	D	E	F
20	22	0.240	0.360	0.240	0.360	0.480	0.600
20	29	.080	.120	.230	.345	.460	.575
20	30	-	-	.150	.225	.300	.375
20	32	-	-	.150	.225	.300	.375
20	36	-	-	.150	.225	.300	.375
21	8	.339	.508	.339	.508	.678	.848
21	10	-	-	.30	.450	.600	.750
21	12	.140	.210	.140	.210	.280	.350
21	16	-	-	.150	.225	.300	.375
21	19	.087	.130	.087	.130	.174	.218
21	21	.200	.300	.200	.300	.400	.500
21	22	.080	.120	.080	.120	.160	.200
21	28	-	-	.150	.225	.300	.375
21	29	.062	.093	.062	.093	.124	.155
21	32	-	-	.150	.225	.300	.375

I	J	PLAN A	B	C
24	16	0.137	0.206	0.137
24	17	.156	.234	.156
24	18	.142	.213	.142
24	20	.087	.130	.087
24	21	.196	.294	.196
24	22	.233	.350	.233
24	23	-	-	.300
24	24	-	-	.150
24	25	.095	.142	.095
24	26	-	-	.150
24	27	.166	.249	.166
24	28	.078	.117	.078
24	29	.237	.356	.237
24	31	.381	.572	.381
24	32	.300	.450	.300

[a] City of Becker.
[b] Reduced rate, increasing at rate specified for plan F resulted in node going dry.
[c] Northern States Power Company Sherco Plant.

Sherburne County model--Continued

D	E	F	I	J	A	B	C	D	E	F
					PLAN					
0.206	0.274	0.342	27	29	0.084	0.126	0.084	0.126	0.168	0.210
.234	.312	.390	27	30	.150	.225	.150	.225	.300	.375
.213	.284	.355	27	34	-	-	.150	.225	.300	.375
.130	.174	.218	27	35	.120	.180	.120	.180	.240	.300
.294	.392	.490	28	13	-	-	.150	.225	.300	.375
.350	.466	.582	29	9	-	-	.150	.225	.300	.375
.450	.600	.750	29	32	.050	.075	.050	.075	.100	.125
.225	.300	.375	29	33	-	-	.150	.225	.300	.375
.142	.190	.238	30	31	-	-	.150	.225	.300	.375
.225	.300	.375	30	32	-	-	.150	.225	.300	.375
.249	.332	.415	30	33	.120	.180	.120	.180	.240	.300
.117	.156	.195	30	37	.292	.438	.442	.663	.884	1.10
.356	.474	.592	31	36	-	-	.150	.225	.300	.375
.572	.762	.952	32	35	-	-	.150	.225	.300	.375
.450	.600	.750	32	36	-	-	.300	.450	.600	.750
			33	35	-	-	.300	.450	.600	.750
			33	36	-	-	.150	.225	.300	.375
			34	35	-	-	.225	.338	.450	.562
			TOTAL		15.643	23.368	26.143	39.217	52.286	64.894

Table 7.--Summary of Sherburne County model analyses

[Budget figures are in cubic feet per second]

Plan	Pumping centers (number)	Hydrologic condition	Pumping stress	Inflow		Outflow				
				Recharge from precipitation	Leakage from streams	Leakage to Streams	Leakage to Bounding streams	Lakes	Evapotranspiration	Pumping
A	Present (96)	Average steady state	Actual	277	3	211	13	29	11	16
B	do	Drought	Actual x 1.5	207	3	149	10	22	6	23
C	Present + hypothetical expansion (153)	Average	Actual + estimated	277	3	202	13	28	11	26
D	do	Drought	(Actual + estimated) x 1.5	207	4	136	10	20	6	39
E	do	Average	(Actual + estimated) x 2	277	3	179	13	26	10	52
F	do	Drought	(Actual + estimated) x 3	207	5	113	10	19	5	65

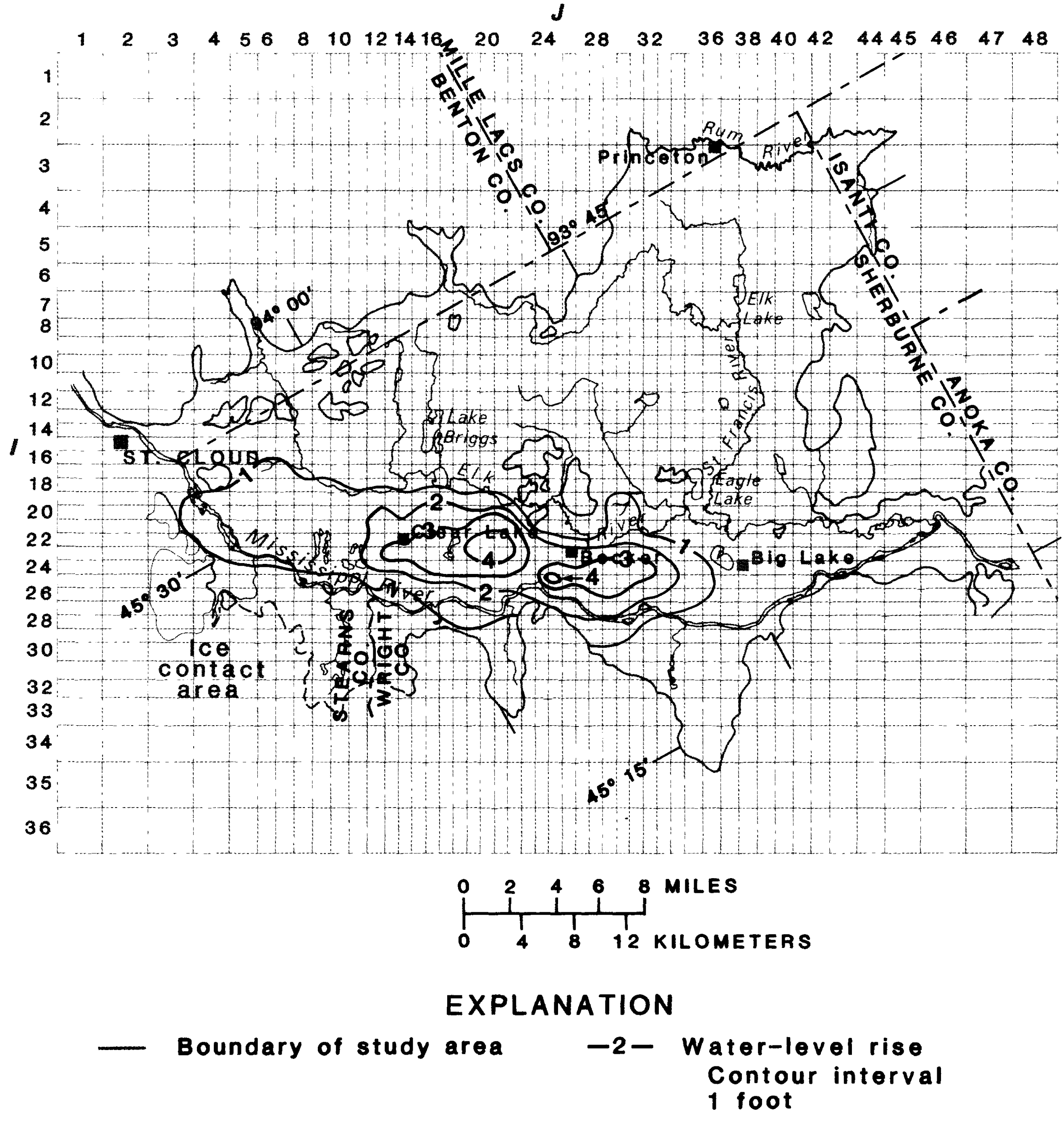


Figure 31.--Water-level rises that occur if pumping is removed from the Sherburne County steady-state model; plan A

Plan B simulates aquifer stresses that might occur during a drought of several years duration at the present level of development. Model-calculated water-level changes that might occur in less than 5 years (fig. 32) result from the combination of decreased recharge and increased pumping to compensate for below-normal precipitation. Reducing the long-term average annual recharge of 4, 8, and 12 inches by 25 percent to 3, 6, and 9 inches accounts for regional water-level declines of 2 to 4 feet. The accompanying increase in pumping causes a maximum of 3 feet of additional head loss.

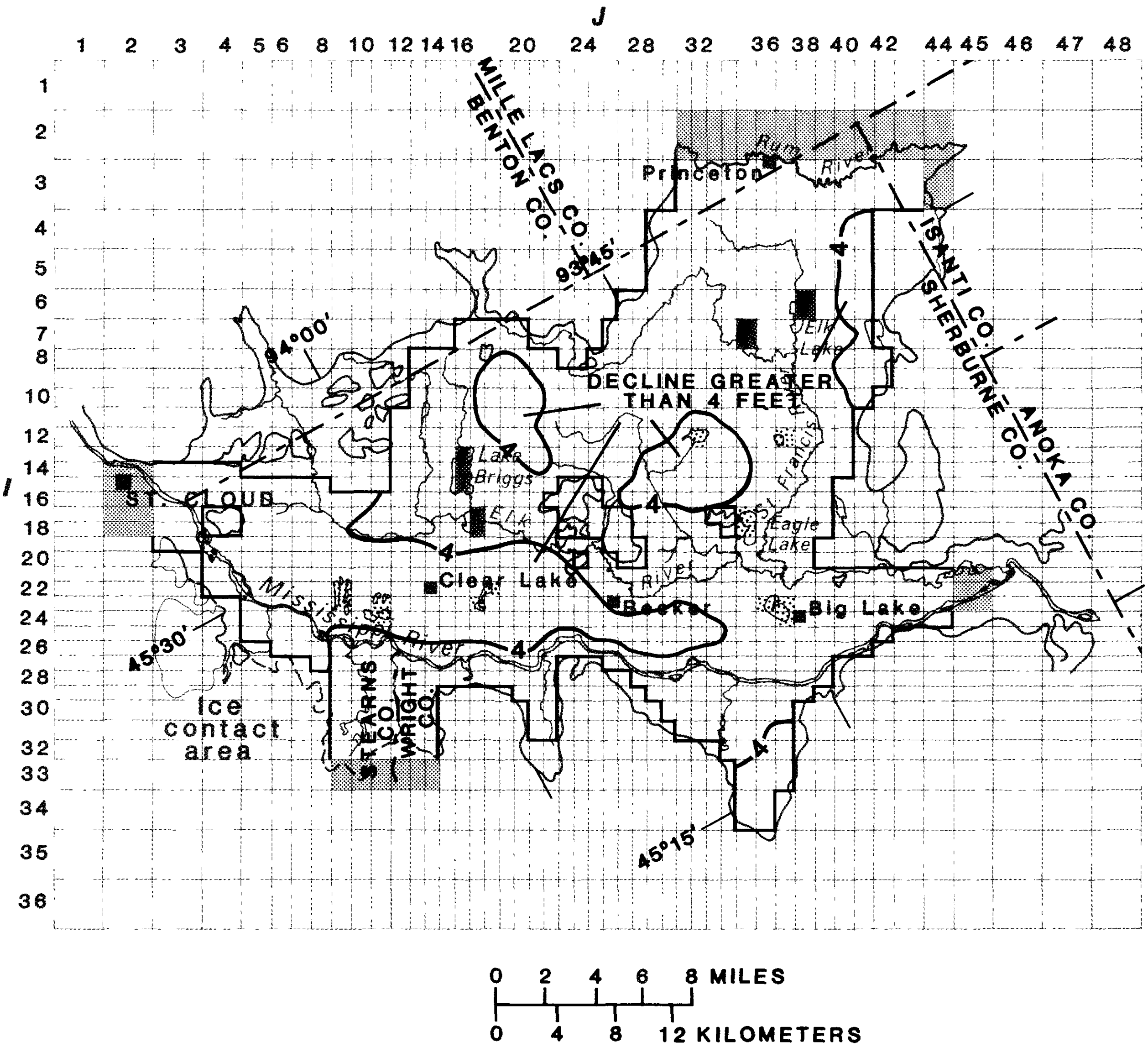
Decreased recharge and increased pumping reduces ground-water discharge to streams and lakes and reduces evapotranspiration as shown in table 7. Withdrawals from wells intercept water that normally would be discharged to streams. Analysis of model results indicates that ground-water discharge to streams would be reduced by about 30 percent in plan B.

Plan C simulates the effects of known pumping centers plus 57 additional centers representing a hypothetical expansion of irrigation. For long-term average conditions, the model indicates that the maximum water-level change due to added withdrawals would be 2 feet. Leakage to streams would be reduced less than 5 percent. During a drought (plan D), decreased recharge and increased pumping might result in water-level changes shown in figure 33. Leakage to streams would be reduced about 35 percent and lake levels would be lowered.

To evaluate the effects of a severe stress on the aquifer, withdrawals simulated in plan C were doubled for plan E. Analysis of model results indicate that water levels might decline as much as 9 feet, with greatest declines in the highly developed area between Becker and Clear Lake (fig. 34). Ground-water discharge to streams would be significantly reduced. Reductions in streamflow of 25 to 75 percent might be expected along the main stem of the Elk River, particularly between Big Lake and Becker. Discharge to streams tributary to and north of the Elk River would be reduced less than 10 percent because pumping centers for irrigation are few and scattered. Model-calculated discharge to the Mississippi River would be reduced about 15 percent.

An even more severe stress on the aquifer was applied in plan F. Model analysis indicates that reduced recharge and pumping at 3 times the rates simulated in plan C would result in water-level changes that locally exceed 16 feet (fig. 35). In areas where original aquifer thickness might be 50 feet or less, water-level changes of that magnitude would considerably reduce individual well yields.

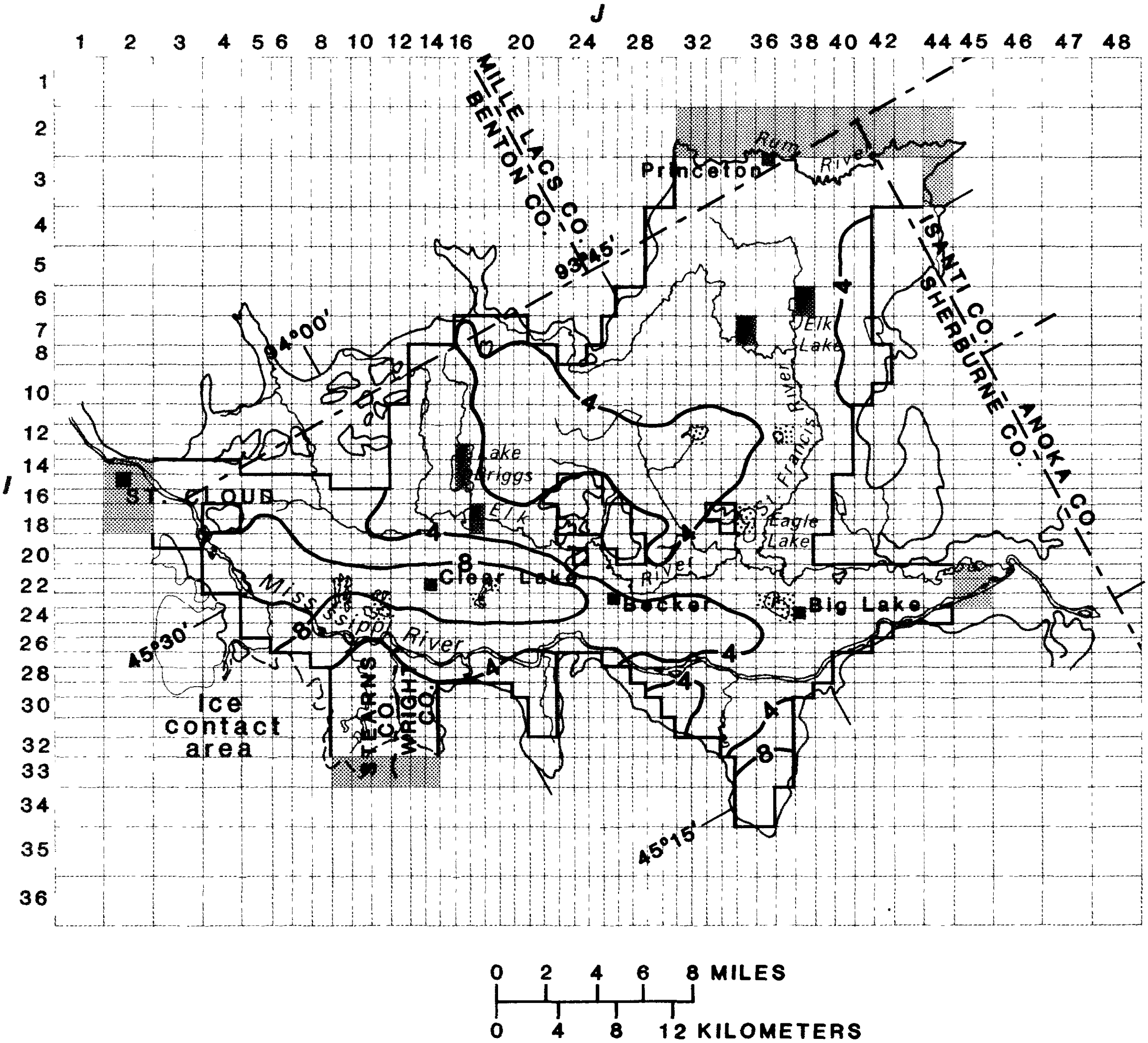
In plan F, discharge to streams would be greatly reduced. The model indicates that ground-water contributions to the main stem of the Elk River might be reduced at least 60 percent and, in several reaches, the Elk River would become a losing stream. Ground-water discharge to tributaries of the



EXPLANATION

- —— Boundary of study area
- —— Boundary of model, no flow
- Constant head node representing model boundary
- Constant head node representing flow-through lake
- Evaporation node representing no outflow lake
- —4— Water-level decline. Contour interval 4 feet

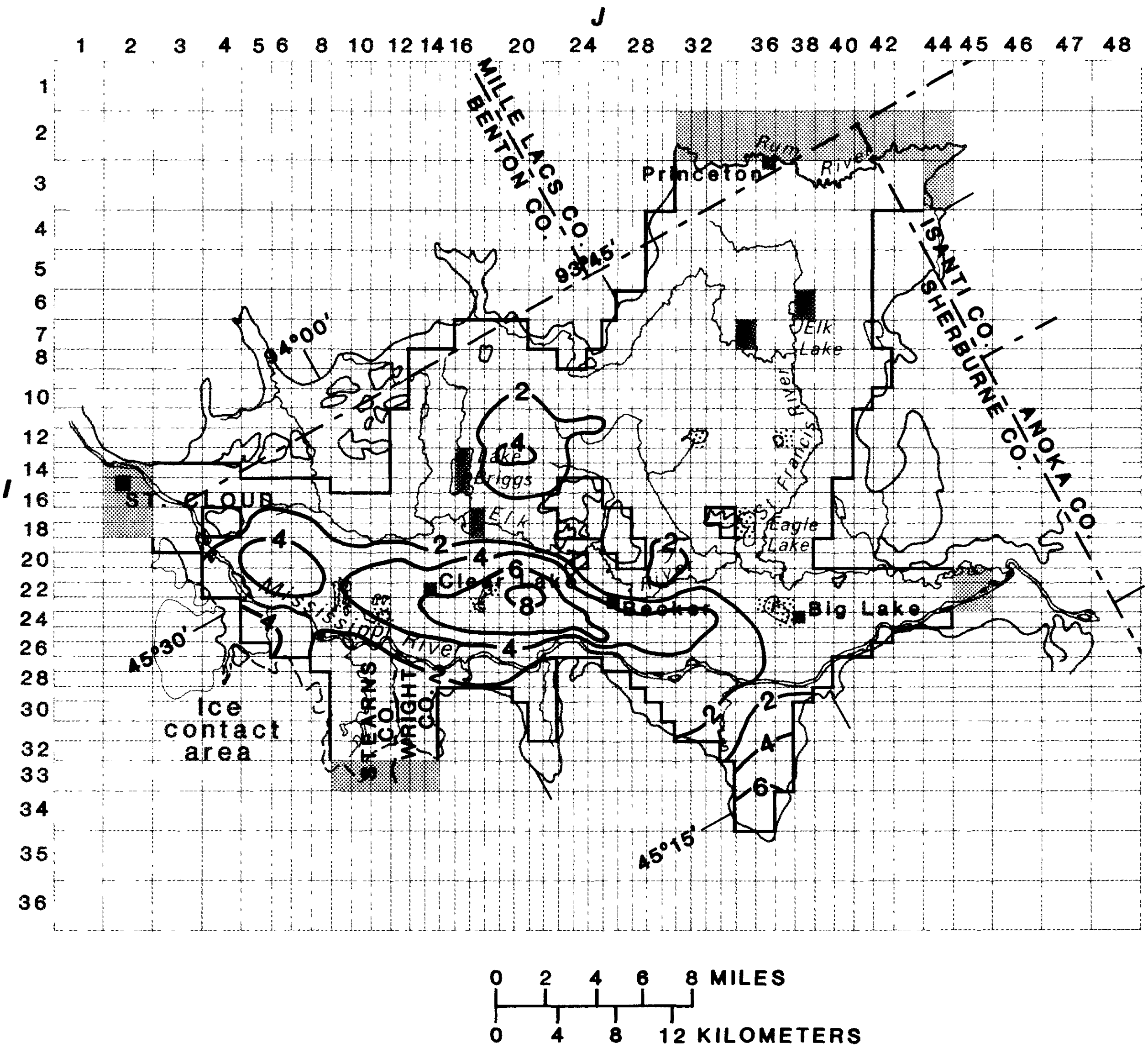
Figure 32.--Water-level declines that occur in Sherburne County model plan B



EXPLANATION

- Boundary of study area
- Boundary of model, no flow
- Constant head node representing model boundary
- Constant head node representing flow-through lake
- Evaporation node representing no outflow lake
- —4— Water-level decline. Contour interval 4 feet

Figure 33.--Water-level declines that occur in Sherburne County model plan D



EXPLANATION

—— Boundary of study area

—— Boundary of model, no flow

Constant head node representing model boundary

Constant head node representing flow-through lake

Evaporation node representing no outflow lake

—4— Water-level decline
Contour interval 2 feet

Figure 34.--Water-level declines that occur in Sherburne County model plan E

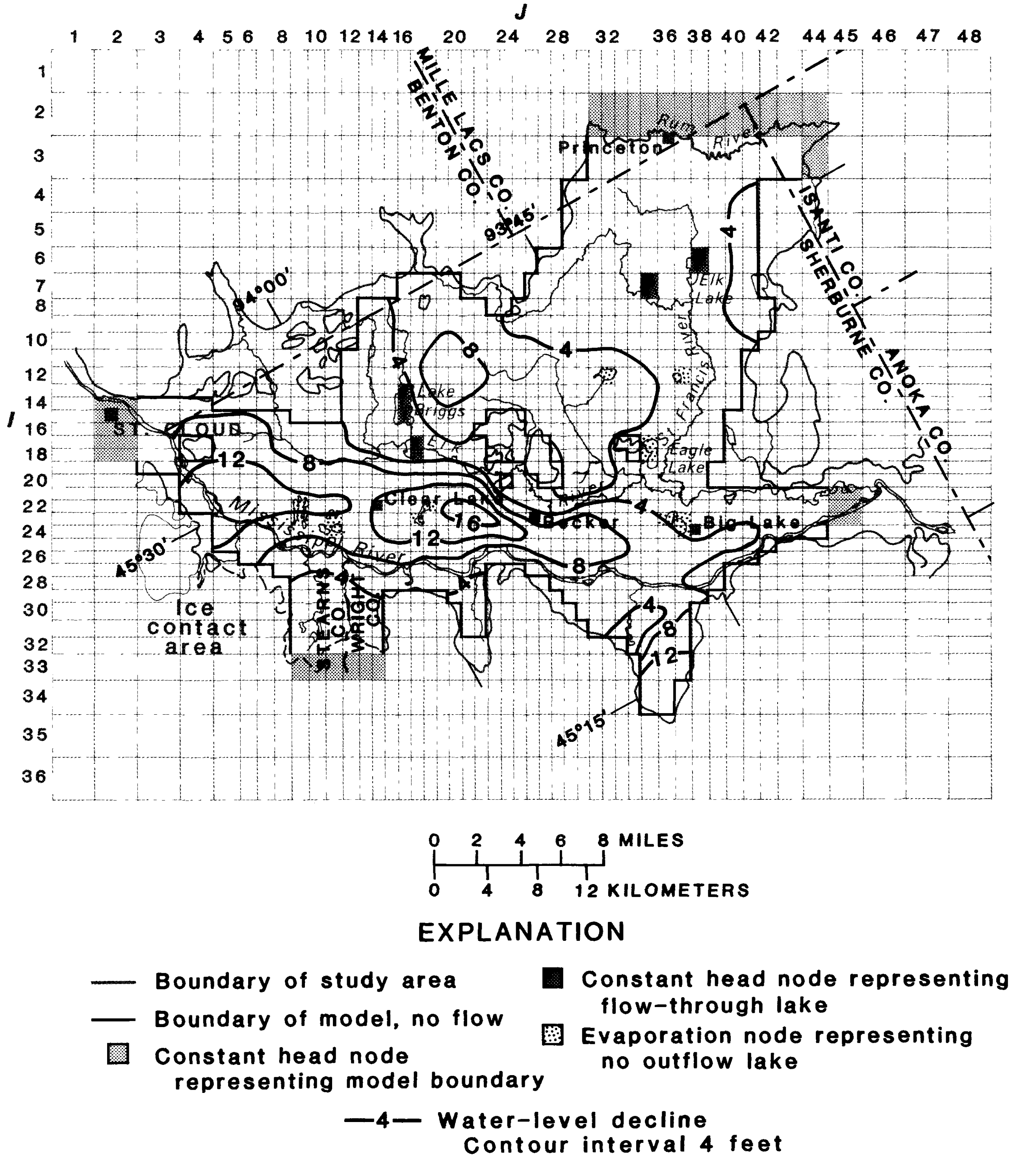


Figure 35.--Water-level declines that occur in Sherburne County model plan F

Elk River might be reduced 25 to 50 percent. The Mississippi River would receive about 40 percent less ground water in plan F. The greatest decreases would be in the reach south of the heavily developed area between Big Lake and Clear Lake.

Analysis of model results indicates that the Sherburne County surficial aquifer is capable of supporting additional withdrawals. Assuming average recharge, the aquifer is capable of supporting at least 150 pumping centers at present withdrawal rates (plan C). Compared to 1977, this would be a 50-percent increase in the number of pumping centers and a 60-percent increase in the total quantity of water pumped. The model indicates that such increases would regionally lower the water table less than 2 feet in the developed area. However, should an extended drought cause a 25-percent reduction in recharge and a 50-percent increase in pumping (plan D), water-level declines of nearly 10 feet might occur in heavily developed areas. Where the aquifer is less than 50 feet thick, the projected lowering of water levels in wells and lakes and decreases in streamflow might be severe.

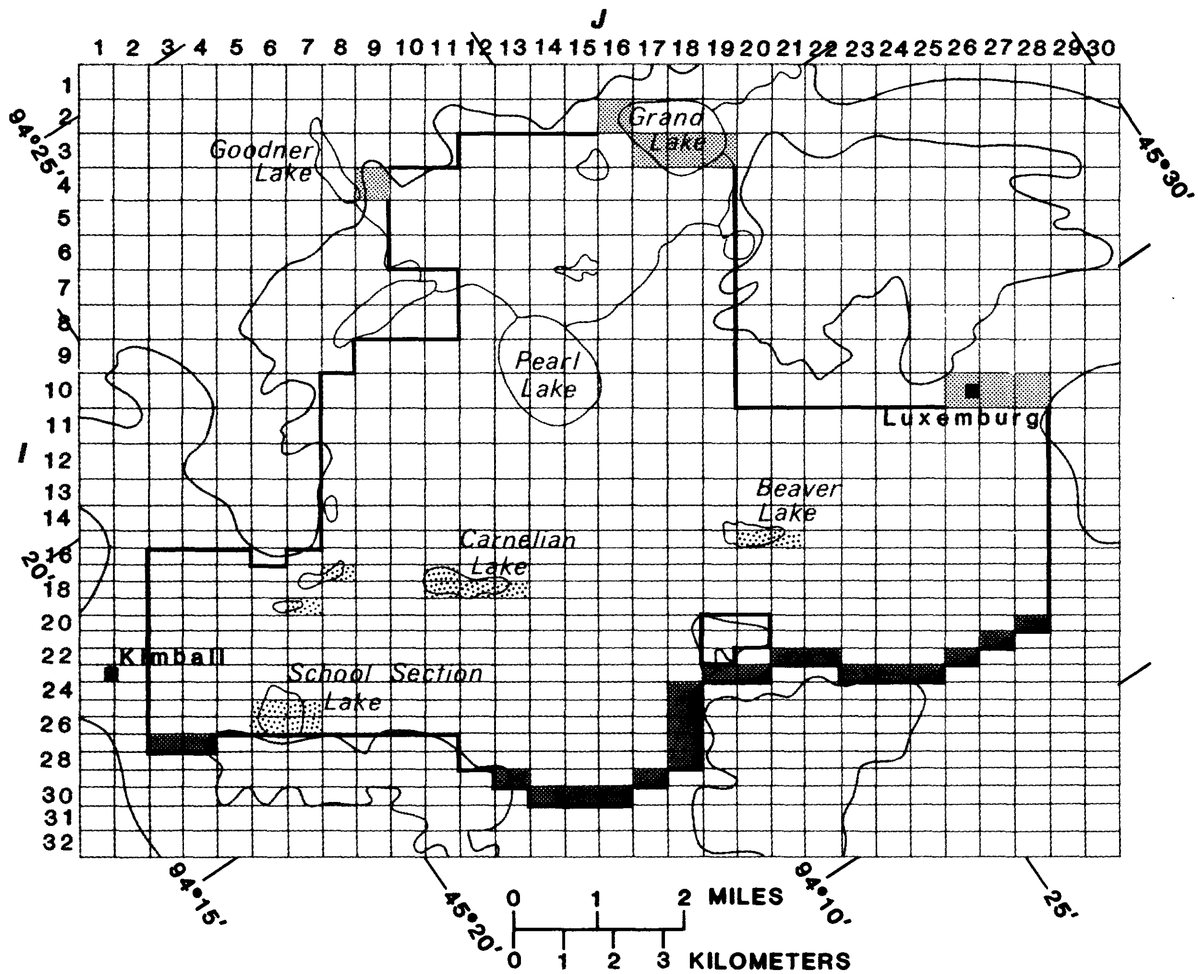
Maine Prairie

The Maine Prairie model represents 48 mi^2 of surficial outwash in southeastern Stearns County. A 32 X 30 variable grid was used to represent the surficial aquifer (fig. 36). The grid was oriented in a northwest-southeast direction. Grid blocks range in size from 0.08 to 0.16 mi^2 (51 to 102 acres), the smallest being in areas where ground water is currently being developed for irrigation and where major transmissivity changes occur within a short distance.

Grand Lake along the northern border and Goodner Lake on the western border were modeled as constant-head boundaries. The northern boundary was also modeled as constant head to simulate underflow into the Maine Prairie.

The water table has a steep gradient in the northeastern part of the modeled area (plate 1). The steep gradient is in an area of geomorphic change; from an outwash plain of higher altitude to a topographically irregular, ice-contact area to the east. At the base of the steep gradient, ground-water discharges to wetlands that are the headwaters for small streams. These streams were modeled as leaky to account for discharge from the aquifer. Pearl Lake and streams flowing in and out of Pearl Lake were modeled as leaky.

Aquifer hydraulic conductivity values were determined from an aquifer test (table 1, 122.28.18BCC) and were estimated from logs of test holes elsewhere. Model analyses indicated that the hydraulic conductivity of streambed materials is 1×10^{-6} (ft/s)/ft of streambed thickness; a value consistent with those obtained for streambed materials in other outwash areas in Minnesota. Underflow along the eastern boundary was simulated



EXPLANATION

- Boundary of study area
- Boundary of model, no flow
- Constant head node representing model boundary
- Leaky node representing underflow out
- Evaporation node representing no outflow lake

Figure 36.--Finite-difference grid and boundary conditions for the Maine Prairie model

using a leakage rate of 1 x 10^{-10} (ft/s)/ft of streambed thickness. The low value reflects rapid thinning of the aquifer and the relatively impermeable streambed materials along the eastern edge. Streams along the eastern edge originate in wetlands where peat restricts upward movement of ground water.

Average annual recharge to the surficial aquifer is estimated to be 8 inches in upland areas and 4 inches in wetlands and lakes (fig. 37).

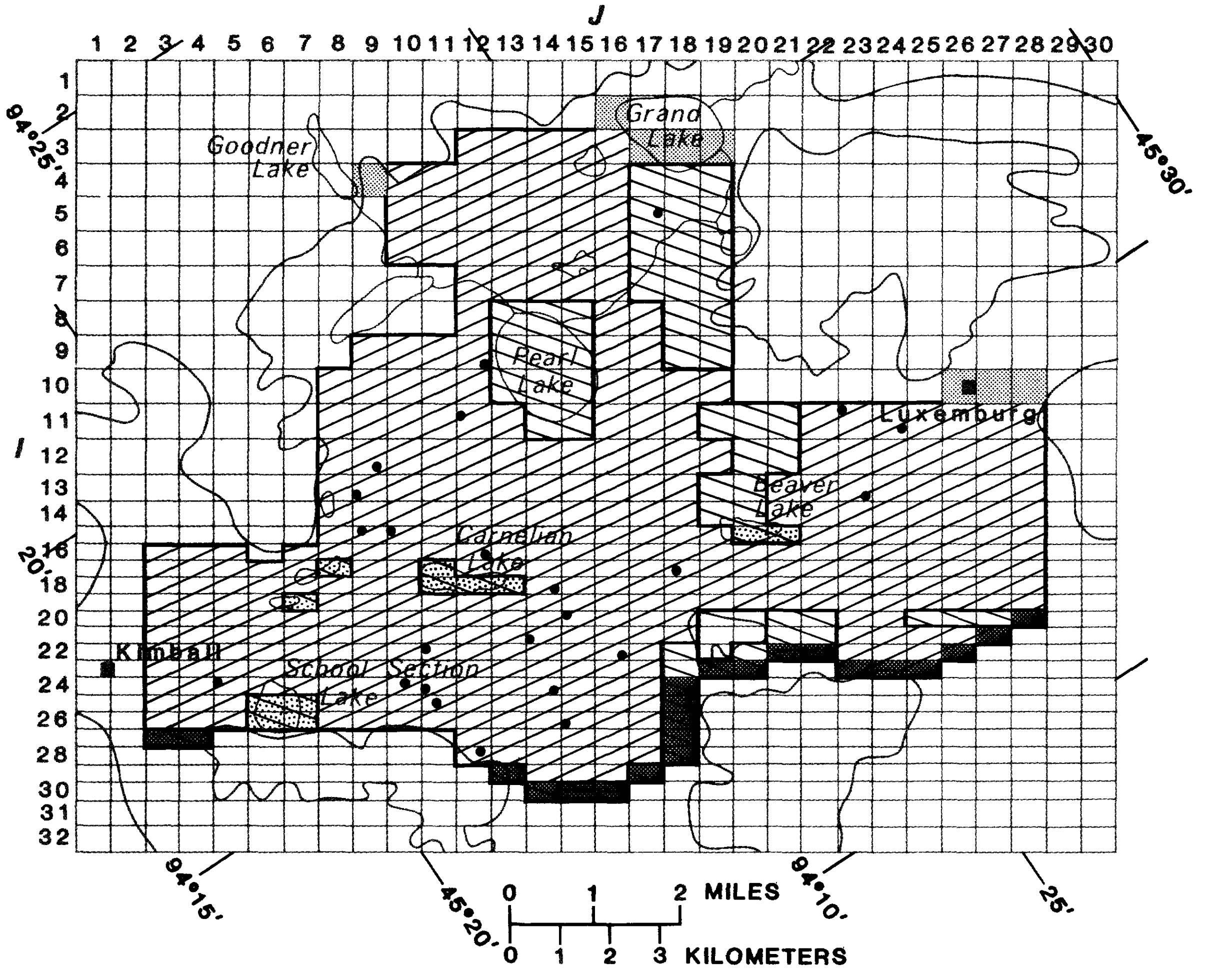
Calibration

The Maine Prairie model was calibrated by comparing model-calculated heads with estimated average aquifer heads determined from records of water-level measurements made. Heads measured in irrigation and observation wells in May 1978 (table 8) are considered to approximate long-term average water levels. Figure 38 compares the configuration of the water table based on measured heads with that based on heads calculated by the model. Similarity of values and configurations indicate that a reasonable calibration was achieved.

Because streamflow is insignificant in the main part of the modeled area, changes in streamflow could not be used for model calibration. However, the total leakage to streams along the eastern boundary is comparable to values measured during base-flow conditions in May 1978.

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

INFLOW	ft^3/s
Recharge from precipitation................	24.7
Leakage from streams.......................	1.3
Total.....	26.0
OUTFLOW	
Leakage to streams.........................	15.9
Leakage to bounding streams and lakes......	6.2
Pumping....................................	2.0
Evapotranspiration.........................	1.9
Total.....	26.0



EXPLANATION

- Boundary of study area
- Boundary of model, no flow
- Constant head node representing model boundary
- Leaky node representing underflow out
- Evaporation node representing no outflow lake
- • Observation well

Annual recharge, in inches:

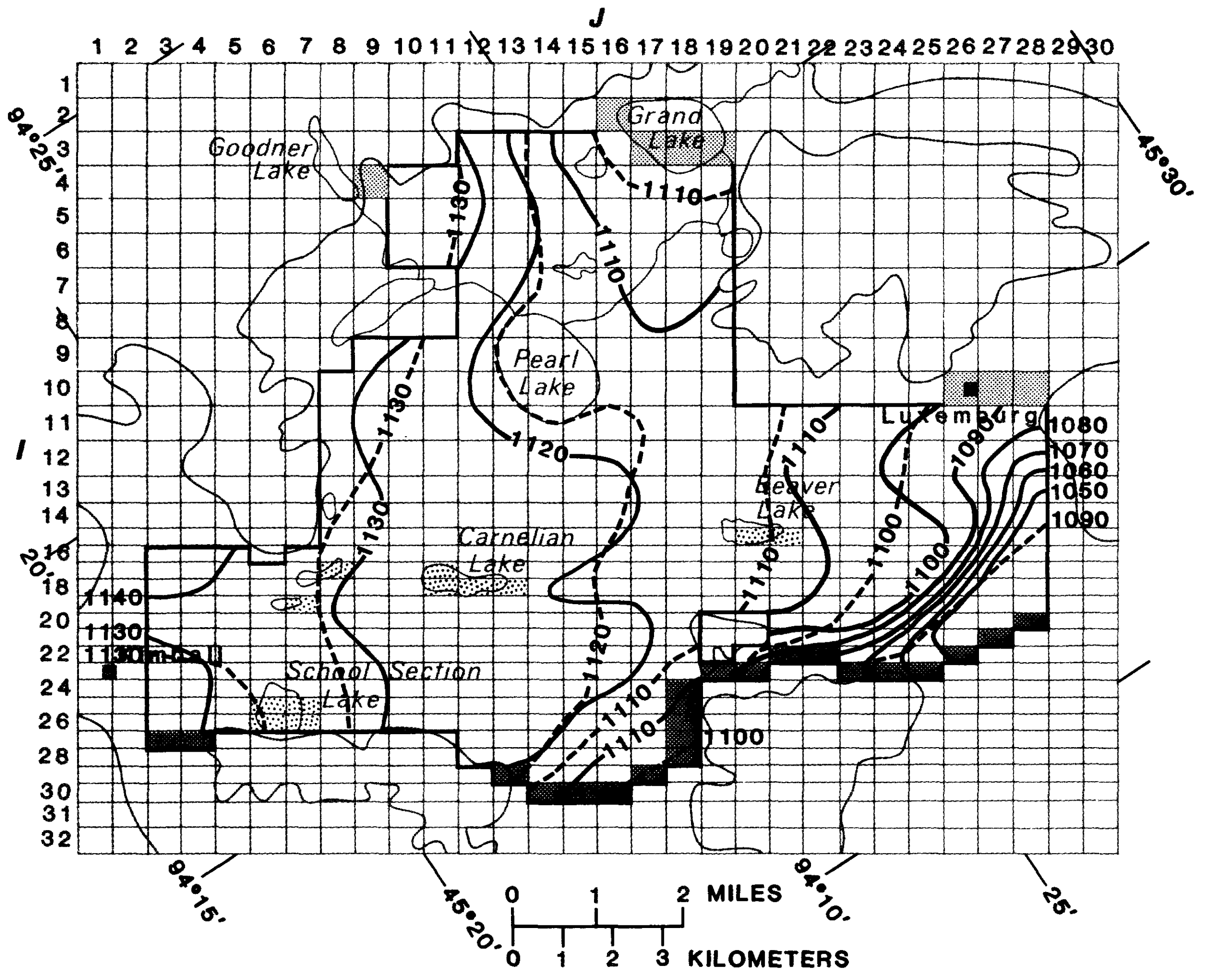
- 4
- 8

Figure 37.--Distribution of modeled recharge to the surficial aquifer

Table 8.--Maine Prairie model-calculated heads compared with measured heads in selected wells, May 1978

Node		Head, datum is mean sea level	
I	J	Estimated, May 1978[b]	Model calculated
5	17	1106	1113
9	12	1121	1123
[a] 11	12	1122	1124
[a] 11	23	1106[R]	1103
11	24	1101	1101
[a] 12	9	1130	1130
[a] 13	9	1132	1130
[a] 13	13	1124	1124
[a] 13	23	1102	1102
[a] 15	9	1133	1129
15	10	1128	1128
[a] 16	12	1130	1125
17	18	1118	1116
[a] 18	14	1118	1123
[a] 20	15	1120	1122
[a] 21	14	1132[R]	1123
[a] 22	11	1130[R]	1127
[a] 22	16	1125	1119
[a] 24	5	1132	1130
24	10	1127	1128
[a] 24	11	1127	1126
[a] 24	14	1123	1122
[a] 25	11	1130[R]	1126
[a] 26	15	1121	1119
[a] 28	12	1125	1124

[a]Irrigation well, head may be affected by residual drawdown.
[b]Measured head was adjusted to estimate head at center of node. See figure 37 for position of well in node.
[R]Reported at time of drilling.



EXPLANATION

- Boundary of study area
- Boundary of model, no flow
- Constant head node representing model boundary
- Leaky node representing underflow out
- Evaporation node representing no outflow lake
- —1130— Water-table contour based on heads measured in May 1978. Contour interval 10 feet. Datum is mean sea level
- --1130--- Water-table contour based on model calculated heads. Contour interval 10 feet. Datum is mean sea level

Figure 38.--Configuration of the water table based on measured heads compared with configuration based on model calculated heads

Stress

The steady-state model simulates long-term "average" hydrologic conditions. Because ground-water withdrawals for irrigation are a significant part of the total water budget, they are included in the steady-state simulation. To estimate the effects of hypothetical increases in development and in pumping during periods of below-normal precipitation (drought), the model was stressed similarly to the Sherburne County model with the following changes:

<u>Plans</u>

A, C, and E ... average recharge equal to 4 and 8 in/yr

B, D, and F ... average recharge equal to 3 and 6 in/yr (represents drought conditions)

Pumping-center locations are shown in figure 39 and pumping rates applied for each plan are listed in table 9.

Results

The model was used to estimate the response of the aquifer to stresses imposed by hypothetical increases in pumpage and by extended drought conditions. Results obtained are considered to be a reasonable approximation of possible water-level changes.

Plan A is a steady-state simulation of average conditions that includes present irrigation pumping. Model-calculated heads compare with measured heads as shown in table 8 and figure 38. Pumpage, as modeled from the surficial aquifer, totaled about 470 million gallons in 1977 distributed as shown in table 9 and figure 39. Removal of all pumping from the steady-state model results in water-level rises of as much as 3 feet (fig. 40). Table 10 is a summary of the modeling plans and aquifer responses.

Plan B simulates aquifer stresses that might occur during an extended drought. As a result of reduced recharge and a 50-percent increase in withdrawal rates, lowering of water levels in excess of 8 feet might be expected (fig. 41). A major part of the decline is attributable to the 25-percent reduction in recharge.

Reduced recharge and increased pumping during a drought effect changes in all budget items as summarized in table 10. Because recharge from precipitation is the major inflow item, the total water available is considerably reduced during a drought. Lowered heads reduce discharge to streams and underflow out of the area to about two-thirds of the long-term average.

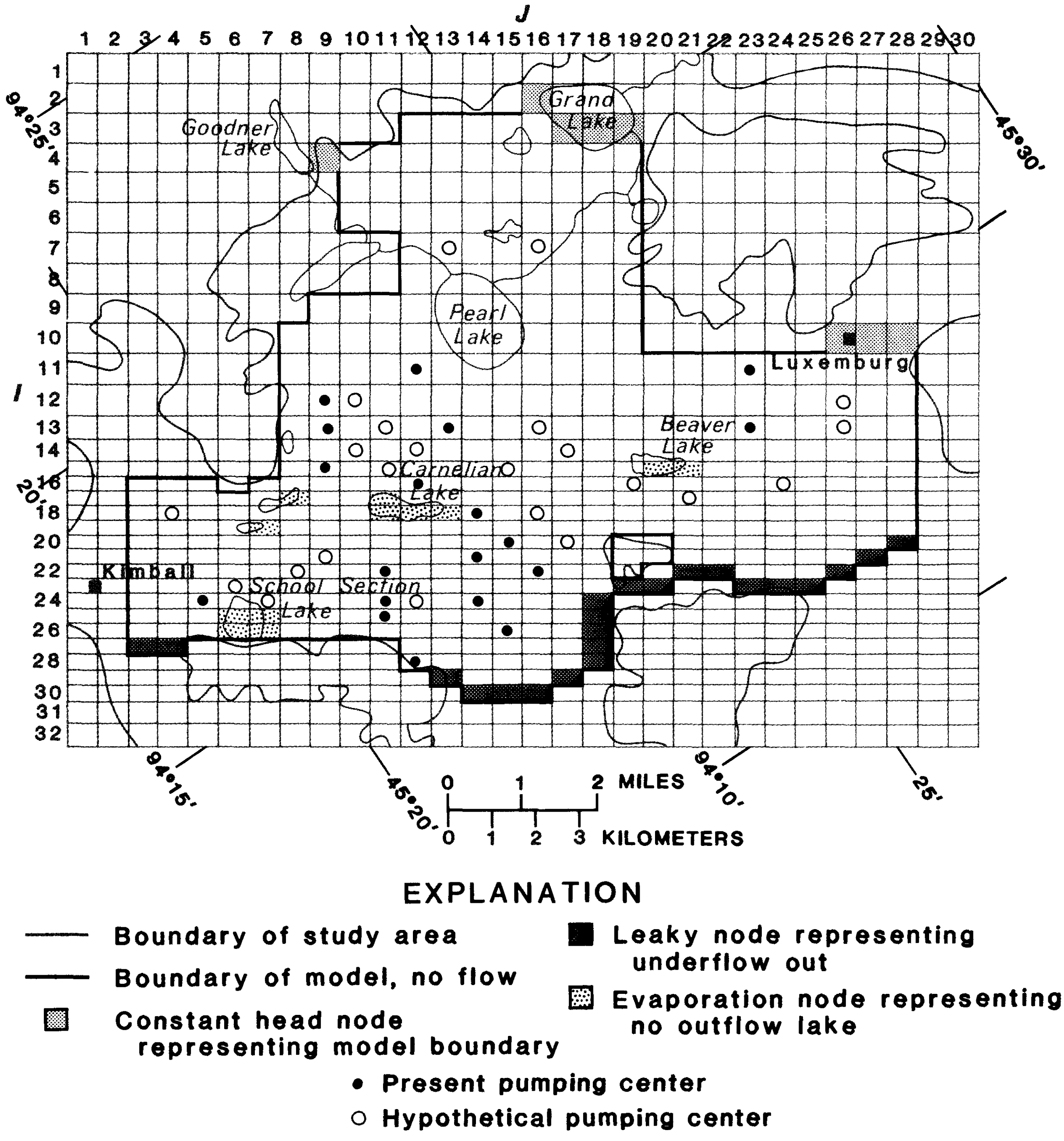
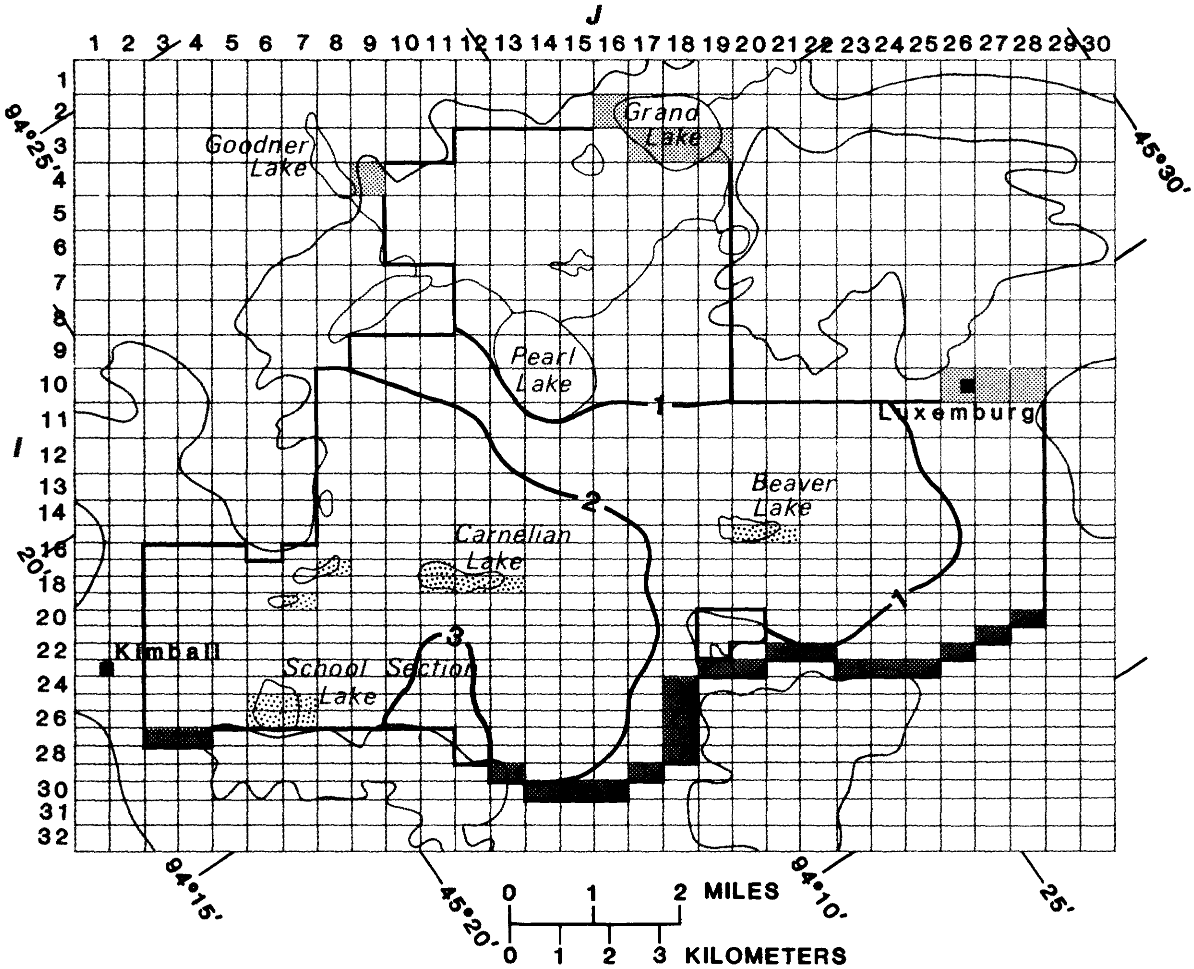


Figure 39.--Pumping center locations for the Maine Prairie model

Table 9.--Nodal withdrawal rates, Maine Prairie model
[in cubic feet per second]

NODE		PLAN					
I	J	A	B	C	D	E	F
7	13	-	-	0.150	0.225	0.300	0.300[a]
7	16	-	-	.150	.225	.300	.375
11	12	0.170	0.255	.170	.255	.340	.425
11	23	.080	.120	.080	.120	.160	.200
12	9	.090	.135	.090	.135	.180	.225
12	10	-	-	.150	.225	.300	.375
12	26	-	-	.150	.225	.300	.375
13	9	.070	.105	.070	.105	.140	.175
13	11	-	-	.150	.225	.300	.375
13	13	.030	.045	.030	.045	.060	.075
13	16	-	-	.150	.225	.300	.175
13	23	.070	.105	.070	.105	.140	.375
13	26	-	-	.150	.225	.300	.375
14	10	-	-	.150	.225	.300	.150[a]
14	12	-	-	.150	.225	.300	.150[a]
14	17	-	-	.150	.225	.300	.375
15	9	.140	.210	.140	.210	.280	.350
15	11	-	-	.150	.225	.300	.150[a]
15	15	-	-	.150	.225	.300	.375
16	12	.080	.120	.080	.120	.160	.200
16	19	-	-	.150	.225	.300	.375
16	24	-	-	.150	.225	.300	.375
17	21	-	-	.150	.225	.300	.375
18	4	-	-	.150	.225	.300	.150[a]
18	14	.120	.180	.120	.180	.240	.300
18	16	-	-	.150	.225	.300	.375
20	15	.090	.135	.090	.135	.180	.225
20	17	-	-	.150	.225	.300	.375
21	9	-	-	.150	.225	.300	.375
21	14	.220	.330	.220	.330	.440	.550
22	8	-	-	.150	.225	.300	.375
22	11	.130	.195	.130	.195	.260	.325
22	16	.080	.120	.080	.120	.160	.200
23	6	-	-	.150	.225	.300	.375
24	5	.100	.150	.100	.150	.200	.250
24	7	-	-	.150	.225	.300	.375
24	11	.080	.120	.080	.120	.160	.200
24	12	-	-	.150	.225	.300	.375
24	14	.070	.105	.070	.105	.140	.175
25	11	.170	.255	.170	.255	.340	.425
26	15	.130	.195	.130	.195	.260	.325
28	12	.080	.120	.080	.120	.160	.200
TOTAL		2.000	3.000	5.450	8.175	10.900	11.900

[a] Reduced rate, increasing at rate specified for plan F resulted in node going dry.



EXPLANATION

—— Boundary of study area

—— Boundary of model, no flow

Constant head node representing model boundary

Leaky node representing underflow out

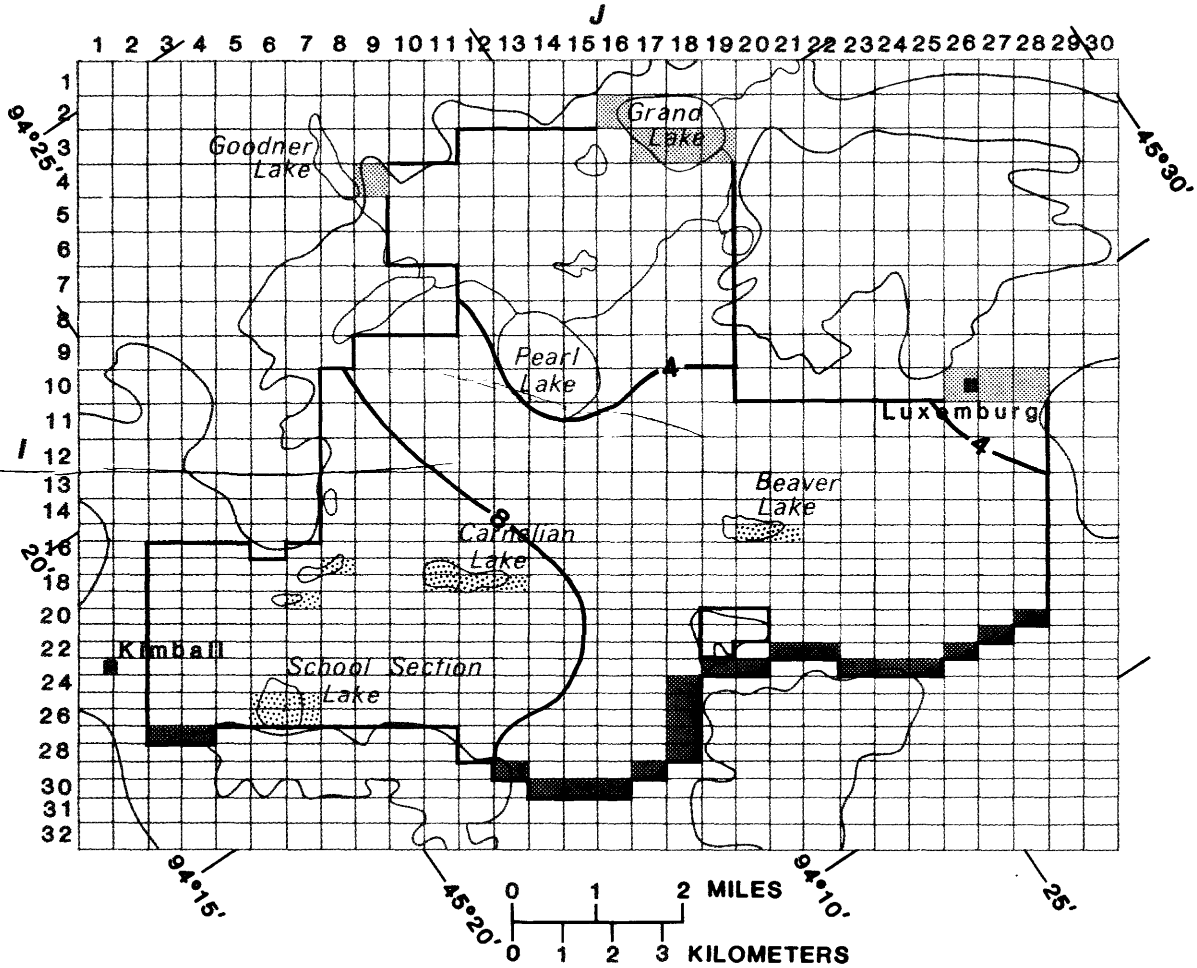
Evaporation node representing no outflow lake

—2— Water-level rise
Contour interval 1 foot

Figure 40.--Water-level rises that occur if pumping is removed from the Maine Prairie steady-state model; plan A

Table 10.--Summary of Maine Prairie model analyses
[Budget figures are in cubic feet per second]

Plan	Pumping centers (number)	Hydrologic condition	Pumping stress	Inflow		Outflow			
				Recharge from precipitation	Leakage from streams	Leakage to		Evapotranspiration	Pumping
						Streams	Bounding streams and lakes		
A	Present (19)	Average	Actual	24.7	1.3	15.9	6.2	1.9	2.0
B	do	Drought	Actual x 1.5	17.6	1.6	10.5	4.3	1.4	3.0
C	Present + hypothetical expansion (42)	Average	Actual + estimated	24.6	1.4	13.4	5.4	1.7	5.5
D	do	Drought	(Actual + estimated) x 1.5	17.6	2.1	6.8	3.5	1.2	8.2
E	do	Average	(Actual + estimated) x 2	24.6	1.6	9.5	4.5	1.3	10.9
F	Present + hypothetical expansion (40)	Drought	(Actual + estimated) x 3	17.5	2.5	4.0	3.1	1.0	11.9



EXPLANATION

- Boundary of study area
- Boundary of model, no flow
- Constant head node representing model boundary
- Leaky node representing underflow out
- Evaporation node representing no outflow lake
- —8— Water-level decline. Contour interval 4 feet

Figure 41.--Water-level declines that occur in Maine Prairie model plan B

Plan C represents a hypothetical increase in the number of irrigation pumping centers. For long-term average hydrologic conditions, doubling the number of pumping centers and nearly tripling withdrawals might lower water levels as shown in figure 42. Discharge to streams and underflow out of the area are reduced 16 and 13 percent, respectively, from plan A conditions.

Under drought conditions in plan D, water-level changes are accentuated due to reduced recharge and increased pumping (fig. 43). Large water-level declines reflect the limited amount of water available in this relatively small aquifer that is bounded largely by impermeable materials. The model indicates that discharge to streams would decrease by more than 50 percent and underflow out of the area would decrease by nearly 50 percent as larger amounts of water are withdrawn from wells.

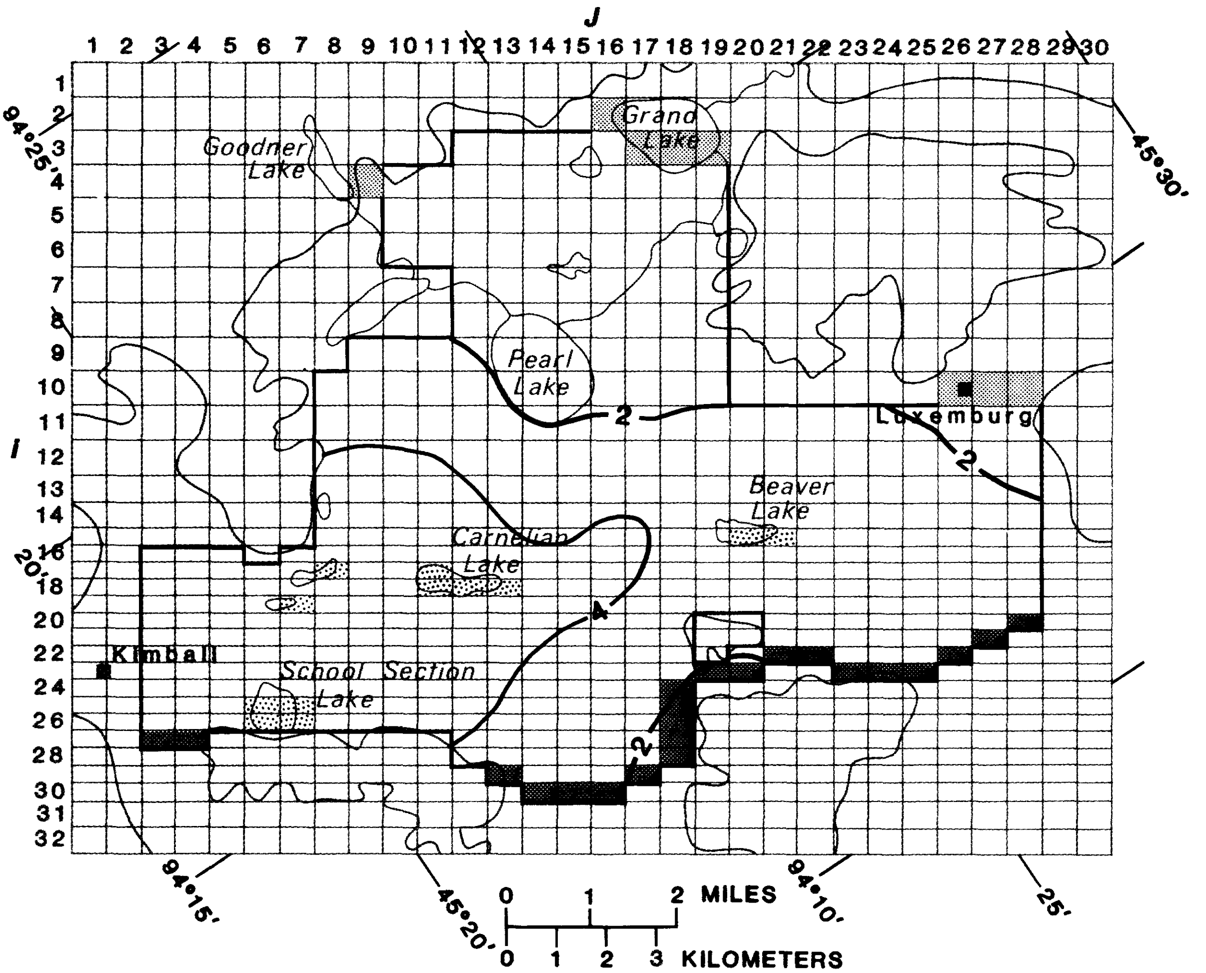
Model plan E imposes a severe pumping stress on the ground-water system when recharge is normal. Withdrawal rates applied in plan C were doubled, resulting in lowering of water levels in excess of 14 feet in the southern part of the area (fig. 44).

The most severe stress on the aquifer occurs in plan F due to increased pumping and drought. Indicated water-level declines (fig. 45) would significantly reduce saturated thickness and, therefore, reduce individual well yields in much of the area. The model analysis indicates that discharge to streams would be reduced to one-fourth of the long-term average. Underflow and evapotranspiration from the aquifer would be one-half that of the long-term average.

The model analyses indicate that the Maine Prairie surficial aquifer is capable of supporting additional withdrawals. Doubling the number of pumping centers (total annual pumping, 1.3 billion gallons, plan C) would lower water levels less than 6 feet when recharge is average. Doubling withdrawal rates at each center would lower water levels as much as 15 feet (total annual pumping, 2.6 billion gallons, plan E). Reduced recharge and increased pumping during an extended drought would have an even greater effect on water levels. If water levels were lowered as much as 20 feet, all components of the ground-water system would be substantially changed. A drought of one or two years duration, such as that experienced in 1976-77, has short-term effects on the ground-water system. Present (1979) data indicate that the system has recovered to pre-drought conditions.

Modeling Limitations

The model is a tool that simulates major components of the ground-water system. Accuracy of results is a function of the conceptualization of that system and the accuracy of input data. Required generalizations of hydrologic parameters make the model a regional approximation; detailed local results should not be expected. The combination of parameters used in this



EXPLANATION

Boundary of study area

Boundary of model, no flow

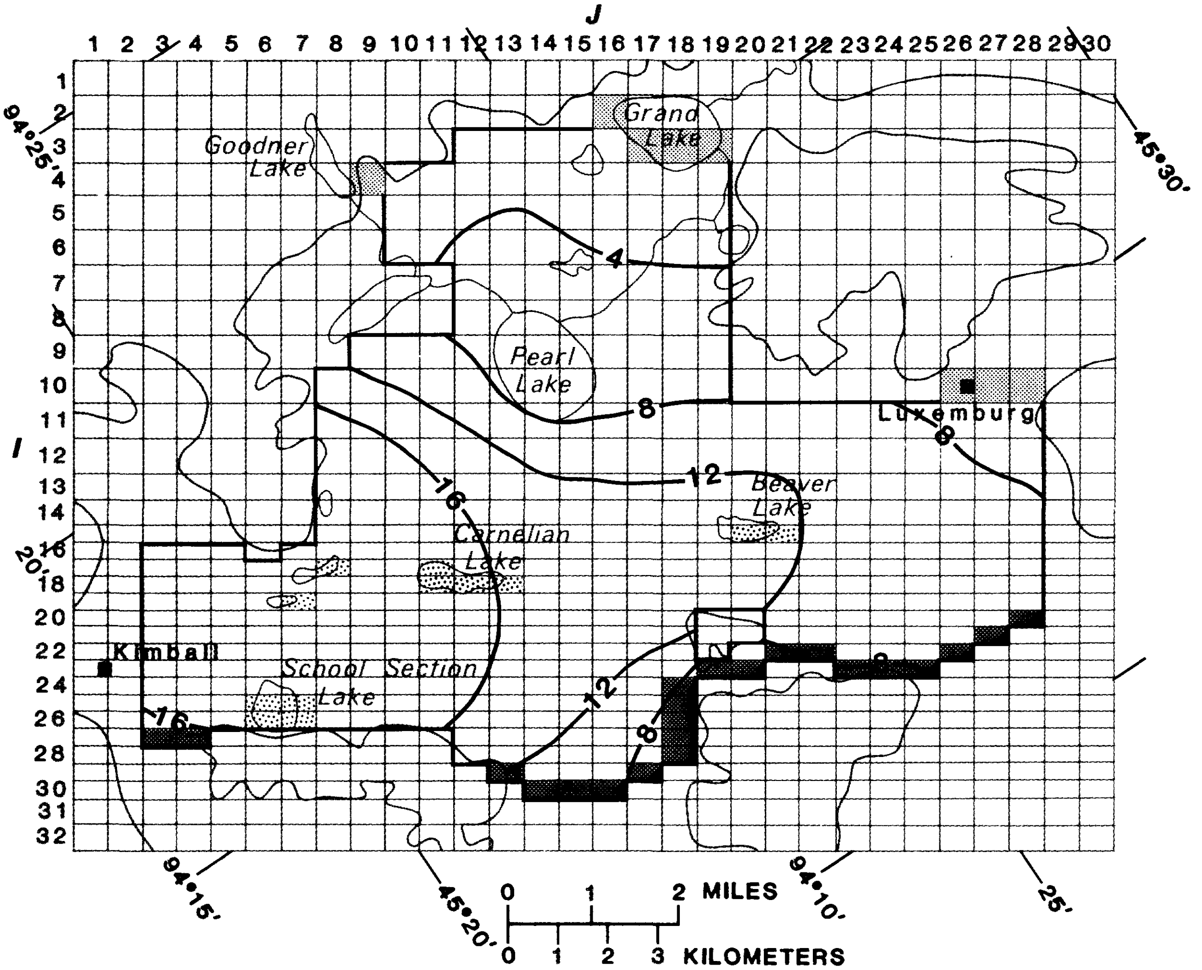
Constant head node representing model boundary

Leaky node representing underflow out

Evaporation node representing no outflow lake

—4— Water-level decline
Contour interval 2 feet

Figure 42.--Water-level declines that occur in Maine Prairie model plan C



EXPLANATION

- Boundary of study area
- Boundary of model, no flow
- Constant head node representing model boundary
- Leaky node representing underflow out
- Evaporation node representing no outflow lake
- —4— Water-level decline. Contour interval 4 feet

Figure 43.--Water-level declines that occur in Maine Prairie model plan D

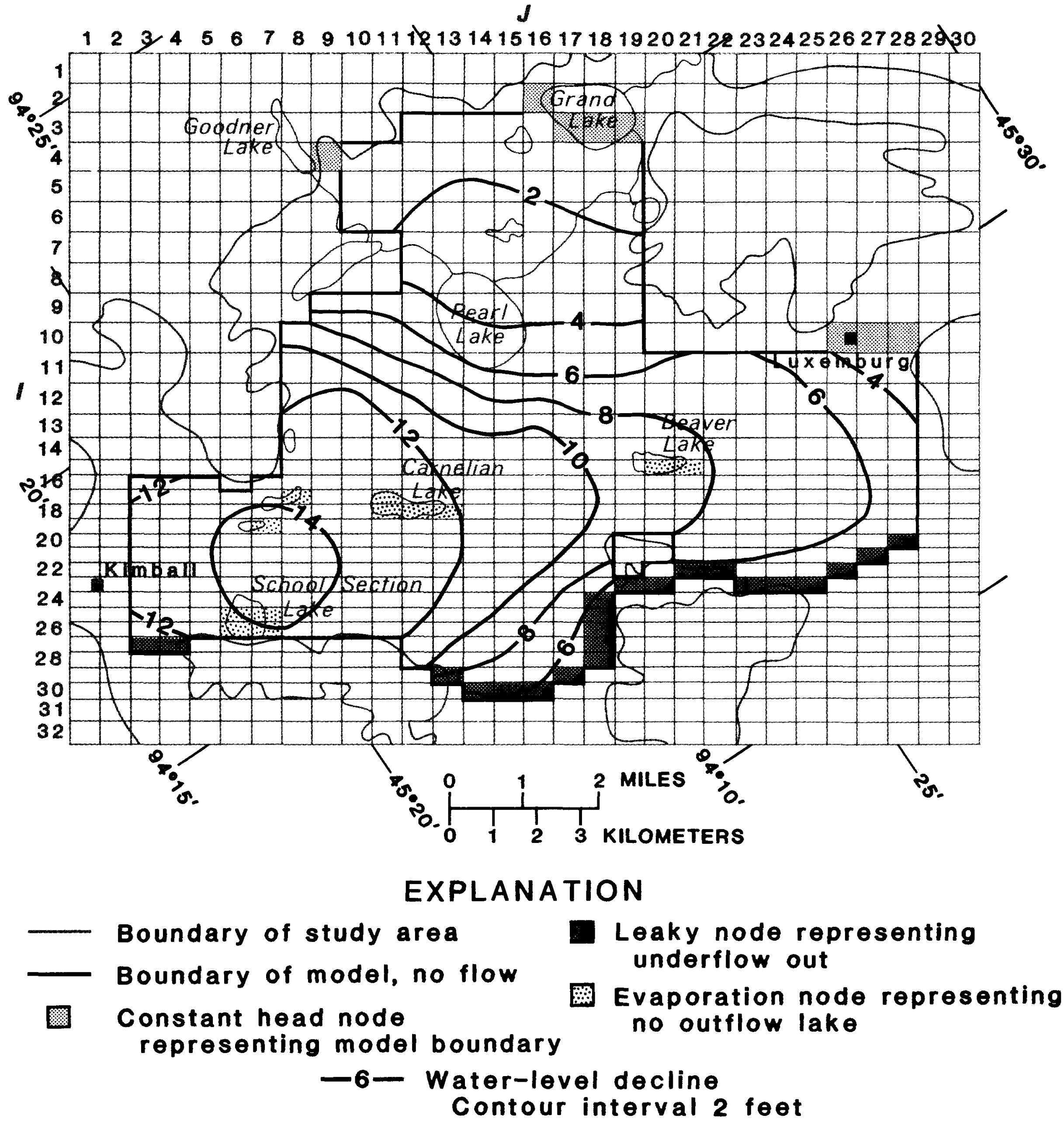
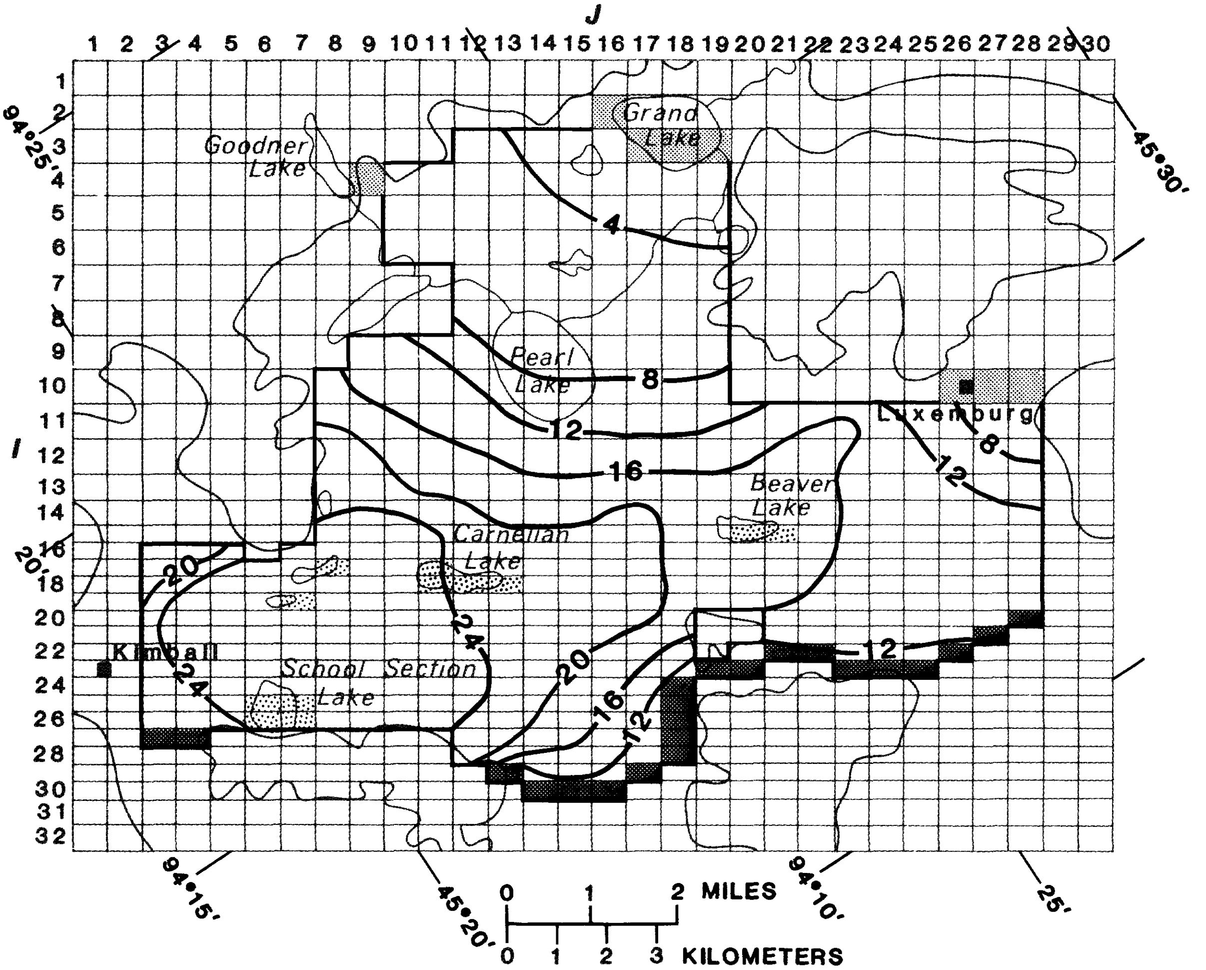


Figure 44.--Water-level declines that occur in Maine Prairie model plan E



EXPLANATION

—— Boundary of study area

—— Boundary of model, no flow

Constant head node representing model boundary

Leaky node representing underflow out

Evaporation node representing no outflow lake

—12— Water-level decline
Contour interval 4 feet

Figure 45.--Water-level declines that occur in Maine Prairie model plan F

study resulted in models that performed well when compared to known aquifer responses. Solutions obtained are not unique and might be achieved with different combinations of parameters. Reasonableness of input data suggests that the solutions obtained approximate realistic values and the model can be used to evaluate the hydrologic effects of a wide range of hypothetical changes in ground-water development.

Several inadequacies in data became apparent during the modeling process.

1. Accurate altitude control is needed to compare subtle head differences. Altitudes used were interpolated from U.S. Geological Survey $7^{1}/2$-minute topographic maps with 10-foot contour intervals.

2. Better definition of head variations with depth is needed to define ground-water-flow systems. The relationship of confined drift and bedrock aquifers to the unconfined aquifer needs to be determined.

3. Hydraulic significance of clay lenses within the surficial aquifer needs to be determined. To do so requires more accurate delineation of the clay lenses. Even though subsurface control appears to be adequate in some areas, glacial deposits commonly change drastically within short distances and correlation of individual units, such as clay lenses, is difficult.

4. The models are most sensitive to hydraulic conductivity of streambed materials. No field data other than scattered observations are available. Quantitative field data are needed.

5. Accurate and complete pumping records are needed. Presently, available data on time of pumping and quantity of water pumped are incomplete and some are of questionable accuracy.

6. The amount of irrigation water returned to the aquifer is unknown.

7. Historical records of aquifer response to known stresses are needed for model calibration. If such were available, the time element could be considered and transient analyses made.

If all of the above were available, the models could be used to predict aquifer response to selected stresses with a greater degree of reliability.

WATER QUALITY

Water in the study area is of the calcium bicarbonate type, based on the most abundant cation and anion, and is suitable chemically for most uses. Table 11 is a compilation of ground-water analyses from the study area. Ground water from drift aquifers is typically very hard (more than 180 mg/L hardness as $CaCO_3$) and contains high concentrations of dissolved iron. The degree of mineralization of water is expressed as the concentration of dissolved solids. The relationship of specific conductance to dissolved solids is shown in figure 46. The most highly mineralized ground water is generally found in Stearns County (fig. 47) where the surficial outwash was derived from the carbonate-rich Des Moines Lobe. The dissolved-solids concentration is nearly as high in water from Mississippi River valley-train deposits in Sherburne County. The least mineralized water is in Benton County where aquifer materials include few carbonate rocks and were derived primarily from the Superior Lobe. Water in streams at base flow is largely ground water and, therefore, is similar in chemical quality (table 12). Concentrations change depending on discharge, as shown for Little Rock Creek, St. Francis River, and Elk River. Areal variations in dissolved solids in lakes and streams at one time are shown in figure 47.

Irrigation is commonly associated with increased use of fertilizers to obtain optimum crop yields. Because infiltration is rapid in sandy soils, ground water in irrigated areas is highly susceptible to quality changes from fertilizer applications in excess of crop requirements. Nitrogen, phosphorus, and potassium, which are major fertilizer constituents, and chloride and dissolved solids were considered as possible indicators of water-quality changes attributable to irrigation in the present study area. Chloride and dissolved-solids concentrations can increase mainly because of greater evapotranspiration resulting from irrigation.

Nitrate and chloride concentrations in ground water are highest in the area between the Elk and Mississippi Rivers in Sherburne County (figs. 48 and 49). Irrigation has been practiced in that area for about 20 years. In several places, nitrate concentrations exceed the limit recommended by the Minnesota Pollution Control Agency for drinking water (table 11). As such they present a health hazard for infants, with the potential for causing methemoglobinemia or blue-baby disease. Nitrate concentrations are considerably lower in less intensively farmed areas such as in and around the Sherburne National Wildlife Refuge.

A general increase in total organic carbon in the same irrigated area suggests a local source of organics entering the ground-water system. Increased crop yields and greater use of pesticides in irrigated areas may have significant effects on the organic load entering the ground water.

Table 11.--Ground-water quality (Analyses by U.S. Geolog
except depth of well, temperature, sodium adsorption

Site number	Well location	Source	Depth of well (feet)	Date of collection	Temperature (°C)	Dissolved silica	Total recoverable iron	Total recoverable manganese	Dissolved calcium	Dissolved magnesium	Dissolved sodium	Dissolved potassium	Bicarbonate
													BENTON
1	38.31.20 BBD	Buried sand	114	7-21-77	7.0	16	0.01	0.00	51	14	2.9	0.8	170
2	38.31.23 AAB	Suficial sand	16	7-18-77	14.0	16	9.2	.34	34	12	2.6	.4	110
3	38.31.29 CAC	do	66	7-17-78	12.0	15	.04	.00	43	10	3.0	.8	120
													SHERBURNE
4	33.26.34 CAB	Sandstone	312	11-13-69	---	---	.56	.19	35	20	3.6	1.8	212
5	33.27.28 ACC	Surficial sand	77	7-20-77	15.0	18	.08	.38	63	20	3.2	1.3	210
6	33.27.28 BDA	Sandstone	230	7-20-77	12.0	16	.02	.01	55	17	2.9	1.2	250
7	33.28.08 ACB	Buried sand (13 feet clay)	80	7-26-78	11.5	19	---	---	74	21	3.1	1.2	180
8	33.28.09 ADD	Surficial sand	80	7-20-77	10.0	20	.03	.00	89	28	5.0	1.6	260
9	33.28.36 BBB	do	34	7-28-78	12.0	18	4.3	.03	67	21	2.7	1.2	200
10	34.26.08 DD	do	59	11-14-69	---	23	.20	.2	35	8.1	2.9	.9	130
11	34.27.22 BBB	do	112	7-28-78	13.0	21	3.4	.26	38	7.3	2.0	.6	140
12	34.28.04 ADA	do	16	7-20-77	14.0	21	.40	.03	13	3.7	1.7	.4	45
13	34.29.07 CDC	Buried sand	122	11-14-69	---	21	.80	.04	58	19	3.9	1.8	261
	34.29.07 CDC	do	122	7-20-78	11.0	21	2.1	.03	62	19	3.8	1.4	260
14	34.29.19 ABB	Surficial sand	48	11-14-69	---	15	.05	.00	55	17	2.8	1.5	210
	34.29.19 ABB	do	48	7-20-78	17.5	15	.09	.00	78	22	8.0	1.8	220
15	34.29.23 ADA	do	50	7-19-78	11.0	18	.07	.00	68	20	3.0	1.2	210
16	34.29.26 BCC	do	68	7-18-77	21.0	19	.04	.00	83	25	3.5	1.1	200
17	34.29.33 DAA	do	70	7-26-78	13.0	22	.26	.57	70	20	2.4	4.2	240
18	34.29.36 DCC	do	57	10-26-77	10.5	16	.00	.00	57	18	3.3	.9	190
19	34.30.13 AAB	Buried sand (17 feet clay)	82	7-26-78	13.5	15	.15	.06	79	24	3.2	1.7	220
20	35.26.15 DBB	Surficial sand	59	7-19-77	15.0	22	7.7	.29	45	16	4.6	1.1	220
21	35.27.29 DBB	do	17	9-28-77	11.0	23	11	.59	43	5.0	3.8	.8	150
22	35.29.12 AAA	do	29	10-19-77	10.0	30	.79	.16	53	11	2.1	.9	200
23	35.30.14 AAC	do	36	7-27-78	11.0	18	.23	.01	90	27	2.9	1.4	240
24	36.29.35 BBD	do	37	7-19-77	21.0	19	.05	.05	43	14	3.5	1.2	170
													STEARNS
25	121.29.02 AAC	Surficial sand	63	8-11-78	10.5	19	.03	.02	68	23	2.1	1.9	270
26	122.27.08 BDD	do	63	8-14-78	12.0	27	2.6	.30	73	26	4.3	2.1	350
27	122.28.18 BCC	do	69	8-10-78	10.5	23	2.2	.14	55	28	2.8	2.2	260
28	122.28.18 CDD	do	73	7-21-77	13.0	21	.06	.02	80	26	1.8	1.7	290
29	122.29.23 CCA	do	65	8-10-78	13.0	18	1.8	.23	70	22	3.9	1.6	310
30	123.29.27 CCC	do	23	7-21-77	7.0	26	11	.60	67	21	4.1	1.9	300
31	123.30.01 DCD	do	50	7-30-78	13.0	18	.75	.00	83	25	3.0	2.2	310
32	123.31.13 AAC	do	28	10-12-77	11.0	21	.59	.12	89	32	4.0	1.6	400
33	124.28.10 BAD	do	33	7-25-78	17.0	20	.37	.31	80	22	7.5	2.4	290
34	124.32.25 DAC	do	19	10-18-77	12.5	8.4	1.6	.23	64	22	2.0	2.8	250
35	125.28.05 DDC	do	96	8-14-78	12.0	24	5.2	.39	72	17	4.5	1.6	270
36	125.33.01 CDD	do	73	7-27-78	13.0	17	1.1	.11	83	31	4.3	2.8	380
													WRIGHT
37	121.25.21 BDC	Surficial sand	58	7-30-78	12.0	24	.55	.04	80	30	2.8	2.6	370
38	122.25.32 DAD	Sandstone	93	11-14-69	---	---	---	---	64	18	4.3	1.3	264

Recommended limits for domestic consumption
(Minnesota Pollution Control Agency, 1972)

*Total nitrate nitrogen approximates dissolved nitrate nitrogen.

ical Survey. Results in milligrams per liter
ratio, specific conductance, pH, and color)

Total nitrate nitrogen	Dissolved sulfate	Dissolved chloride	Dissolved fluoride	Total nitrogen	Total organic nitrogen	Total ammonia nitrogen	Dissolved boron	Total phosphorus	Dissolved solids (residue on evaporation at 180°C)	Hardness Total	Hardness Non carbonate	Sodium-adsorption ratio	Specific conductance (micromhos per cm at 25°C)	pH	Color (platinum cobalt units)	Use	Total organic carbon
COUNTY																	
9.3	7.6	9.0	0.1	9.3	0.01	0.00	0.01	0.03	237	190	46	0.01	505	7.8	4	Irrigation	0.0
3.5	34	4.5	.1	4.0	.44	.05	.01	.19	173	130	44	.1	420	7.8	8	Observation	14
11	12	6.5	.1	11	.23	.24	.08	.04	205	150	50	.1	326	8.1	10	Irrigation	9.2
COUNTY																	
---	5.0	.6	.2	---	---	---	---	---	186	168	---	---	323	7.9	--	Municipal	---
.01	57	20	.1	.08	.04	.03	.01	.03	295	240	67	.1	685	7.8	4	Domestic	1.7
.74	8.5	1.0	.1	.75	.00	.01	.01	.08	219	210	2	.1	440	7.8	4	Irrigation	.0
.23	18	29	.1	.23	.00	.00	.03	.01	390	270	120	.1	580	7.6	4	do	1.8
23	25	29	.1	23	.00	.00	.02	.02	454	340	120	.1	755	7.4	7	do	.2
16	30	11	.0	16	.00	.00	.04	.12	381	250	90	.1	615	7.8	30	Abandoned domestic	---
.75	15.5	.2	.2	---	---	---	.00	---	170	121	14	---	246	7.4	1	Office	.8
.19	8.1	2.2	.1	.24	.00	.05	.02	.05	162	130	10	.1	275	7.8	20	State park	3.2
1.3	10	1.6	.1	1.3	.01	.00	.01	.04	73	48	11	.1	122	8.5	6	Observation	2.4
.96	16.5	1.2	.2	---	---	.00	.00	---	263	222	8	.1	430	7.7	1	Commercial	---
1.0	17	2.2	.1	1.0	.00	.00	.03	.09	267	230	20	.1	550	7.5	7	do	---
6.8	17	1.8	.2	---	---	.00	.01	---	258	207	35	.1	403	8.1	1	Domestic	8.7
14	18	35	.1	14	.00	.00	.00	.01	379	290	110	.2	625	7.9	4	do	---
15	20	22	.0	15	.24	.00	.00	.01	308	250	80	.1	565	8.0	3	Irrigation	1.5
18	45	41	.1	18	.05	.00	.02	.02	408	310	150	.1	675	7.4	7	do	2.8
6.1	26	15	.1	6.6	.04	.47	.03	.06	311	260	60	.1	536	7.5	1	do	.9
6.5	31	23	.1	7.7	1.2	.00	.02	.02	241	220	61	.1	470	7.7	1	do	4.9
7.2	55	27	.1	7.3	.00	.14	.03	.04	368	300	120	.1	650	7.5	2	do	.4
																	9.2
.00	8.9	1.1	.2	.22	.10	.12	.02	.11	203	180	0	.1	385	7.7	5	Observation	1.9
.26	8.8	.8	.2	.66	.22	.18	.01	.17	152	130	5	.1	315	7.4	11	do	2.1
.00	8.5	1.3	.1	.74	.09	.65	.02	.08	199	180	14	.1	340	7.6	12	do	2.2
22	13	12	.1	22	.05	.01	.04	.01	331	340	140	.1	710	7.4	7	Irrigation	11
.22	22	8.8	.1	.25	.03	.00	.01	.02	194	170	26	.1	345	7.9	3	do	.0
COUNTY																	
8.1	19	9.1	.1	8.1	.00	.00	.02	.01	332	260	43	.1	650	7.6	5	Irrigation	2.6
.02	10	1.9	.1	.47	.25	.20	.06	.05	311	290	2	.1	575	7.6	60	Domestic	3.7
1.9	4.0	9.2	.1	2.7	.62	.18	.01	.04	277	250	39	.1	535	7.6	30	Irrigation	8.0
7.6	30	14	.1	7.6	.00	.00	.01	.01	359	310	69	.0	625	7.4	4	do	.5
1.0	12	8.3	.1	1.4	.22	.20	.01	.06	294	270	11	.1	620	7.3	10	do	2.7
.03	13	4.2	.2	.21	.03	.15	.03	.15	281	250	8	.1	610	7.9	7	Observation	5.1
9.6	14	15	.1	10	.32	.10	.02	.00	371	310	56	.1	700	7.4	1	Irrigation	1.1
1.7	21	5.7	.2	2.1	.18	.23	.04	.05	359	350	26	.1	470	7.6	4	do	1.4
3.3	65	18	.1	3.5	.15	.01	.04	.00	440	290	52	.2	702	7.6	1	Domestic	5.7
.00	40	3.7	.1	.45	.06	.39	.02	.12	265	250	45	.1	495	7.6	9	Irrigation	1.2
1.4	19	7.5	.1	2.0	.46	.15	.04	.08	326	250	28	.1	600	7.5	200	do	4.7
.09	32	3.8	.1	.22	.10	.03	.06	.00	364	340	23	.1	775	7.3	25	do	3.6
COUNTY																	
3.2	31	4.1	.1	3.5	.29	.01	.03	.02	428	320	20	.1	690	7.5	1	Domestic	5.4
---	15	13.8	---	---	---	---	---	---	304	235	--	---	466	8.1	---	Industrial	---
10*	250	250	1.5						500						15		

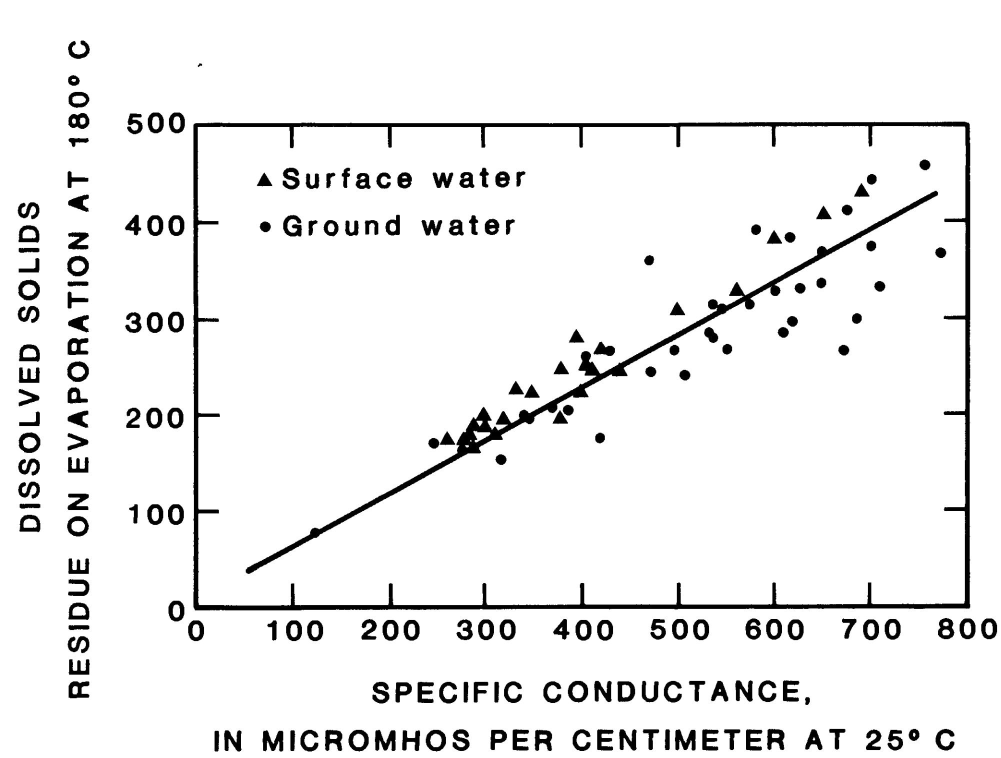
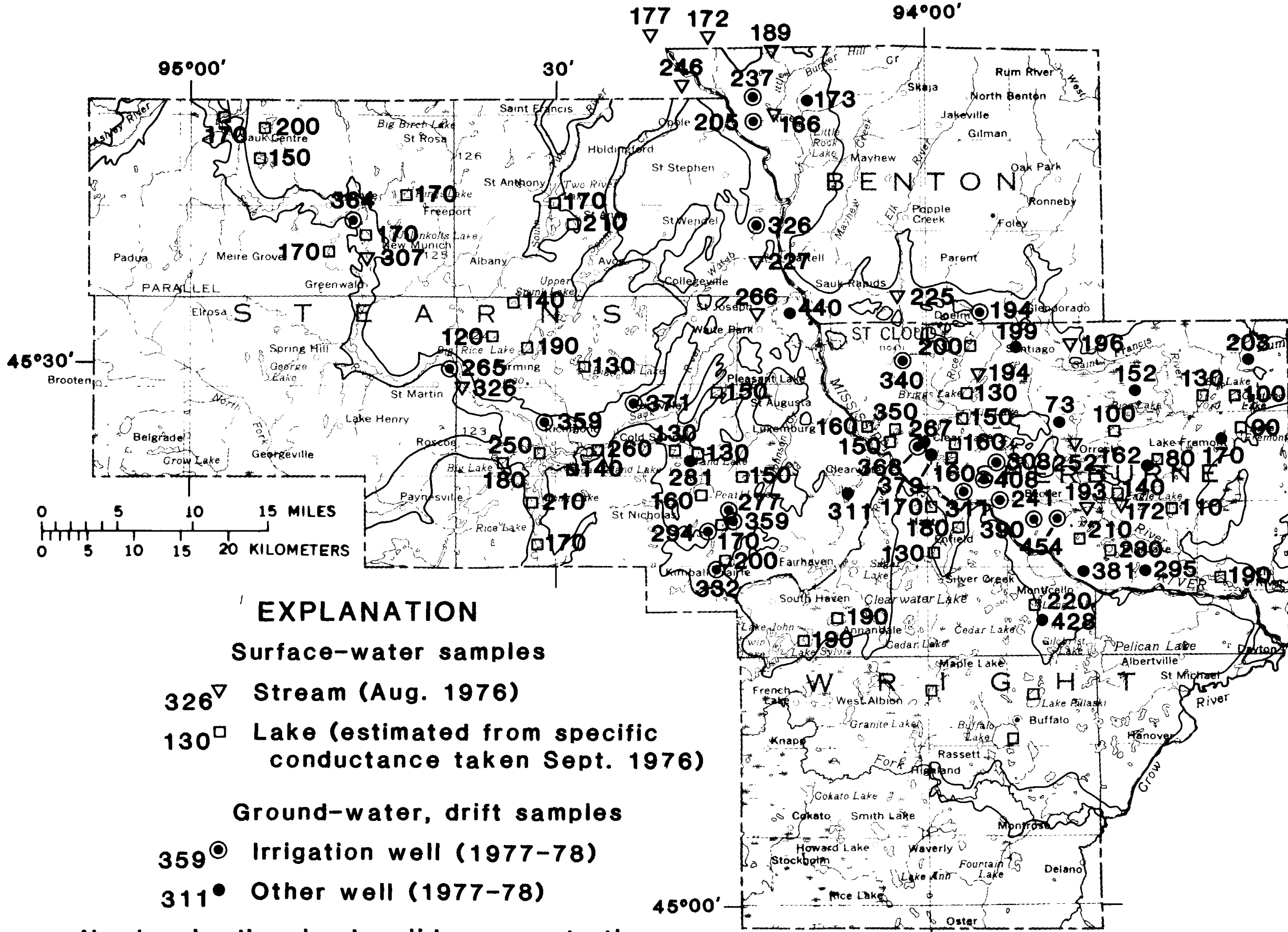


Figure 46.--Relationship of specific conductance to dissolved-solids concentration



EXPLANATION

Surface-water samples

326▽ Stream (Aug. 1976)

130□ Lake (estimated from specific conductance taken Sept. 1976)

Ground-water, drift samples

359◉ Irrigation well (1977-78)

311● Other well (1977-78)

Number is dissolved-solids concentration in milligrams per liter (residue on evaporation at 180°C)

Figure 47.--Dissolved-solids concentration in ground water and surface water

Table 12.--Surface-water quality (Analyses by U.
per liter except temperature, sodium adsorption

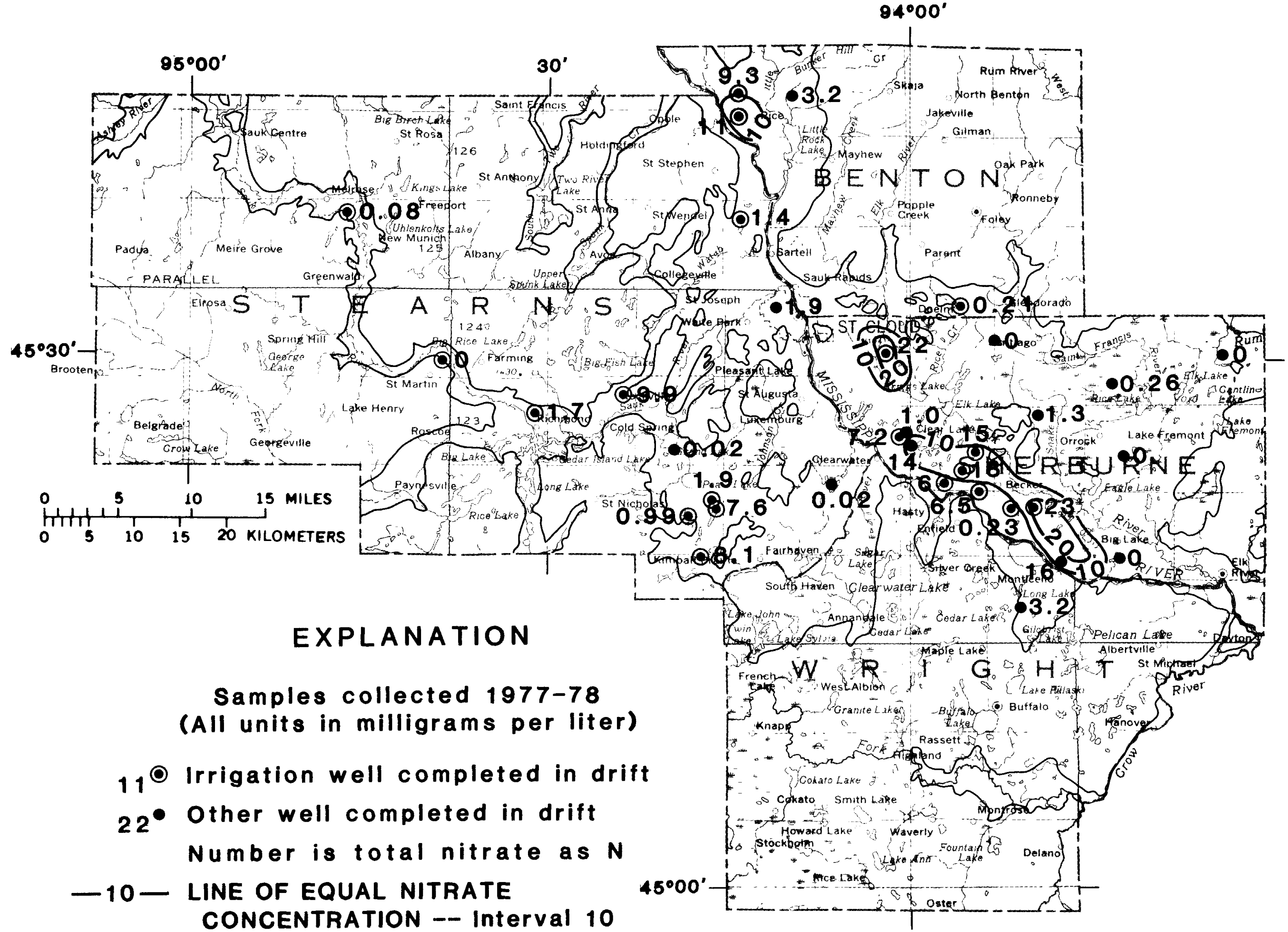
Station or site number	Station name	Date of collection	Discharge (ft^3/s)	Temperature (°C)	Dissolved silica	Total recoverable iron	Total recoverable manganese	Dissolved calcium	Dissolved magnesium	Dissolved sodium
05267000	Mississippi River near Royalton	8-23-76	853	24.0	7.7	---	---	32	14	9.2
05267580	Spunk Creek near Royalton	8-18-76	0.53	27.0	7.3	1.5	0.26	52	23	6.7
05268000	Platte River at Royalton	9-29-76	3.8	12.5	3.3	.28	.08	38	13	7.3
05268500	Little Rock Creek near Royalton	9- 6-78	3.2	17.0	17	.39	.14	43	10	4.6
05268700	Little Rock Creek at Rice	8-18-76	7.7	18.5	12	.32	.10	40	10	4.7
		5-23-78	19	19.5	12	.93	.23	48	11	5.0
		9- 6-78	15.8	21.0	15	.76	.16	43	10	4.5
05274000	Elk River near St. Cloud	8-19-76	2.5	24.0	13	.33	.23	50	17	7.8
		5-22-78	19	20.5	7.1	.74	.26	51	17	8.2
05274350	Briggs Creek near Clear Lake	8-20-76	1.2	20.0	20	.55	.42	49	12	3.3
05274470	Snake River near Orrock	8-19-76	2.4	17.0	18	3.9	.47	63	13	2.9
05274390	Elk River above Big Lake	8-19-76	4.6	26.0	7.8	.28	.20	39	17	4.7
		11- 8-77	91	---	7.9	.26	.08	50	17	6.0
		5-24-78	100	20.0	2.5	.73	.29	50	16	6.2
05274700	St. Francis River at Santiago	8-19-76	1.2	24.0	12	.88	.57	41	12	4.7
05274900	St. Francis River near Big Lake	8-20-76	15	25.0	15	.59	.23	40	11	3.4
		11- 8-77	67	10.5	14	.77	.12	41	12	4.6
		5-23-78	94	21.0	13	1.0	.22	44	12	4.4
05269800	Watab River near Sartell	8-18-76	5.3	24.0	5.3	.23	.06	47	21	9.3
05270230	Sauk River at New Munich	8-17-76	13	18.5	9.9	.22	.15	48	26	25
05270350	Sauk River near Farming	8-17-76	17	22.0	15	1.3	.18	61	26	21
05270440	Sauk River at Cold Spring	8-18-76	71	22.0	8.8	.30	.10	43	22	12
05270550	Sauk River near St. Cloud	8-20-76	72	24.5	9.5	.28	.15	51	23	12
05273100	Three Mile Creek near Fairhaven	9- 6-78	1.4	19.5	22	.96	.19	85	27	3.4

Recommended limits for domestic consumption
(Minnesota Pollution Control Agency, 1972).

* Total nitrite plus nitrate nitrogen approximates dissolved nitrate nitrogen.

S. Geological Survey. Results in milligrams ratio, specific conductance, pH, and color)

Dissolved potassium	Bicarbonate	Dissolved sulfate	Dissolved chloride	Dissolved fluoride	Total nitrite plus nitrate nitrogen	Dissolved boron	Dissolved solids (residue on evaporation at 180°C)	Hardness Total	Hardness Noncarbonate	Sodium-adsorption ratio	Specific conductance (micromhos per cm at 25°C)	pH	Color (platinum cobalt units)
2.3	---	13	5.0	0.2	0.01	---	177	140	5	0.3	285	8.6	---
3.5	245	24	7.6	.2	.04	0.05	246	220	17	.2	440	9.4	15
3.2	164	20	4.7	.2	.04	.05	172	150	14	.3	280	---	17
2.0	170	9.1	3.5	.1	.99	.02	189	150	9	.2	290	7.6	30
1.0	165	11	3.0	.2	1.4	.02	166	140	6	.2	290	9.7	5
1.4	170	13	4.7	.1	.87	.04	199	170	26	.2	300	7.6	40
1.6	170	11	3.9	.1	.53	.03	188	150	9	.2	290	7.7	25
2.0	208	14	9.2	.2	.55	.02	225	190	24	.2	330	8.2	3
3.0	230	16	9.6	.1	.36	.09	278	200	9	.3	395	---	70
.9	203	6.8	3.6	.2	.25	.02	194	170	5	.1	320	7.7	15
1.0	234	12	2.1	.1	.47	.03	252	210	19	.1	405	8.4	7
1.9	171	15	8.0	.2	.46	.02	193	170	27	.2	380	8.5	7
2.0	210	24	8.7	.1	.45	.04	224	190	23	---	380	7.9	23
2.6	210	18	8.8	.1	.22	.06	244	190	18	.2	410	---	50
1.3	150	23	6.4	.1	.24	.03	186	150	29	.2	300	8.4	3
.9	174	11	2.4	.2	.12	.02	172	150	2	.1	260	8.4	8
1.5	170	17	5.3	.2	.15	.04	179	150	12	.2	340	---	37
2.0	180	9.7	6.4	.1	.03	.08	222	160	12	.2	350	---	60
2.5	217	24	12	.2	.03	.06	227	200	26	.3	400	8.5	15
5.4	258	30	28	.3	.51	.05	307	230	15	.7	500	8.1	18
4.6	283	31	26	.3	.79	.05	326	260	21	.6	560	8.5	12
4.1	210	25	16	.2	.01	.06	247	200	26	.4	380	9.7	22
4.5	232	25	17	.3	.25	.06	266	220	32	.4	420	8.0	22
1.8	370	28	5.2	.1	.71	.05	378	320	20	.1	600	---	50
		250	250	1.5	10*		500						15



EXPLANATION

Samples collected 1977-78
(All units in milligrams per liter)

11◉ Irrigation well completed in drift

22● Other well completed in drift

Number is total nitrate as N

—10— LINE OF EQUAL NITRATE CONCENTRATION -- Interval 10 milligrams per liter

Figure 48.--Nitrate concentration in ground water

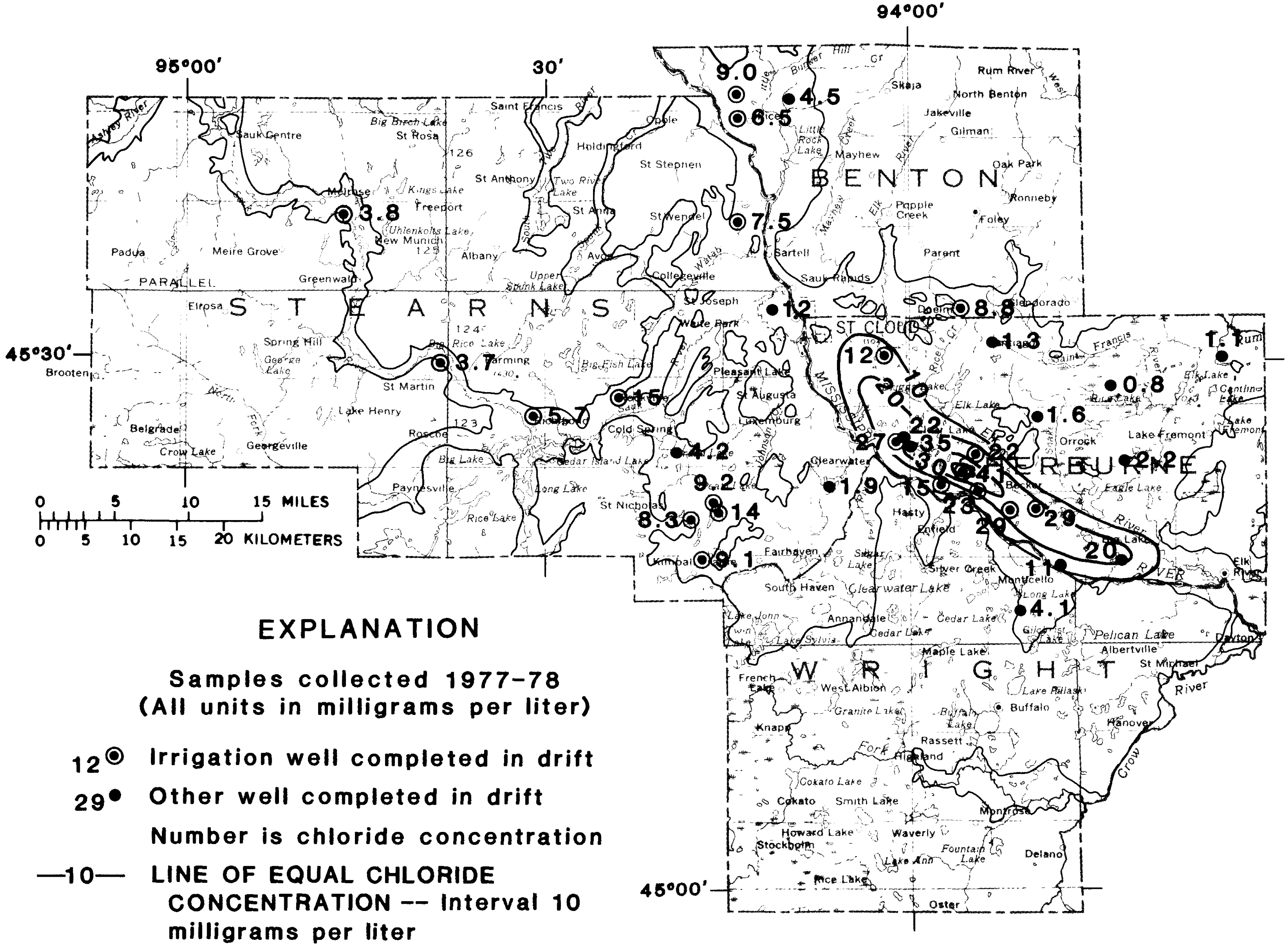


Figure 49.--Chloride concentration in ground water

Dissolved phosphorus and potassium concentrations have no definite pattern of distribution although highest values are found in irrigated areas. Dissolved-solids concentrations in water from drift aquifers are markedly higher in irrigated than in nonirrigated areas. Differences in concentrations of constituents in water from irrigation versus other wells are shown in table 11.

To determine possible changes in water quality with time in a heavily irrigated area, wells at sites 13 and 14, originally sampled in 1969, were resampled in 1978. Water quality in the surficial aquifer at site 14 changed considerably, whereas water from a buried-drift aquifer at nearby site 13 changed very little except for an increase in total iron, which is thought to be due to sampling error. Although concentrations of many constituents increased at site 14, the most noteable changes were increases in chloride, nitrate, total and noncarbonate hardness, and dissolved solids and a decrease in pH. Similar changes were noted in irrigated areas of southern Wadena County between 1967 and 1972 (U.S. Geological Survey, unpub. data).

Analyses for minor elements and pesticides were made of water from sites 12, 16, and 28. Very little or no arsenic, barium, cadmium, chromium, copper, cyanide, mercury, silver, or selenium were found, all amounts being well below the Minnesota Pollution Control Agency's recommended limits for untreated drinking water (1972). Pesticide residues, if present, were below detectable limits at each site.

Water-quality information collected for this study will serve as baseline data against which future data can be compared. There are indications that ground-water quality might be changing with time in heavily irrigated areas. If so, periodic sampling may be warranted to monitor such changes so that positive steps can be taken to maintain desired water quality.

SUMMARY

Surficial-outwash aquifers are the most easily developed and economical source of large water supplies in much of central Minnesota. In several areas, most notably in western Sherburne and in southeastern Stearns Counties, ground-water supplies are being developed rapidly for irrigation. The maximum thickness of the aquifers is about 100 feet in the Maine Prairie area of Stearns County and about 80 feet in the northeast-trending outwash-filled valleys in Sherburne County. Theoretically, individual well yields from 2,000 to 3,000 gal/min are possible in parts of these areas. Where the aquifers are at least 40 feet thick, yields of 500 gal/min or more are possible. It is in these areas, where topography and soils are also favorable, that irrigation development is taking place. The drought of 1976 resulted in a rapid increase in irrigation pumping centers and in total pumpage.

Mean annual precipitation is 27.1 inches, 8 of which is recharged to the surficial aquifer. Of the 22.2 inches lost annually as evapotranspiration, 2.4 inches is from the aquifer. Regionally, ground water moves toward the Mississippi River; locally, toward tributary streams and lakes. All streams are gaining streams. Mean gains of the Mississippi River main stem ranged from 2.5 to 4.9 ft^3/s per mile. Mean gains of tributary streams ranged from 0.2 to 2.2 ft^3/s per mile. Irrigation is the greatest single use of ground water. In 1976, a drought year, 23,651 acre-feet of ground water was withdrawn for irrigation from 183 pumping centers.

Ground water is of the calcium bicarbonate type and is suitable chemically for most uses. In heavily irrigated areas, nitrate and chloride concentrations are increasing in the surficial aquifer. Deterioration of ground-water quality may be a major concern in these areas.

Numerical-flow models were used to simulate the surficial aquifer and estimate the probable regional effects of development. Model analyses indicate that under present development, cumulative water-level declines of up to 4 feet might be attributable to pumping. Adding more pumping centers at estimated withdrawal rates causes little additional lowering of water levels if recharge is normal. However, if recharge is reduced and if pumping rates are increased, as might happen during a drought, water-level declines of 10 to 15 feet are possible.

Results of model analyses must be considered to be approximations because ground-water systems are complex and modeling requires generalizations. The models can be used, however, as a tool to guide the future development of the ground-water resource.

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