GEOHYDROLOGY AND WATER QUALITY OF CONFINED-DRIFT AQUIFERS IN THE BROOTEN-BELGRADE AREA, WEST-CENTRAL MINNESOTA

By Geoffrey N. Delin

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CONVERSION FACTORS

Multiply inch-pound unit	By	To obtain SI unit
foot (ft)	0.3048	meter (m)
foot per day (ft/d)	0.3048	meter per day (m/day)
foot squared per day (ft^2/d)	0.09294	meter squared per day (m^2/day)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic feet per day (ft^3/d)	2446.8	cubic meter per day (m^3/d)
gallon	3.785	liter (L)
gallon per minute (gal/min)	0.06308	liter per second (L/s)
million gallons per year (Mgal/yr)	0.00012	cubic meter per second (m^3/s)
inch (in)	25.4	millimeter (mm)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
foot per mile	0.1894	meter per kilometer

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD Of 1929)-- a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Sea Level Datum of 1929."

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ABSTRACT

Confined-drift aquifers in six aquifer zones identified in a 1,300-square-mile area of west-central Minnesota near Brooten and Belgrade range in thickness from 5 to 110 feet. Transmissivities generally range from 500 to 10,000 feet squared per day, and theoretical well yields generally range from 100 to 900 gallons per minute.

Regional ground-water flow in the confined-drift aquifers is to the southeast with local discharge to the East and Middle Branches of the Chippewa River, the North Fork Crow and Sauk Rivers, and to smaller streams, lakes, wetlands, and wells. Water levels near high-capacity pumped wells generally fluctuate 5 to 40 feet annually, compared to annual fluctuations of less than 5 feet in the unconfined aquifer.

Water from confined-drift aquifers generally is suitable for most uses. The water is hard to very hard and contains locally elevated concentrations of iron, manganese, and dissolved solids.

Results from a ground-water-flow model indicate that increased pumping from confined aquifers in the area would not adversely affect water levels. The addition of 10 to 20 hypothetical wells, pumping 123 to 246 million gallons per year, generally resulted in regional water-level declines of 0.1 to 1.0 feet. Simulations showed that the reduced recharge and increased pumping resulting from a 3-year drought probably would lower water levels between 5 and 10 feet regionally in the confined-drift aquifers and as much as 20 feet locally in the unconfined aquifer. Ground-water discharge to the East Branch Chippewa and North Fork Crow Rivers during the simulated drought would be reduced by 38 percent of 1984 conditions.

INTRODUCTION

In recent years, withdrawal of water from confined-drift aquifers (hereafter called confined aquifers) has increased for irrigation and for municipal, agricultural-products processing, and other industrial water supplies in Minnesota. The Minnesota Department of Natural Resources (MDNR) is concerned about the rapid increase in withdrawals from confined aquifers in various parts of the state because of uncertainty about (1) long-term yields of wells open to these aquifers, (2) effect of pumping on ground-water levels, and (3) possible interference between nearby wells pumping from the same aquifer. In the Brooten-Belgrade area, west-central Minnesota (fig. 1), withdrawals from confined-drift aquifers is increasing rapidly. Over about half the area, popularly known as the Bonanza Valley, an unconfined sand and gravel (surficial) aquifer provides adequate yields for irrigation systems (Van Voast,

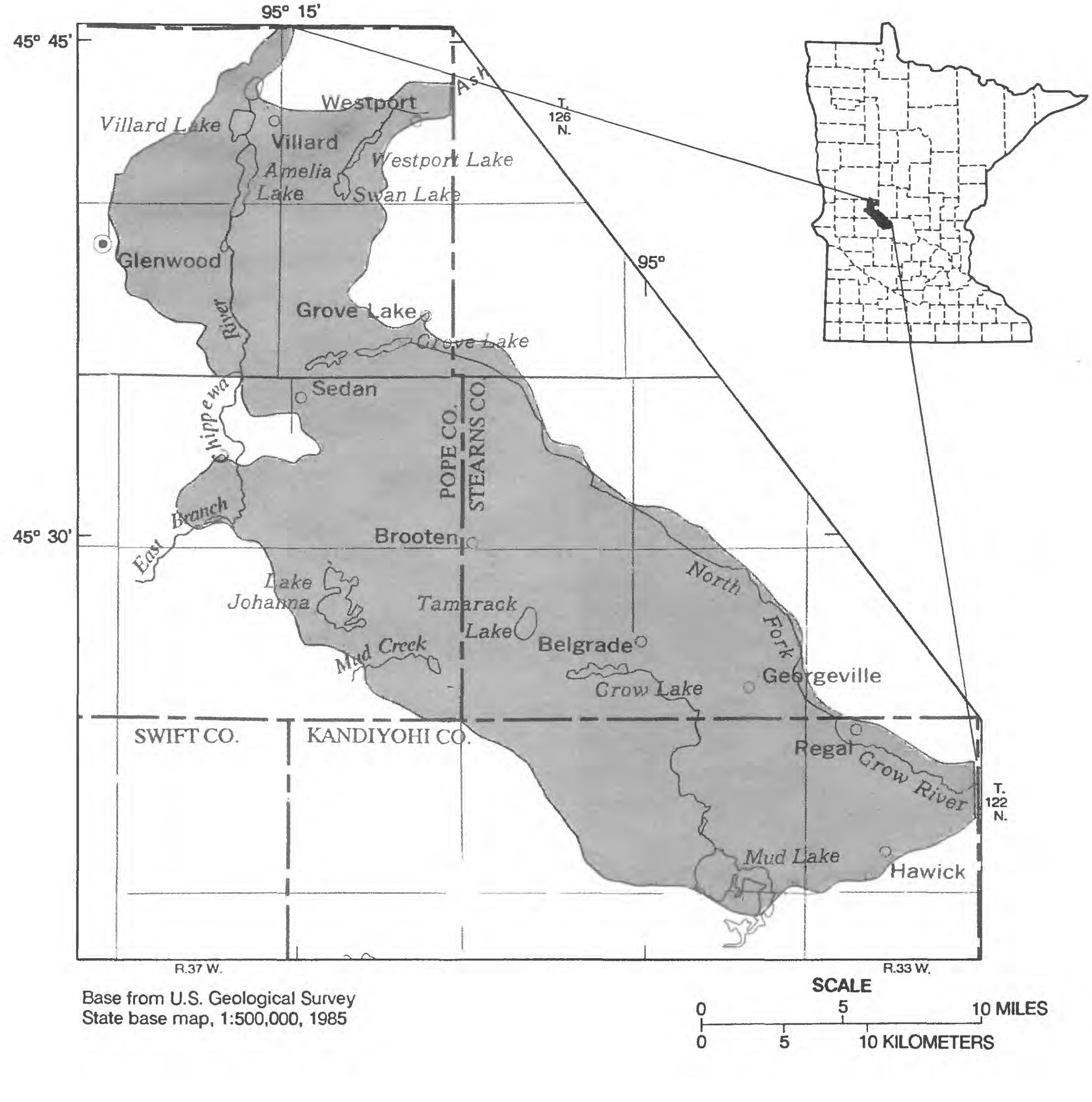


Figure 1.--Location of study area

1971). However, in the remaining area, the unconfined aquifer is thin and wells have been drilled into confined aquifers. These confined aquifers are separated from the unconfined aquifer by till and clay. The confined aquifers consist of glacial outwash of Quaternary age and sandstone of Cretaceous age.

Although numerous wells and test holes have been completed in the confined aquifers, little was known about the continuity or the hydraulic response of these aquifers to pumping. The water quality and long-term yield of wells in the aquifers also was poorly known. These uncertainties made it difficult for the MDNR to issue appropriation permits and to manage the ground-water resources efficiently. Consequently, the MDNR requested the Minnesota District of the U.S. Geological Survey to investigate the areal extent, hydraulic properties, and water quality of confined aquifers in the Brooten-Belgrade area, and to determine the probable effects of continued development on water levels, storage, potential well yields, and water quality in the confined and unconfined aquifers.

The objectives of this study were to (1) determine the areal extent, thickness, and hydraulic properties of confined-drift and Cretaceous rocks in the study area, (2) investigate the vertical hydraulic connection between confined-drift and surficial aquifers and estimate the quantity of vertical leakage into confined-drift aquifers from overlying deposits, (3) estimate the long-term yield of wells penetrating confined-drift aquifers, (4) estimate the effects of continued development on ground-water levels and on streamflow, (5) provide the MDNR with a set of management tools that can be used to assess the effects of future ground-water withdrawals, and (6) assess the quality of water from aquifers in confined-drift and Cretaceous rocks and suitability of the water for irrigation and other purposes.

Purpose and Scope

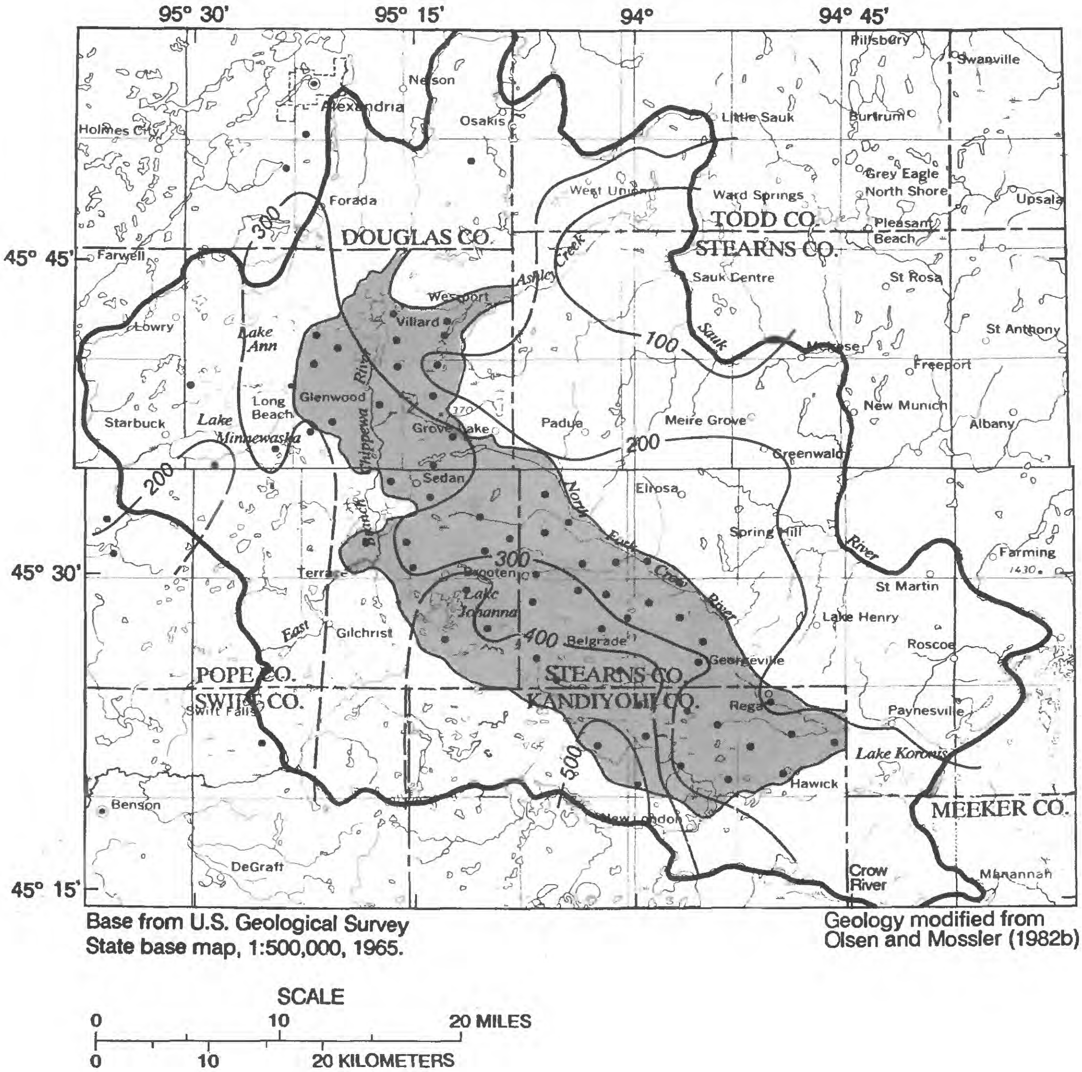
The purpose of this report is to describe (1) the hydrogeology of confined aquifers in the study area, (2) the quality of water in the confined aquifers, (3) ground-water flow in the glacial-drift system, and (4) summarize results of the ground-water-flow model, a tool used to better manage the ground-water system. This report supplements other U.S. Geological Survey reports published in conjunction with this study. Delin (1988) provides a detailed description of the three-dimensional ground-water-flow model constructed for this study. Stoner and Strietz (1987) present results of geophysical testing conducted in the area, and Delin (1986c) provides a general description of confined-drift aquifer studies in Minnesota.

Previous Investigations

Winchell and Upham (1888) first summarized the geology and natural history of west-central Minnesota. An early description of the glacial geology in the area is presented by Leverett (1932). A more recent interpretation of the glacial geology is described by Wright and Ruhe (1965) and Wright (1972a). Wright (1972b) provides a general description of the physiography of the study area. Hall and others (1911) and Theil (1944) investigated the hydrology of southern Minnesota including Kandiyohi County. A general description of the geology and ground water in Pope and Stearns Counties is included in a report by Allison (1932). A general description of ground water in the study area is provided by Lindholm and Norvitch (1976). A general description of the geology and water resources of the study area is presented in the hydrologic atlases of the Crow River watershed by Lindholm and others (1974), the Chippewa River watershed by Cotter and others (1968), and Mississippi and Sauk Rivers watershed by Helgesen and others (1975). A general description of irrigation potential in the Bonanza Valley (Brooten-Belgrade) area is presented by Ross (1971). Ground-water resources of surficial aquifers in the study area were studied in detail by Van Voast (1971). Wolf (1976) provided a general description of buried aquifers in the area. The effects of agricultural practices on the quality of water in sand-plain aquifers in Douglas, Kandiyohi, Pope, and Stearns Counties, including the Brooten-Belgrade area, are described by Anderson (1987).

Location and Description of Study Area

The study area is about 125 mi (miles) west of Minneapolis and St. Paul and covers approximately 300 mi^2 (square miles), including parts of Pope, Stearns, and Kandiyohi Counties (fig. 1). To more accurately simulate ground-water flow in the area, the area of investigation was expanded to natural hydrologic boundaries in parts of Swift, Meeker, Douglas, and Todd Counties (fig. 2). The total area of investigation thus includes approximately 1,300 mi^2. The area is drained by the East Branch Chippewa River, a tributary of the Minnesota River, and the North Fork Crow River and Ashley Creek, tributaries of the Mississippi River. The topography is generally flat or gently rolling. Average daily maximum temperatures range from about 21 °F (degrees Fahrenheit) in January to 84 °F in July (Baker and Strub Jr., 1965). Average daily minimum temperatures range from about 1.0 °F in January to 60 °F in July. Mean annual precipitation is about 24 in. (inches) (Baker and Kuehnast, 1978), with a large part of it occurring from May to September. Mean potential evapotranspiration is about 24 in. and average annual runoff is about 3.5 in. (Baker and others, 1979).



EXPLANATION

Brooten-Belgrade sand plain

Hydrologic boundary of study area

—*100*— — Line of equal thickness of drift. *Dashed where approximately located. Interval 100 feet.*

• U.S. Geological Survey test hole or private well

Figure 2.--Thickness of drift in the study area

Sources of Data

The study was conducted from April 1984 through September 1987. Lithologic logs from 26 test holes drilled for this study (Appendix) and 46 logs from previous U.S. Geologic Survey studies were used to determine the thickness, depth, composition, and areal extent of confined aquifers in the study area. Data from approximately 800 wells and test holes supplemented data for test holes drilled for this study. These data were used in constructing the geologic maps published in this report and for the ground-water-flow model.

Test-Hole and Well-Numbering System

The system of numbering wells and test holes in this report is based on the U.S. Bureau of Land Management's system of land subdivision (township, range, and section). Figure 3 illustrates the system of numbering data-collection points for location. The first number of a location indicates the township, the second the range, and the third the section in which the point is located. Uppercase letters after the section number indicate the location within the section; the first letter denotes the 160-acre tract (quarter section), the second the 40-acre tract (quarter-quarter section), and the third the 10-acre tract (quarter-quarter-quarter section). The letters A, B, C, and D are assigned in a counterclockwise direction, beginning in the northeast corner of each tract. The number of letters indicates the accuracy of the location number; if a point can be located within a 10-acre tract, three letters are shown in the location number. For example, the number 124.36.15ADC indicates a test hole or well located in the southwestern 1/4 of the southeastern 1/4 of the northeastern 1/4 of section 15, township 124 north, range 36 west. In the area, all townships are north and ranges are west of the fourth principal meridian.

Acknowledgments

The author is grateful to well owners, well drillers, and to State and local-agency personnel for data used in preparing this report. Thanks are given to Mr. Charles Singsank who permitted an aquifer test using his irrigation well, to land owners who permitted the drilling of test holes and the installation of observation wells, and to well owners who permitted sampling of their wells and measurement of water levels.

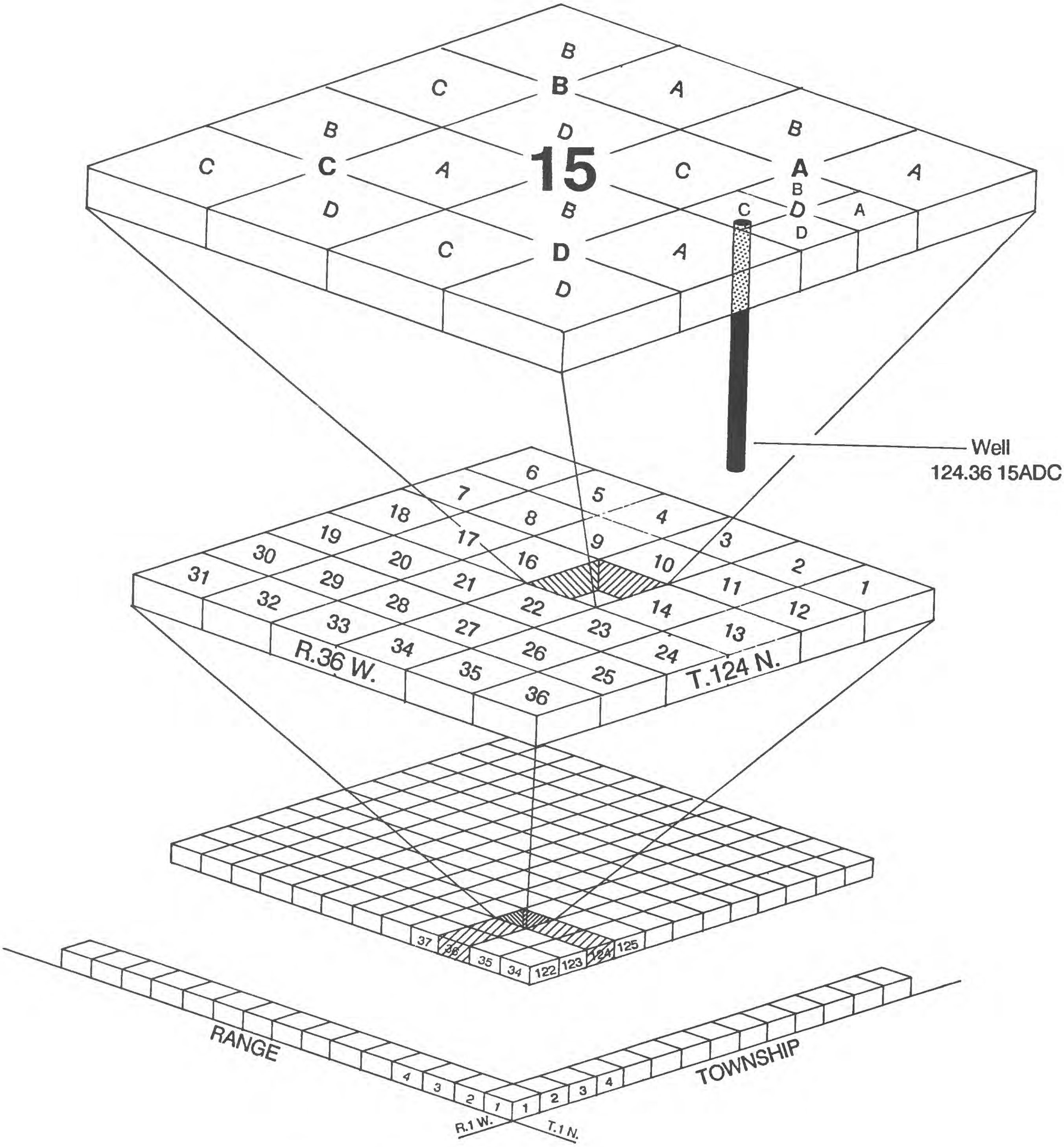


Figure 3.--Test-hole and well numbering system

HYDROGEOLOGIC SETTING

Drift

Glacial deposits cover the entire study area. These deposits are termed drift, and consist primarily of till and of outwash sand and gravel. The deposits range in thickness from about 100 ft in the eastern part of the area to about 500 ft where they fill bedrock valleys in the southwestern part of the area (fig. 2).

The drift was deposited by various mechanisms during successive glacial advances and retreats during the Wisconsin glaciation and reflects a complex glacial history. During glacial advances till was deposited at the base of the glaciers. During periods of glacial stagnation silt and clay were deposited in glacial ponds and lakes. During glacial retreats melt-water streams deposited sand and gravel in stream channels, outwash plains (commonly referred to as sand plains), kames, eskers, and beach ridges. Some sand and gravel deposits were covered by till during subsequent glacial advances. These sand and gravel units are present throughout most of the study area and are covered by till ranging in thickness from 5 to 330 ft.

The stratigraphy of the drift in the Brooten-Belgrade area is more complex than in other parts of the state. For example, the drift is thicker and includes more confined aquifers in the Brooten-Belgrade area than drift in the Pomme de Terre-Chippewa area located primarily in Swift County west of the study area (Delin, 1986a). The confined aquifers in the study area are areally less continuous than those in the Pomme de Terre-Chippewa area, and have more complex spatial geometries.

Drift in the area has been hydrogeologically subdivided into three types: (1) sand and gravel deposits at land surface that compose the unconfined aquifers; (2) till deposits that overlie and confine deeper sand and gravel deposits, and (3) deeper sand and gravel deposits that compose the confined aquifers. The hydraulic properties of these three drift types are distinctly different and are described in the following sections.

Unconfined Aquifer

The unconfined aquifer consists of a broad outwash deposit (sand plain) (fig. 4) bounded on the sides and bottom by till and ice-contact deposits (Van Voast, 1971). The topography in till areas is rolling and irregular; in outwash areas it is nearly flat to gently rolling. The aquifer generally consists of very fine to coarse sand and gravel, deposited during the last glacial retreat. Saturated thickness of the outwash deposit ranges from about 10 ft in the north and northeast to about 60 ft in the southwest (Van Voast, 1971). Clay beds as much as 30 ft thick exist locally within the outwash.

Transmissivities range from about 40 ft^2/d (feet squared per day) in the east to 500 ft^2/d in the southwest (Van Voast, 1971). Theoretical maximum well yields range from about 100 gal/min (gallons per minute) in the east to 1,000 gal/min in the west (Van Voast, 1971). The unconfined aquifer locally does not supply sufficient water for irrigation, particularly in the east. Consequently, irrigation wells have been completed in confined aquifers in these areas. The unconfined aquifer supplies water to several springs located on slopes surrounding Lake Minnewaska, including the spring used by the city of Glenwood until the 1970's. Regional ground-water flow is toward the southeast. Locally, flow is toward the North and Middle Forks of the Crow River, the East Branch of the Chippewa River, Ashley Creek, and Lake Minnewaska. Van Voast (1971) provides a detailed description of unconfined aquifers in the area.

Till Confining Units

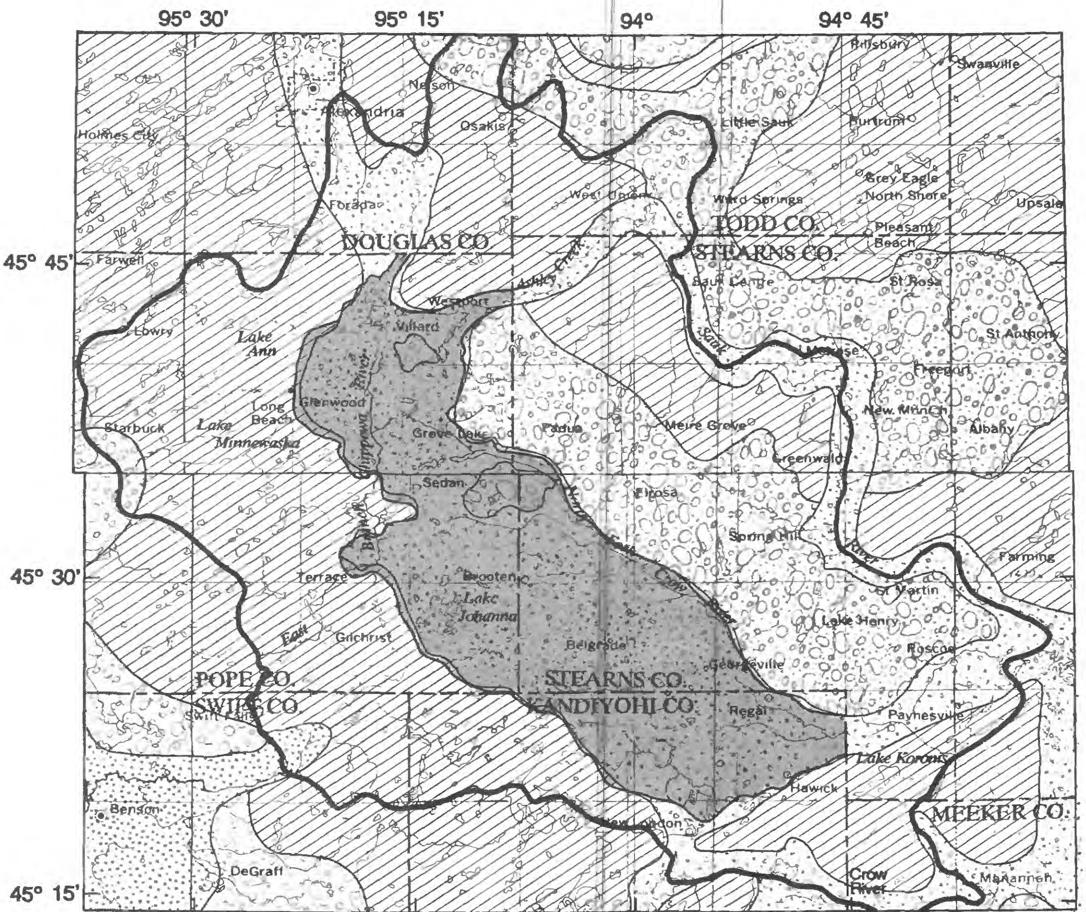
Till consists of an unsorted mixture of clay, silt, sand, gravel, and boulders generally deposited beneath stagnated or advancing glaciers. However, some clayey till may have been deposited by proglacial lakes. The gray till in the area, although sandy, consists primarily of clay and silt.

Because the vertical hydraulic conductivity of till generally is much lower than the hydraulic conductivity of outwash, till controls vertical ground-water flow between aquifers in the drift and is considered to be a confining unit. The vertical hydraulic conductivity of till in the area, based on analysis of four aquifer tests, ranged from 8.6×10^{-6} to 1.8 ft/d (feet per day), with a mean value of 4.0×10^{-1} ft/d. This mean value is somewhat higher than the mean value of 2.5×10^{-2} ft/d for till in the Pomme de Terre-Chippewa area of Minnesota (Delin, 1986a) and the value of 1.8×10^{-2} ft/d for till in the Detroit Lakes area of Minnesota (Miller, 1982). These data indicate that till in the Brooten-Belgrade area is more transmissive (sandy) than in other parts of Minnesota. The vertical hydraulic conductivity of till in Minnesota generally is somewhat higher than values reported for other parts of the glaciated northern United States. Permeameter tests conducted by Prudic (1982), for example, indicate that the vertical hydraulic conductivity of till in Cattaraugus County, New York, ranges from 3.1×10^{-5} to 4.3×10^{-4} ft/d.

The horizontal hydraulic conductivity of till was measured at three sites in the study area. Data from eight slug tests were analyzed using methods of Papadopulos and others (1973). The calculated mean horizontal conductivity was 1.4×10^{-1} ft/d, which is in the range of values for till given by Heath (1983) and for alluvial clay given by Lohman (1972).

Confined Aquifers

The confined aquifers are comprised of saturated sand and gravel that, within the area, are bounded above and below by lower permeability till. These aquifers are the main source of ground-water where unconfined aquifers are thin or absent. The extent and hydraulic properties of confined aquifers in the study area will be described in later sections of the report.



Base from U.S. Geological Survey
State base map, 1:500,000, 1965.

Geology modified from
Hobbs and Goebel, 1982

SCALE
0 10 20 MILES
0 10 20 KILOMETERS

EXPLANATION

- Brooten-Belgrade sand plain
- Glacial outwash: *stratified sand and gravel*
- Till: *unsorted mixture of clay, silt, sand, gravel, and boulders*
- Ice-contact deposit: *till interbedded with ice-contact sand and gravel*
- Silt and fine sand
- Hydrologic boundary of study area

Figure 4.--Surficial geology in the study area

Bedrock

Proterozoic (Precambrian) igneous and metamorphic rocks directly underlie the drift throughout most of the study area. To fully understand the occurrence and movement of water in the overlying drift, these older rocks must be described. The rocks consist primarily of granite, with some gneiss and schist. The lithology is largely inferred from gravity and magnetic data (Sims, 1970). Water occurs only in fractures and in weathered zones near the top of these rocks, which generally are very dense with low porosity and permeability. Although isolated wells are known to yield as much as 14 gal/min from these rocks, they are not considered to be a major confined aquifer in the area.

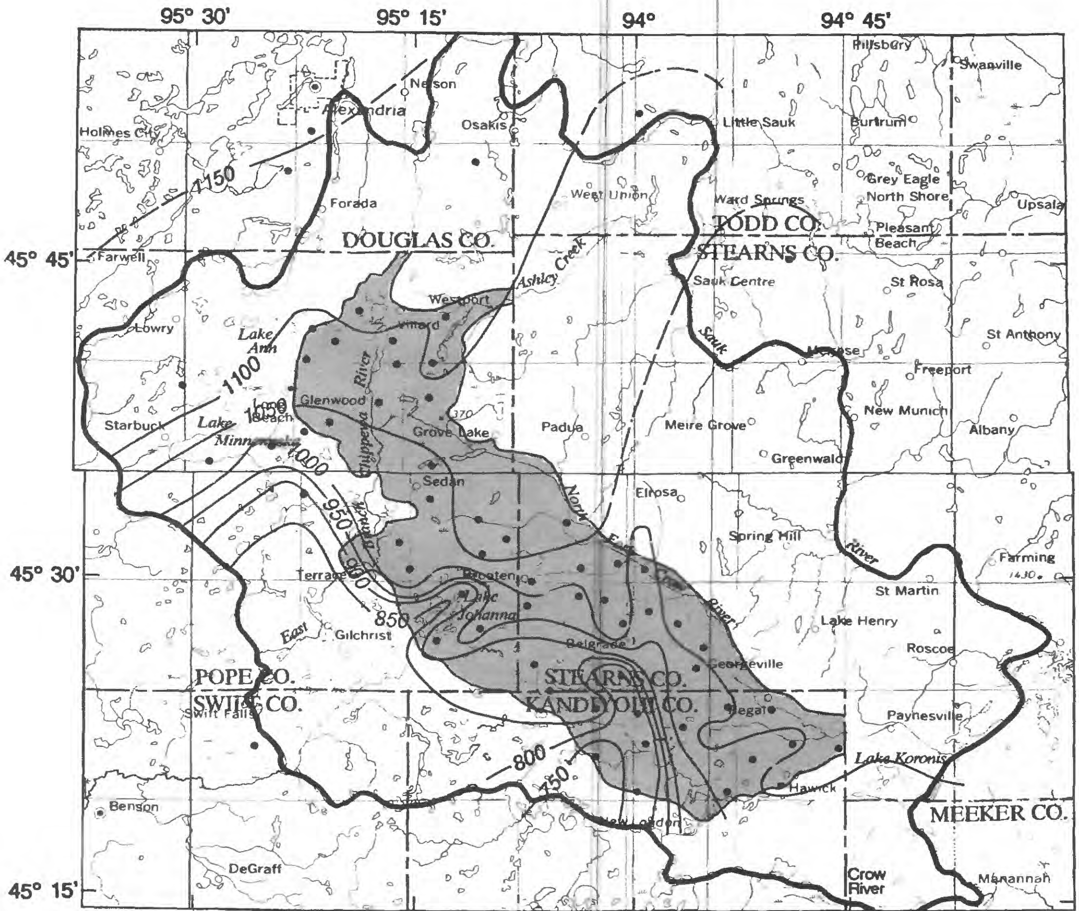
The bedrock surface is irregular, with as much as 100 ft of relief in one mile (fig. 5). The bedrock surface generally slopes to the south and several now-buried valleys dissect the bedrock surface in the southern part of the area. These bedrock valleys probably reflect the drainage system of glacial or preglacial streams. Erosion from glacial streams and ice during the Wisconsin glaciation further altered the bedrock surface.

Wolf (1976) identified deposits of Cretaceous age, consisting of sandstone and shale, overlying the Proterozoic rocks in parts of the area. Cretaceous deposits penetrated during test drilling for Wolf's study ranged in thickness from 7 to 112 ft and averaged 43 ft. Examination of drill cuttings from Wolf's study by the Minnesota Geological Survey (Minnesota Geological Survey, oral commun., 1987), however, indicated that much of the material identified as being of Cretaceous age may, in fact, be Pleistocene drift. These discontinuous and generally semi-consolidated deposits are difficult to differentiate from drift. Cretaceous deposits were penetrated at two locations during test drilling for this study (Appendix I). These deposits ranged in thickness from 2 to 8 ft. Although isolated wells are known to yield as much as 150 gal/min from Cretaceous rocks, the rocks are not considered to be a major confined aquifer in the area. The hydrogeologic and water-quality characteristics of Cretaceous rocks in southwestern Minnesota are described in greater detail by Woodward and Anderson (1984).

GEOHYDROLOGY OF CONFINED AQUIFERS

Extent and Hydraulic Properties

Confined sand and gravel deposits in the area were grouped into aquifers using a method first described by Winter (1975) and later modified by Delin (1986a). The basic assumptions for this method are that (1) well screens at a given altitude are completed in a single aquifer, which is supported by available aquifer-test data and geologic logs, (2) the sand and gravel deposits forming each aquifer are continuous between known points of occurrence, which also is supported by aquifer-test data, and (3) thin (less than 5 feet thick), areally discontinuous sand and gravel deposits are considered to be distributed randomly and, therefore, are not addressed in this report. Thin, discontinuous deposits could supply water sufficient for domestic purposes but not for long-term high-capacity water supplies. In addition to the criteria described



Base from U.S. Geological Survey
State base map, 1:500,000, 1965.

Geology modified from Wolf (1976)
and Olsen and Mossler (1982a)

SCALE

0 10 20 MILES

0 10 20 KILOMETERS

EXPLANATION

Brooten-Belgrade sand plain

Hydrologic boundary of study area

— 750 — — Structure contour. *Shows altitude of top of Proterozoic surface. Interval 50 feet. Dashed where approximately located. Datum is sea level.*

• U.S. Geological Survey test hole or private well

Figure 5.--Configuration of the Proterozoic crystalline-rock surface in the study area

above, correlation of adjacent sand and gravel deposits was aided by comparison of aquifer thickness, depth below land surface, thickness of overlying till, known well yield, hydraulic conductivity, and storage coefficient.

The drift system in the Brooten-Belgrade area is too complex and data too insufficient to accurately identify and map the many interconnected sand and gravel deposits. Although geologic logs and aquifer-test data indicate that confined aquifers are extensive, it is difficult to verify their continuity. Due to the complexity of the drift system, generalizations must be made in describing the confined aquifers and in mapping their hydrologic properties. Consequently, confined aquifers identified using the technique described above were combined into aquifer zones for mapping purposes. Sand and gravel deposits at relatively similar altitudes were mapped as being in the same aquifer zone. The sand and gravel deposits in each aquifer zone may or may not be directly connected; however, the deposits have been included in the same zone. The complexity of the drift system is clearly shown in the enclosed hydrogeologic sections. Figure II-1 shows the locations of sections A-A' through J-J' (Appendix II).

Confined aquifers were identified in six aquifer zones (fig. II-2). The complexity of drift in the area is clearly shown in this figure. The result of combining several separate confined sand and gravel deposits into one aquifer zone also is illustrated, particularly for zone C. A description of confined aquifers in each zone, in order of increasing depth below land surface, is presented in the following sections.

Maps showing the thickness, configuration of top, and transmissivity of confined aquifers in each aquifer zone are included in Appendix III - Zones A-F. Later sections of the report describe the annual reported water use, ground-water movement, and theoretical well yields for each aquifer zone. The aquifer boundaries shown on each hydrogeologic map represent the known areal extent of sand and gravel deposits in each zone. Some of the hydrologic properties of each aquifer zone are summarized in table 1.

Many of the enclosed maps indicate that aquifers within a given zone are horizontally continuous in areas where hydrogeologic sections indicate that aquifers are vertically discontinuous. This is the result of combining individual aquifers into aquifer zones for mapping purposes. In areas such as this, aquifers within a zone are overlapping, rather than horizontally continuous, and are actually separated by till. For example, figure III-11 shows how aquifers in zone C have been mapped as laterally continuous in the vicinity of Brooten and Belgrade. However, hydrogeologic section A-A' (fig. II-2) indicates a vertical discontinuity between zone-C aquifers in this area. In locations where more than one aquifer is present vertically in an aquifer zone, the hydrogeologic sections should be utilized to view the relative vertical locations of the aquifers.

Hydraulic conductivity and transmissivity are indicators of an aquifer's ability to yield water to wells. Variations in hydraulic conductivity reflect differences in aquifer texture, sorting, and the amount of clay- and silt-sized material. An estimate of aquifer hydraulic conductivity can be made using table 2, which provides a typical range of values for various glacial deposits in an adjacent part of the state (Lindholm, 1980). Transmissivity is the product of hydraulic conductivity and aquifer thickness. An average hydraulic conductivity for each aquifer zone was multiplied by aquifer thickness in constructing each transmissivity map. Aquifer tests and specific capacity tests were used for control, with greater confidence being placed on the aquifer-test results. Areas of greatest aquifer transmissivity are areas where greatest well yields can be expected. Storage coefficient is an indicator of an aquifer's ability to store or release water. The greater the storage coefficient, the greater the aquifer's ability to release water to wells. Confined-aquifer storage coefficients are several orders of magnitude less than for unconfined aquifers. Thus, wells completed in unconfined aquifers will yield water with much less drawdown than wells completed in confined aquifers when both wells are pumped at the same rate.

Several of the confined aquifers are known to coalesce with either the unconfined aquifer or another confined aquifer in an overlying or underlying zone. These areas are described in following sections of the report. Other areas where aquifers coalesce probably exist. Locating and identifying all these areas, however, was beyond the scope of this study.

Aquifer Zone A

Aquifers in zone A, which underlies approximately 270 mi^2, are located primarily in the northern part of the study area and in various locations outside the area (fig. III-1). This is the shallowest confined-aquifer zone in the area. The maximum known thickness, 47 ft, is west of Lake Johanna; the average thickness is 15 ft (fig. III-1). Depth below land surface to the top of aquifers in the zone ranges from about 40 ft near Sedan to 152 ft (table 1) northwest of Villard (fig. III-2). The average depth to aquifers in zone A is 65 ft. Till confining the aquifers ranges in thickness from about 5 feet northwest of Sedan to 95 feet east of Lake Reno and averages 45 feet.

Geologic logs indicate that aquifers in zone A may coalesce with the unconfined aquifer northwest of Lake Johanna and along Ashley Creek to the northeast (fig. III-2). Aquifers in the zone also may coalesce with the unconfined aquifer between Glenwood and Sedan where till thickness between the two aquifers is less than 5 ft. Data also indicate that aquifers in the zone may coalesce with underlying aquifers in zone B southwest of Lake Amelia and southeast of Padua. Springs from the aquifer may be present along the slopes surrounding Lake Minnewaska.

Hydraulic properties of aquifers in zone A were determined from analysis of 21 specific-capacity tests. The hydraulic conductivity ranges from 30 to 530 ft/d and averages 125 ft/d. Transmissivities generally range between 500 and 2,000 ft^2/d (fig. III-3). Although data were not available to determine a storage coefficient for aquifers in zone A, an estimated value for storage coefficient of 1.0×10^{-4}, similar to that for other confined aquifers in the area, is used in this report. Reported well yields for aquifers in zone A range from about 10 to 1,000 gal/min. The average depth to water below land surface is 32 ft.

Table 1.--*Summary of hydrologic characteristics for major confined aquifer zones in the Brooten-Belgrade area, west-central Minnesota*

[Hydrogeologic information from Minnesota Geological Survey water-well database; mi^2, square miles; ft/d, feet per day; ft^2/d, feet squared per day; gal/min, gallons per minute]

Aquifer zone	Approximate areal extent (mi^2)	Maximum known thickness (feet)	Average thickness (feet)	Range and average depth below land surface (feet)	Range and average hydraulic conductivity (ft/d)	Typical range in transmissivity (ft^2/d)	Range and average depth to water below land surface (feet)	Range in reported well discharge (gal/min)	Primary use of water (1986) irrigation (I), [domestic and/or stock (DS), municipal (M), or industrial (IN)]
A	270	47	15	40-152 (65)	30-530 (125)	500-2,000	10-70 (32)	10-1,000	I,DS,
B	315	60	20	20-130 (70)	20-525 (180)	1,500-3,000	4-40 (19)	8-1,100	I,DS
C	645	70	20	30-175 (85)	10-550 (150)	1,000-5,000	+15-140 (33)	10-1,800	I,M,IN,DS
D	590	100	15	20-209 (105)	10-600 (150)	1,500-9,000	0-140 (32)	10-1,300	I,M,DS
E	510	74	20	80-300 (170)	20-590 (125)	800-3,000	+10-105 (34)	10-1,400	I,DS
F	350	110	15	120-300 (240)	20-750 (125)	500-2,000	0-114 (36)	5-710	I,IN,DS

Table 2.--*Hydraulic conductivity of glacial deposits*
(From Lindholm, 1980, table 2.)
[mm-millimeters]

Predominant grain size (Wentworth scale)	Hydraulic conductivity (feet per day)
Clay or silt (less than 0.0625 mm)	10
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 (greater than 2.0 mm)	500-700

Aquifer Zone B

Aquifers in zone B, which underlies approximately 315 mi^2 miles, are located primarily in the northern part of the study area and in various locations outside the area (fig. III-6). The maximum known thickness, 60 ft, is near Villard; the average thickness is 20 ft (fig. III-6). Depth below land surface to the top of aquifers in zone B ranges from 20 ft in the east to 130 ft north of Villard (fig. III-7). The average depth to the aquifers is 70 ft. Till confining the aquifers ranges in thickness from about 5 ft southeast of Padua to 115 ft southwest of Osakis and averages 55 ft.

Geologic logs indicate that the aquifers in zone B may coalesce with aquifers in zone A southwest of Lake Amelia and southeast of Padua (fig. III-7). Springs from aquifers in zone B may be present along the slopes surrounding Lake Minnewaska.

Hydraulic properties of aquifers in zone B were determined from analysis of 13 specific-capacity tests and 2 aquifer tests. The hydraulic conductivity ranges from 20 to 525 ft/d and averages 180 ft/d. Transmissivities generally range between 1,500 and 3,000 ft^2/d (fig. III-8). A storage coefficient of 6.1×10^{-4} was computed for aquifers in this zone. Reported well yields for the aquifers in zone B range from 8 to 1,100 gal/min. The average depth to water below land surface is 19 ft.

Aquifer Zone C

Aquifers in zone C, which underlies approximately 645 mi^2, are located throughout most of the study area and in various locations outside the area (fig. III-11). The municipal water supply for the city of Glenwood is obtained from wells completed in aquifers in this zone as is part of the supply for the town of Brooten. The maximum known thickness of the zone is 70 ft north of Spring Hill; the average thickness is 20 ft (fig. III-11). Depth below land surface to the top of aquifers in the zone ranges from about 30 ft locally outside the area to 175 ft west of Glenwood (fig. III-12). The average depth to aquifers in the zone is 85 ft. Till confining the aquifers ranges in thickness from about 5 ft in the south to 150 ft near West Union and averages 70 ft.

Geologic logs indicate that aquifers in zone C may coalesce with the unconfined aquifer south of Georgeville and west of Paynesville in the study area and along the Sauk River east of the study area (fig. III-12). Till separating the two aquifers in these areas generally is less than 5 ft thick. Data indicate that aquifers in this zone may coalesce with the aquifers in zone D south of New London and north of Belgrade. Springs from aquifers in zone C issue from slopes surrounding Lake Minnewaska. Springs from aquifers in the zone also may be present along the banks of the Sauk River and where the aquifer crops out at land surface west of Sibley State Park and south of Lake Johanna.

Hydraulic properties of aquifers in zone C were determined from analysis of 82 specific-capacity tests and 2 aquifer tests. The hydraulic conductivity ranges from about 10 to 550 ft/d and averages 150 ft/d. Transmissivities generally range from 1,000 to 5,000 ft^2/d (fig. III-13). A storage coefficient of $1.6x10^{-4}$ was computed for aquifers in this zone. Reported well yields for aquifer zone C range from about 10 to 1,800 gal/min. The average depth to water below land surface is 33 ft.

Aquifer Zone D

Aquifers in zone D, which underlies approximately 590 mi^2, are located in the eastern part of the study area and in various locations outside the area (fig. III-16). Municipal water supplies for the towns of Belgrade, Paynesville, and Starbuck are obtained from wells completed in aquifers in this zone. Water supplies for the town of Brooten are also obtained, in part, from wells in aquifers in this zone. The maximum known thickness of 100 ft is located northwest of Paynesville; the average thickness is 15 ft (fig. III-16). Depth below land surface to the top of aquifers in zone D ranges from 20 ft locally in the south to 209 ft (table 1) in the north (fig. III-17). The average depth to aquifers in the zone is 105 ft. Till confining the aquifers ranges in thickness from about 5 ft south of New London to 235 ft northeast of Glenwood and averages 90 ft.

Geologic logs indicate that aquifers in zone D may coalesce with the unconfined aquifer along the Sauk River to the east, the Middle Fork Crow River to the south, and northeast of Paynesville (fig. III-17). Data indicate that aquifers in the zone also may coalesce with aquifers in zone C south of New London, with aquifers in zone E west of New London, and with sediments beneath Lakes Minnewaska and Koronis. Hydraulic properties of aquifers in zone D were determined from analysis of 127 specific-capacity tests and one aquifer test. The hydraulic conductivity ranges from 10 to 600 ft/d and averages 150 ft/d. Transmissivities generally range from 1,500 to 9,000 ft^2/d (fig. III-18). A storage coefficient of $1.6x10^{-2}$ was computed for aquifers in this zone. Reported yields of wells in aquifer zone D range from 10 to 1,300 gal/min. The average depth to water below land surface is 32 ft.

Aquifer Zone E

Aquifers in zone E, which underlies approximately 510 mi^2, are located primarily in the southern part of the study area and in various locations outside the area (fig. III-21). The maximum known thickness of 74 ft is located southeast of Lake Johanna; the average thickness is 20 ft (fig. III-21). Depth below land surface to the top of aquifers in the zone ranges from 80 ft locally in the south to 300 ft in the west and north (fig. III-22). The average depth to aquifers in the zone is 170 ft. Till confining the aquifers ranges in thickness from 5 ft north of New London to 290 ft west of Lake Johanna and averages 135 ft.

Geologic logs indicate that aquifers in zone E may coalesce with aquifers in zone D west of New London (fig. III-22). Data also indicate that aquifers in the zone may coalesce with aquifers in zone F southeast of Lake Koronis.

Hydraulic properties of the aquifers in zone E were determined from analysis of 45 specific-capacity tests and one aquifer test. The hydraulic conductivity ranges from 20 to 590 ft/d and averages 125 ft/d. Transmissivities generally range from 800 to 3,000 ft^2/d (fig. III-23). Although data were not available to determine a storage coefficient for aquifers in zone E, a storage coefficient of $1.0x10^{-4}$, similar to that for other confined aquifers in the area, is estimated for this report. Reported yields of wells in aquifer zone E range from 10 to 1,400 gal/min. The average depth to water below land surface is 34 ft.

Aquifer Zone F

Aquifers in zone F, which underlies approximately 350 mi^2, are located primarily southwest of the study area (fig. III-26). This is the deepest areally extensive confined-aquifer zone in the area. The maximum known thickness of about 110 ft is located south of Belgrade; the average thickness is 15 ft (fig. III-26). Depth below land surface to the top of aquifers in the zone ranges from 120 ft in the southwest to 300 ft south of Glenwood (fig. III-27). The average depth to aquifers in zone F is 240 ft. Till that confines aquifers in the zone ranges in thickness from 5 ft southeast of Paynesville to 220 ft in various locations south and southwest of the area. The average thickness of till confining the aquifer is 160 ft. Geologic logs indicate that the aquifers in zone F may coalesce with aquifers in zone E southeast of Lake Koronis (fig. III-26).

Hydraulic properties of aquifers in zone F were determined from analysis of 45 specific-capacity tests and 2 aquifer tests. The hydraulic conductivity ranges from 20 to 750 ft/d and averages 125 ft/d. Transmissivities generally range from 500 to 2,000 ft^2/d (fig. III-28). Although data were not available to determine a storage coefficient for aquifers in this zone, a storage coefficient of $1.0x10^{-4}$, similar to that for other confined aquifers in the area, is estimated for this report. Reported yields of wells in aquifers in zone F range from 5 to 710 gal/min. The average depth to water below land surface is 36 ft.

Ground-Water Flow

Ground water moves under the force of gravity in the direction of decreasing head. The direction and rate of movement is related to recharge and discharge rates, hydraulic conductivity, and hydraulic gradient. Ground water flows not only through aquifers, but also across confining beds. Because the hydraulic conductivity of aquifers is much greater than of confining beds, aquifers offer the least resistance to flow. Consequently, flow in aquifers is predominantly horizontal, whereas flow in confining beds is predominantly vertical (fig. 6).

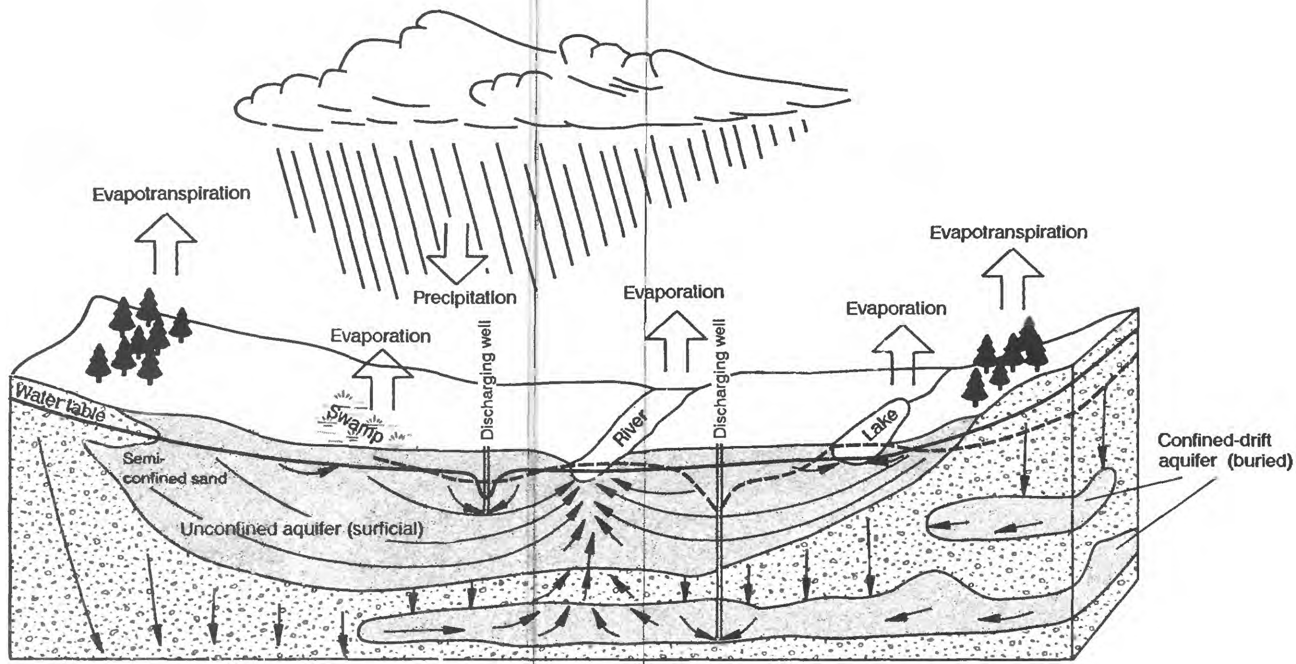
The general direction of horizontal ground-water movement in each aquifer zone in 1985 is shown in Appendix III - Zones A-F. Ground water generally flows from upland areas in the north to the southeast; it discharges locally to lakes, wetlands, wells, and streams such as the East Branch Chippewa, North Fork Crow, and Middle Fork Crow Rivers. Ground water also moves into and out of the study area where the drift aquifers extend beyond the boundaries of the study area. Lateral hydraulic gradients in the aquifers generally are between 2 and 10 feet per mile. The average and range in depth to water below land surface for each aquifer zone is listed in table 1.

Where a confined aquifer coalesces with the unconfined aquifer, ground water can flow directly between the aquifers in response to natural or pumping stresses. In the absence of pumping stresses, ground water generally flows under a natural head gradient from the confined aquifer into the unconfined aquifer with which it coalesces.

The head in each confined aquifer generally decreases with depth, indicating downward flow. Four well nests constructed for this study indicate that heads in the unconfined aquifer throughout most of the area are 0.5 to 11.0 ft above heads in the confined aquifers. Near streams, lakes, and wetlands, however, the head increases with depth and flow is upward. Five well nests indicate that heads in the confined aquifers near these discharge areas are between 0.3 and 11.0 ft higher than in the unconfined aquifer. Hydrogeologic section F-F' (fig. II-7) illustrates this reversal of ground-water flow, and surrounding head relationships, near the North Fork Crow River. Near the Middle Fork Crow River, water-level data indicate that heads in aquifer zone F were 4 ft higher than in the unconfined aquifer in November 1986; heads in aquifer zone D were 10.8 ft higher than in the unconfined aquifer near the North Fork Crow River north of Belgrade in October 1986.

Areal Recharge

The major source of recharge to the ground-water system is precipitation. Recharge is greatest in areas where the unconfined aquifer is present (glacial outwash in figure 4). Areal recharge usually is greatest in spring due to snowmelt, spring rain, and little evapotranspiration, which results in rising ground-water levels. Conversely, ground-water levels generally decline in summer because most precipitation is lost as evaporation or as transpiration by plants. Areal recharge sometimes occurs in the fall, depending on rainfall, runoff, and evapotranspiration conditions.



EXPLANATION

- - - - - Potentiometric surface

← Direction of ground-water flow

Sand

Till

Figure 6.--Generalized ground-water-flow system showing source and discharge areas for ground-water (from Delin, 1986a)

The rate at which water reaches the water table, where the unconfined aquifer is present, can be estimated using a method of hydrograph analysis (Rasmussen and Andreason, 1959). The method assumes that (1) all water-level rises in the unconfined aquifer result from areal recharge and (2) the rate of areal recharge per year nearly equals the sum of individual water-level rises within the year multiplied by the specific yield of the unconfined aquifer. The water-level rise thus calculated, however, falls short of the true water-level rise by the amount of water-level decline that would have occurred if recharge had not taken place. To account for this part of areal recharge, the hydrograph, prior to the rise, is extrapolated to the date on which the peak occurred. The corrected areal recharge rate, therefore, equals the difference between the peak stage and the projected water-level decline, on the day of the peak, multiplied by the specific yield of the unconfined aquifer in the area (fig. 7). Annual recharge was computed for 1982-84 using hydrographs from 15 observation wells. Areal recharge ranged from 2.6 to 16.5 in/yr and averaged 10.7 in/yr.

Although areal recharge to the ground-water system is greatest where the unconfined aquifer is present, areal recharge also occurs where till is present at land surface. Leakage to confined aquifers in these areas depends on (1) the head difference between the water table in the overlying till confining bed and the water level in the confined aquifer, (2) the vertical hydraulic conductivity of the till confining bed, and (3) the thickness of the till confining bed. Leakage rates to confined aquifers, in the areas where the unconfined aquifer is absent, were estimated using the following form of Darcy's Law:

$$Q_c = \frac{K'}{m'} h A_c,$$

where:

Q_c = leakage through confining bed to confined aquifers, in ft^3/d;

K' = vertical hydraulic conductivity of confining bed, in ft/d;

m' = confining bed thickness, in ft;

h = difference between head in confined aquifer and in source bed above confining bed through which leakage occurs, in ft; and

A_c = area of confining bed through which leakage occurs, in ft^2.

Leakage rates to confined aquifers for 9 sites were computed to be 0.06 to 1.60 in/yr using this formula; the average rate is 0.61 in/yr.

Discharge

Discharge from the ground-water system occurs naturally and artificially. Ground water discharges naturally to streams, lakes, and wetlands and by evapotranspiration (fig. 6). Artificial discharge is by means of wells.

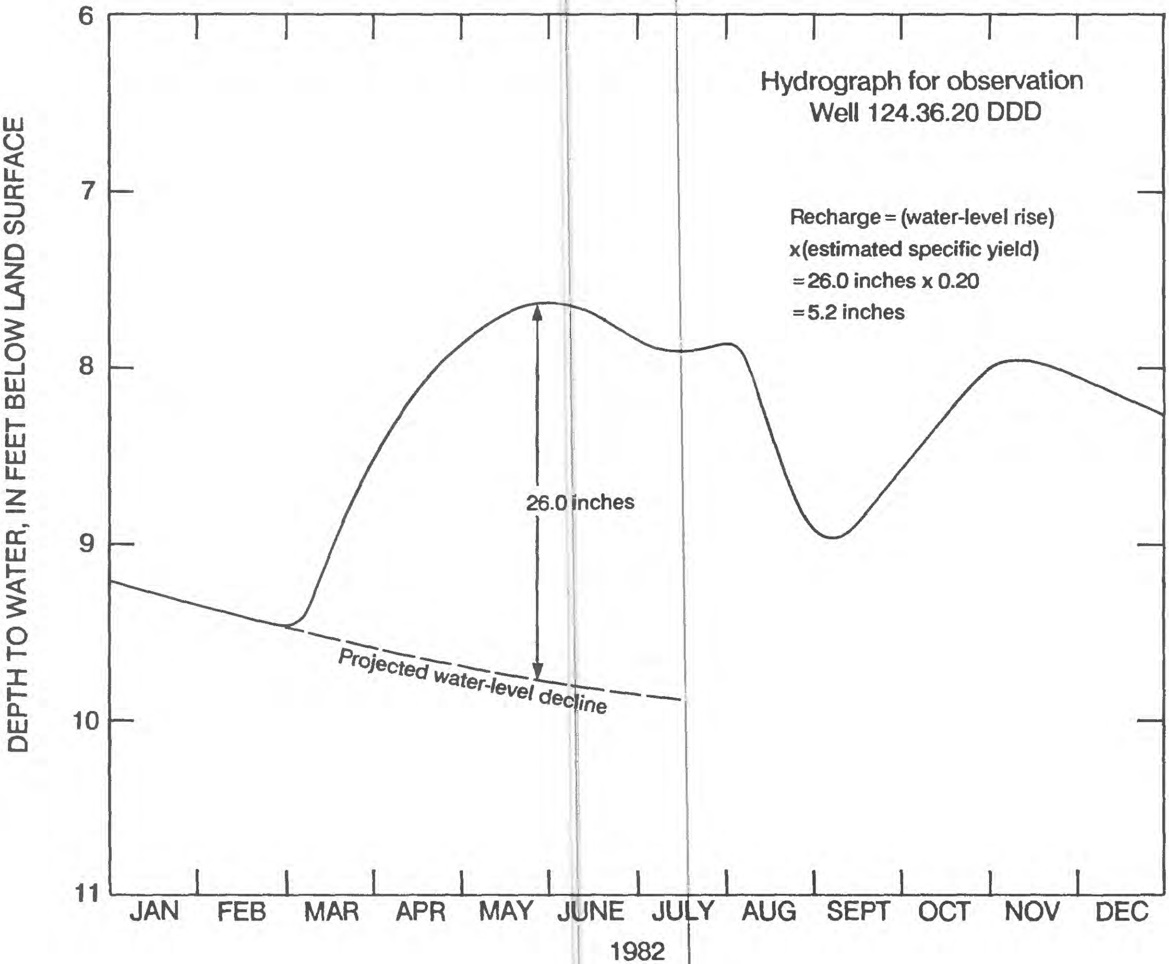


Figure 7.-- Method of estimating recharge to the surficial aquifer

Ground-Water Discharge to Streams

A significant part of discharge from the ground-water system is to streams. The amount of this discharge was estimated for the East Branch Chippewa, Middle Fork Crow, and North Fork Crow Rivers from measurements made in August 1985 and August 1986 (U.S. Geological Survey files, Montevideo and St. Paul, Minnesota). Discharge to or from the rivers depends on (1) thickness of the riverbed material, (2) vertical hydraulic conductivity of the riverbed material, and (3) head differences between the aquifer and river. In general, ground-water discharge to rivers is greater than leakage from rivers into the ground-water system.

Streamflow measurements indicate a wide range in base-flow conditions, probably as a result of the above-normal precipitation which occurred during 1985 and 1986. Flow durations for both the East Branch Chippewa and North Fork Crow Rivers were between 80 and 90 percent during the gaging periods in 1985 and 1986. A flow duration of 80 percent means that streamflow was equal to or greater than the flow that would be expected 80 percent of the time. From these data, it is apparent that the discharge for both the East Branch Chippewa and North Fork Crow Rivers was above normal, or excessive, when both streamflow measurements were made. Because streamflow measurements used to define baseflow conditions for streams ideally should be made during periods of low flow, the estimated discharge rates shown below probably are not an accurate representation of long-term ground-water discharge to the streams. The data are presented, however, for comparison purposes if additional data are collected in the future during baseflow conditions.

Ground-water discharge to the East Branch Chippewa River ranged between -0.86 and 2.39 (ft^3/s)/river mile (cubic feet per second per river mile) in August 1985 and between -8.06 and 10.16 (ft^3/s)/river mile in August 1986. Similar ground-water discharge rates to the other major streams in the area were observed. Ground-water discharge to the North Fork Crow River ranged from -1.88 to 4.03 (ft^3/s)/river mile in August 1985 and from -15.64 to 11.71 (ft^3/s)/river mile in August 1986. Ground-water discharge to the Middle Fork Crow River ranged from 0.39 to 12.39 (ft^3/s)/river mile in August 1985 and from -5.43 to 12.32 (ft^3/s)/river mile in August 1986.

Evapotranspiration

The amount of ground water lost to evapotranspiration depends on (1) water availability (depth to the water table below land surface), (2) the solar energy supplied, (3) air temperature, (4) humidity of the air, and (5) type of vegetation. The rate of evapotranspiration is assumed to be maximum at land surface and to decrease to zero at the root-zone depth. The root-zone depth for vegetation in the study area is assumed to be 5 ft. The mean potential evapotranspiration rate in the area is about 24 in/yr (Baker and others, 1979).

Large quantities of water are discharged from the ground-water system through evapotranspiration during summer. These losses decrease rapidly in fall and are near zero in winter. This variation in ground-water loss to evapotranspiration with time is approximately the same from year to year, provided the vegetation cover does not change significantly. Ground-water loss to evapotranspiration is greatest in the southwestern part of the study area, which is characterized by wetlands and depths to water less than 5 ft.

Ground-Water Pumpage

Ground-water pumpage is a significant part of the total water budget locally in the area. Ground-water pumpage for irrigation has increased greatly over the past two decades. Total irrigated acreage in Pope and Stearns Counties, for example, increased from about 1,000 acres in 1966 to 23,000 acres in 1976 and 45,000 acres in 1984 (Jerry Wright, University of Minnesota West-Central Experimental Station, written communication, 1987). Total irrigated acreage in the study area increased from about 26,300 acres in 1977 to about 37,500 acres in 1981, a 30-percent increase in 5 years. Unconfined aquifers provided most of the ground water used prior to 1975; since then, an increasing portion of the ground water used has been from confined aquifers.

The primary use of ground water from each confined-aquifer zone in 1984, as shown in table 1, was for irrigation. Significant amounts of water also are pumped for municipal and industrial purposes. The six major confined-aquifer zones identified in the study area all are used for irrigation and for domestic and stock supplies. Aquifer zones C, D, and F also are used for municipal and industrial supplies.

Many municipalities in the area obtain water supplies from wells in unconfined aquifers. Several municipalities, however, obtain water supplies from wells in confined aquifers. Well-log information indicates that the towns of Belgrade, Paynesville, and Starbuck obtain all or part of their municipal supplies from aquifer zone D; the city of Glenwood obtains most of its municipal supply from aquifer zone C; and the town of Brooten obtains its municipal supply from aquifer zones C and D.

Pumpage shown in table 3 represents annual ground-water pumpage reported to the Minnesota Department of Natural Resources (MDNR) Water-use Data System during 1980-84 by permitted high-capacity ground-water users (irrigators, municipalities, and industries). These data represent most of the ground water used in the study area; domestic and stock uses of ground water are insignificant compared to irrigation, municipal, and industrial use. It is beyond the scope of this study to account for all water withdrawn from the ground-water system. Pumpage shown in table 3 is totaled by county and by aquifer, and includes a comparison of pumpage from confined and unconfined aquifers. Pumpage included in the unidentified-aquifer category probably represents pumpage from one or more of the five confined aquifer zones listed.

Based on data in table 3, ground-water withdrawals in the area are greatest in Pope County and aquifers in zones C and D were the most heavily used from 1980-84. A comparison of data for confined and unconfined aquifers shows that pumpage from confined aquifers accounts for approximately 33 percent of total ground-water pumpage in the area with the remaining 66 percent coming from the unconfined aquifer. Withdrawals from confined aquifers generally were less in 1981 than in 1980, remained fairly constant from 1981 to 1983, and increased in 1984. Pumpage for crop irrigation generally is greatest during the summer when soil moisture is lowest.

Table 3.--*Annual pumpage from confined and unconfined aquifers in and near the Brooten-Belgrade area, west-central Minnesota, 1980-84*

(Data from Minnesota Water-use Data System; pumpage, in millions of gallons)

Aquifer Zone	Year	Kandiyohi County	Pope County	Stearns County	Ground-water pumpage totals (by zone)
A	1980	0.0	94.4	0.0	94.4
	1981	0.0	107.9	0.0	107.9
	1982	0.0	76.7	0.0	76.7
	1983	0.0	55.1	0.0	55.1
	1984	0.0	126.4	0.0	126.4
B	1980	16.7	47.7	57.0	121.4
	1981	24.8	40.7	61.7	127.2
	1982	3.8	47.0	47.9	98.7
	1983	4.6	40.8	23.2	68.6
	1984	4.8	73.5	15.5	93.8
C	1980	5.0	462.9	404.9	872.8
	1981	5.0	364.5	263.5	633.0
	1982	5.0	364.5	354.4	723.9
	1983	0.0	331.6	352.7	684.3
	1984	0.0	449.1	397.7	846.8
D	1980	70.5	148.4	634.5	853.4
	1981	68.9	47.4	76.7	193.0
	1982	33.5	228.2	108.0	369.7
	1983	49.8	67.9	231.4	349.1
	1984	35.9	47.0	768.6	851.5
E	1980	146.2	0.0	14.4	160.6
	1981	361.4	0.0	24.5	385.9
	1982	148.8	0.0	21.7	170.5
	1983	172.4	0.0	19.8	192.2
	1984	193.3	0.0	22.0	215.3
F	1980	33.0	30.9	0.0	63.9
	1981	29.4	23.0	0.0	52.4
	1982	27.7	43.2	0.0	70.9
	1983	7.3	28.8	0.0	36.1
	1984	17.1	0.0	0.0	17.1
Unidentified confined aquifer zone	1980	52.2	16.3	41.5	110.0
	1981	47.5	25.2	11.1	83.8
	1982	68.0	15.8	152.8	236.6
	1983	74.8	67.0	29.4	171.2
	1984	45.9	112.5	31.4	189.8
Confined aquifer pumpage totals (by county)	1980	323.6	800.6	1,152.3	2,276.5
	1981	537.0	608.7	437.5	1,583.2
	1982	286.8	775.4	684.8	1,747.0
	1983	308.9	591.2	656.5	1,556.6
	1984	297.0	808.5	1,235.2	2,340.7
Surficial aquifer pumpage totals	1980	870.9	1,851.9	1,699.2	4,422.0
	1981	581.2	2,078.4	1,456.1	4,115.0
	1982	535.9	1,176.1	1,510.1	3,222.1
	1983	460.6	1,694.8	1,143.0	3,298.4
	1984	545.9	2,123.9	1,433.2	4,103.0

Precipitation measured at Glenwood betweem 1980 and 1984 (table 4) during the primary pumping season of June through September indicates that pumping for irrigation should be greater in 1982 and 1983 compared to 1980, 1981, and 1984. Ground-water pumpage data in table 3, however, do not agree with this assumption. This lack of agreement may be due to (1) inaccurate reporting of irrigation pumpage to the MDNR, (2) locally excessive precipitation at the recording station during a storm, (3) local areas of high and low precipitation within the study area that are not reflected in data from one recording station, or (4) application of fertilizers or pesticides with an irrigation system during periods of adequate soil moisture.

Water-Level Fluctuations

Water levels fluctuate in response to seasonal variations in recharge to and discharge from the ground-water system. Variations in ground-water pumping, evapotranspiration, soil moisture, vegetation type, precipitation, and runoff are the major factors affecting water-level fluctuations.

Water levels in wells completed in confined aquifers generally fluctuated 5 to 10 ft annually (figs. 8-9). During periods of below-normal precipitation, however, such as in the summer of 1987, short-term water-level declines of as great as 40 ft were known to occur. Water levels in confined aquifers rose or remained fairly constant during periods of above-normal precipitation, such as in 1986 (figs. 8-9). Water levels in the unconfined aquifer generally fluctuated 1 to 3 ft annually (fig. 9), even within approximately one mile of a high-capacity well. Fluctuations in the vicinity of a high-capacity pumping well are greater for confined aquifers than for unconfined aquifers because they do not release as much water from storage per unit change in head as unconfined aquifers.

Figure 10a shows the water-level declines between April and August 1987 for wells completed in confined aquifers. A majority of these water levels were measured in observation wells installed in heavily irrigated areas where pumpage from confined aquifers is large. Data in figure 10a indicate that significant water-level declines result from seasonal irrigation pumpage. Water-level declines of at least 5 ft were measured in aquifer zones A, B, C, D, and E throughout much of the study area. Water-level-change data for aquifer zone C have been contoured in figure 10b, as an example, to illustrate the declines that occurred in this zone. A similar contour pattern exists for aquifer zone D. Water-level declines of at least 30 ft occurred in an area of approximately 30 mi^2 in aquifer zones C and D in the vicinity of Brooten and Belgrade. The maximum measured water-level decline during 1987 of 42 ft was in aquifer zone C about 2 miles northwest of Belgrade.

Water levels in unconfined aquifers in the area generally recover to prepumping levels following each irrigation season. Water levels in confined aquifers also recover to prepumping levels. Thus, although water levels in confined aquifers decline significantly during years of intense pumping for irrigation, such as in 1987, the water levels generally return to prepumping levels.

Table 4.--*Precipitation and departure from normal precipitation at Glenwood, 1980-84*

[Precipitation values in inches]

Year	June - September precipitation	Departure from normal	Annual precipitation	Departure from normal
1980	17.64	5.01	24.09	-0.04
1981	15.06	2.43	27.06	2.93
1982	12.23	-0.40	24.26	0.13
1983	13.07	-0.06	22.84	-1.29
1984	13.67	0.54	26.95	2.82

Ground-water levels in the study area generally fluctuate around mean water levels that remain relatively constant over long periods of time--that is, the ground-water system in the area is in dynamic equilibrium. If the system were not in dynamic equilibrium, the general trend of ground-water levels would be rising or falling. A period of falling water levels throughout the area would indicate that recharge to the ground-water system was less than discharge from the system.

Theoretical Maximum Yield of Wells in Confined Aquifers

The theoretical maximum yield of wells in confined aquifers was estimated using a method developed by Meyer (1963) that relates well diameter and specific capacity, and aquifer transmissivity and storage coefficient. The relation shows that for confined aquifers (storage coefficients less than about 0.005), large differences in storage coefficient correspond to relatively small differences in specific capacity. Therefore, inaccurate estimation of aquifer storage is not a serious limiting factor in estimating theoretical well yields. The relation shows that for transmissivities from about 270 to 13,000 ft^2/d, the ratio of transmissivity to specific capacity is about 320 to 1. The ratio is larger for greater transmissivities. Therefore, for confined aquifers with transmissivities of 13,000 ft^2/d or less, the specific capacity can be approximated by dividing the transmissivity by 320. The theoretical maximum well yield at a specific site can then be estimated by multiplying the specific capacity by an arbitrarily selected drawdown, such as 30 ft. The estimates of theoretical maximum well yield included in this report were based on the following assumptions:

1. The aquifer is homogeneous, isotropic, and infinite in areal extent.

2. The well is screened through the entire thickness of the aquifer, is 100 percent efficient, and has a diameter of 12 inches.

3. The well is pumped continuously for 24 hours.

4. Drawdown is 30 ft.

5. Effects of recharge, hydrologic boundaries, and other pumping wells are negligible.

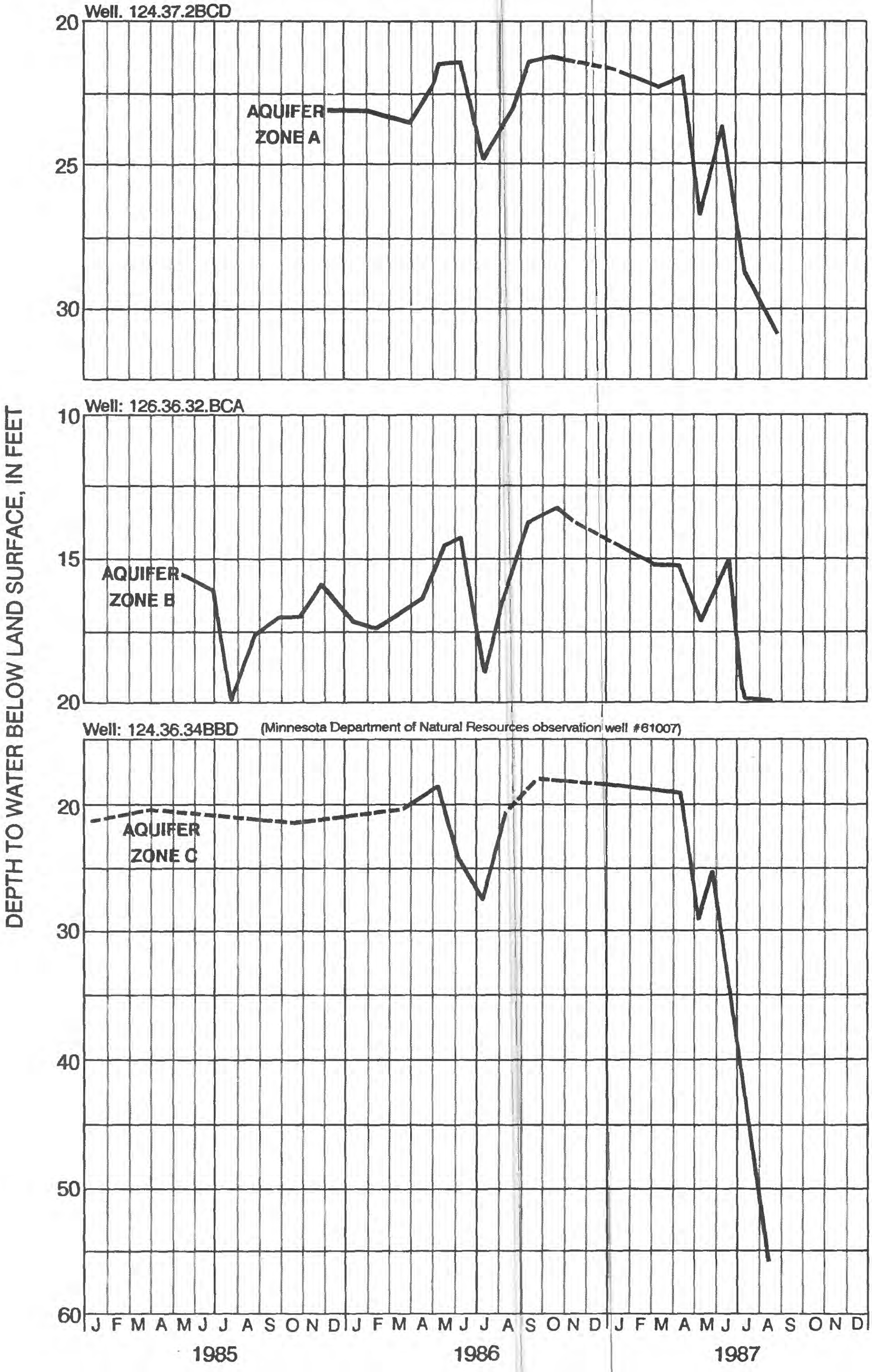


Figure 8.--Hydrographs for wells completed in aquifer zones A, B, and C, 1985-87

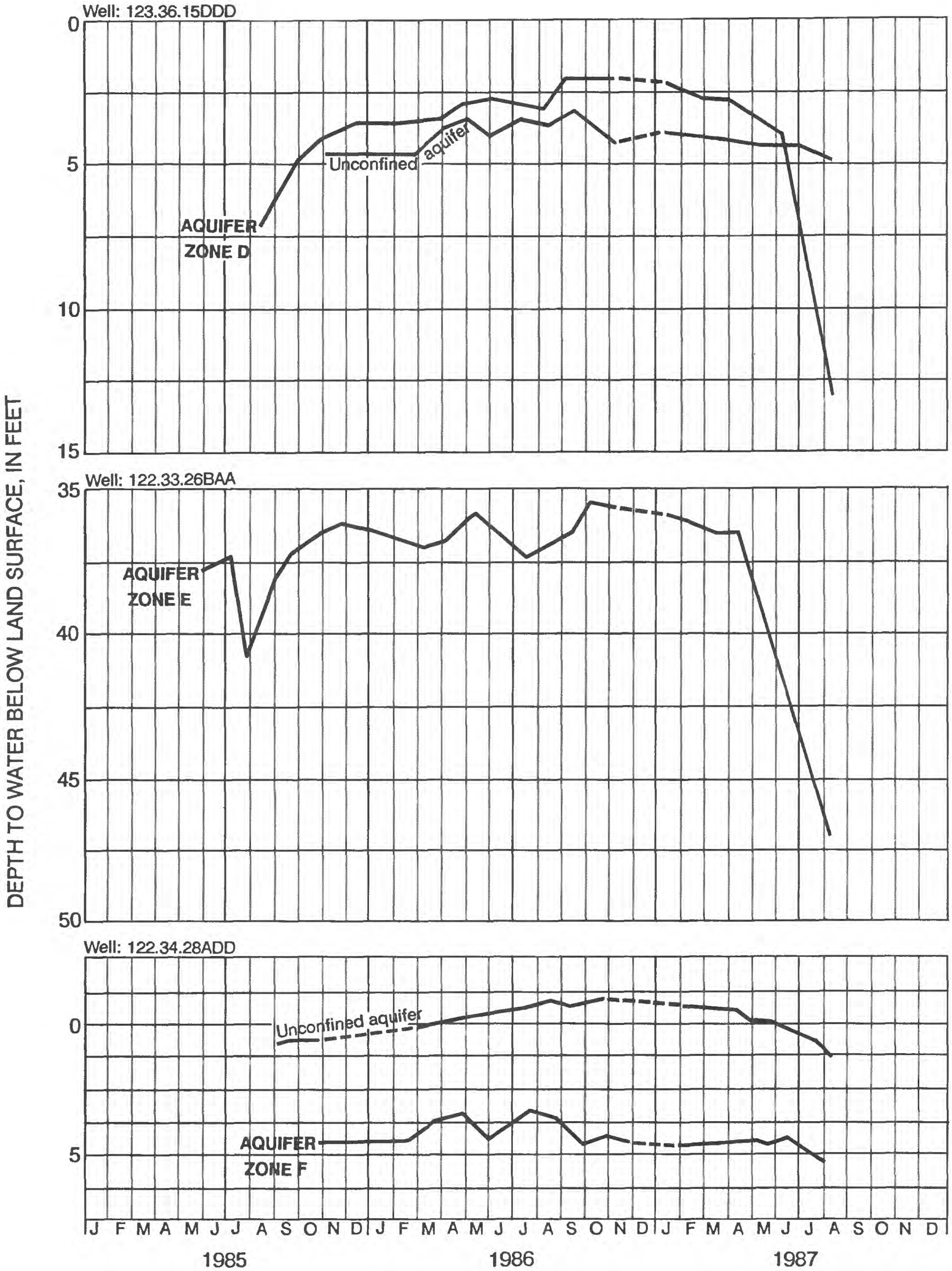
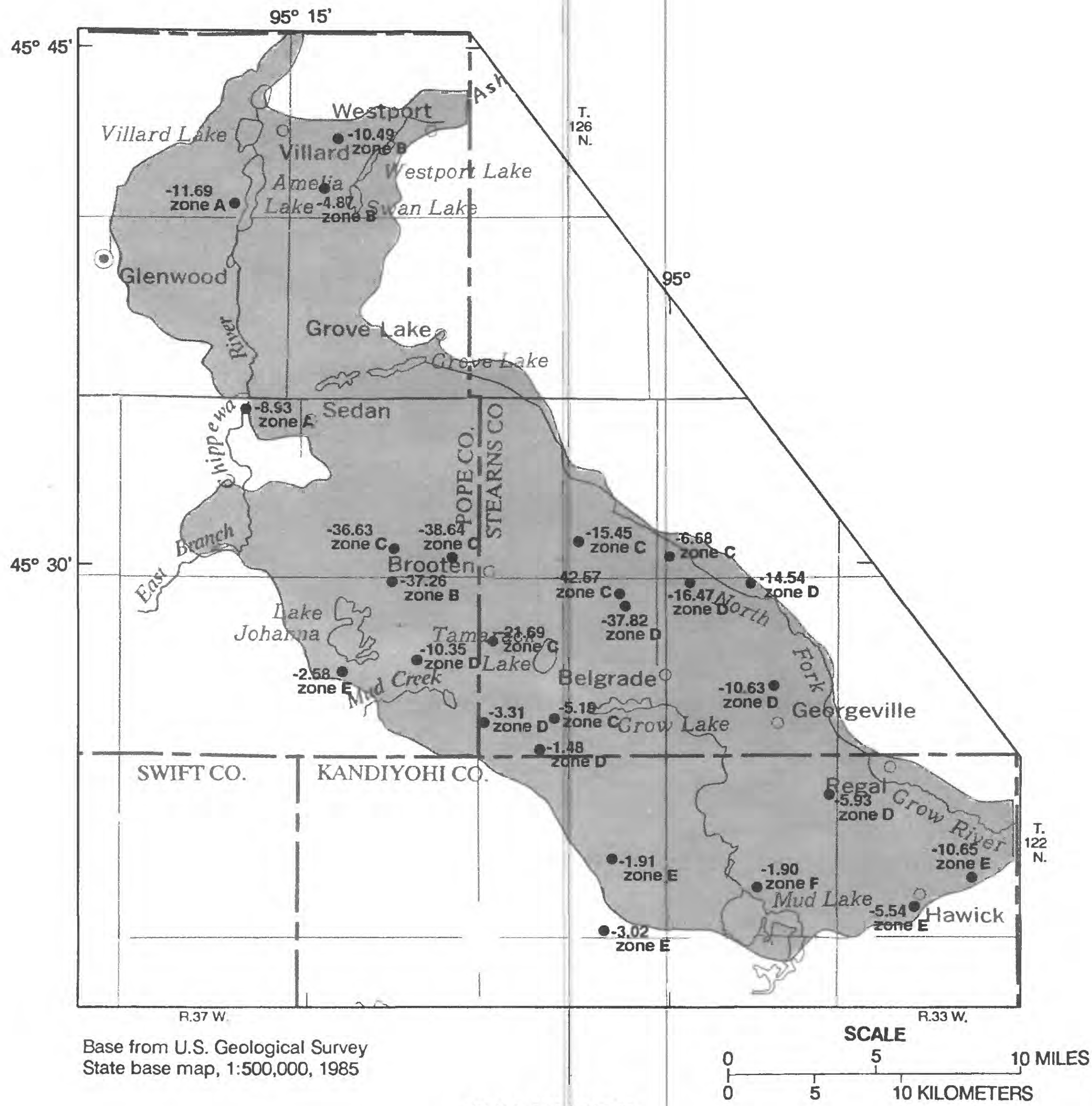


Figure 9.--Hydrographs for wells completed in aquifer zones D, E, and F and the unconfined aquifer, 1985-87



EXPLANATION

● -14.54 zone D — Well, water-level change, and aquifer zone

Figure 10a.--Water-level changes from April through August 1987 for confined aquifers in the Brooten-Belgrade area

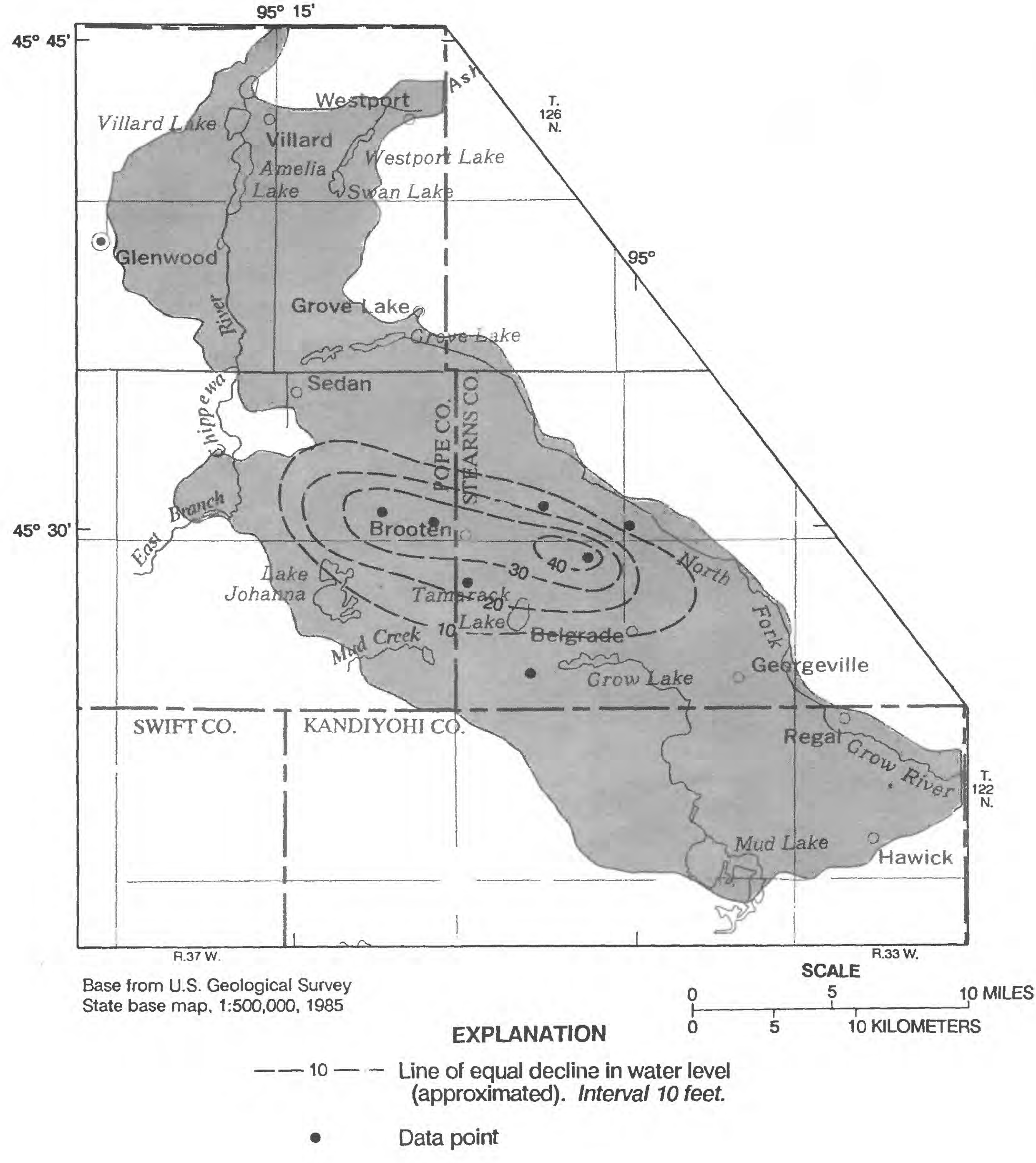


Figure 10b.--Water-level changes from April through August 1987 for aquifer zone C

It should be noted that no aquifer or well fully satisfies the above assumptions. Local variations in aquifer hydraulic properties, recharge, proximity of the well to other pumping wells, aquifer inhomogeneities, well diameter and efficiency, and duration of pumping will cause local exceptions to the values shown in Appendix III - Zones A-F as figures III-5, 10, 15, 20, 25 and 30. The actual yields could vary both above and below the values shown. For example, if greater than 30 ft of drawdown were available at a given location, the expected yield would be greater than the yield shown on an enclosed map. The theoretical maximum well yields for each confined aquifer are intended to show only general conditions and relative differences in water-yielding capability. The maps cannot be used for accurate projection of well yields at a given location; however, they can be used to determine the most favorable areas for test drilling.

The areas of greatest theoretical maximum yield (figs. III-5, 10, 15, 20, 25, 30) coincide with areas of greatest transmissivity. The theoretical maximum well yields shown range from about 100 to 1,000 gal/min. High-capacity wells generally are located in these areas. The maximum reported discharge values for wells completed in the aquifers shown in table 1 locally exceed the theoretical maximum discharge shown in figures III-5, 10, 15, 20, 25, 30 because one or more of the assumptions listed on page 80 were not met. Furthermore, regional averages are shown on the maps, which do not reflect local variations in aquifer transmissivity.

Well Interference

Pumping a well lowers nearby ground-water levels, forming a depression in the water table or potentiometric surface that commonly is referred to as a cone of depression (fig. 11a). The difference between the nonpumping water level and the lowered water level caused by the pumping is drawdown. Where pumping wells are spaced relatively close together, pumping one well causes drawdown in the others. Total drawdown in a pumping well is equal to its own drawdown plus the drawdown, at that point, caused by other pumping wells (fig. 11b). This additional drawdown is referred to as well interference.

Well interference is of greatest concern to owners of wells completed in confined aquifers. Figure 12 illustrates the measurable limit of the cone of depression for wells, pumping at the same rate, completed in unconfined and confined aquifers. From this figure it is clear that the cone of depression around a well completed in a confined aquifer extends much farther from the well than the cone of depression around a well completed in an unconfined aquifer. Withdrawals from unconfined aquifers (fig. 12a) dewater the aquifer. The cone of depression expands slowly because water of sufficient quantity to sustain pumping is available in the immediate area. Conversely, withdrawals from confined aquifers (fig. 12b) cause a drawdown in the potentiometric surface that normally does not result in aquifer dewatering. The cone of depression expands very rapidly because confined aquifers have very small storage coefficients and the pumped water is derived from expansion of water in the aquifer and from compression of the sand and gravel framework of the aquifer.

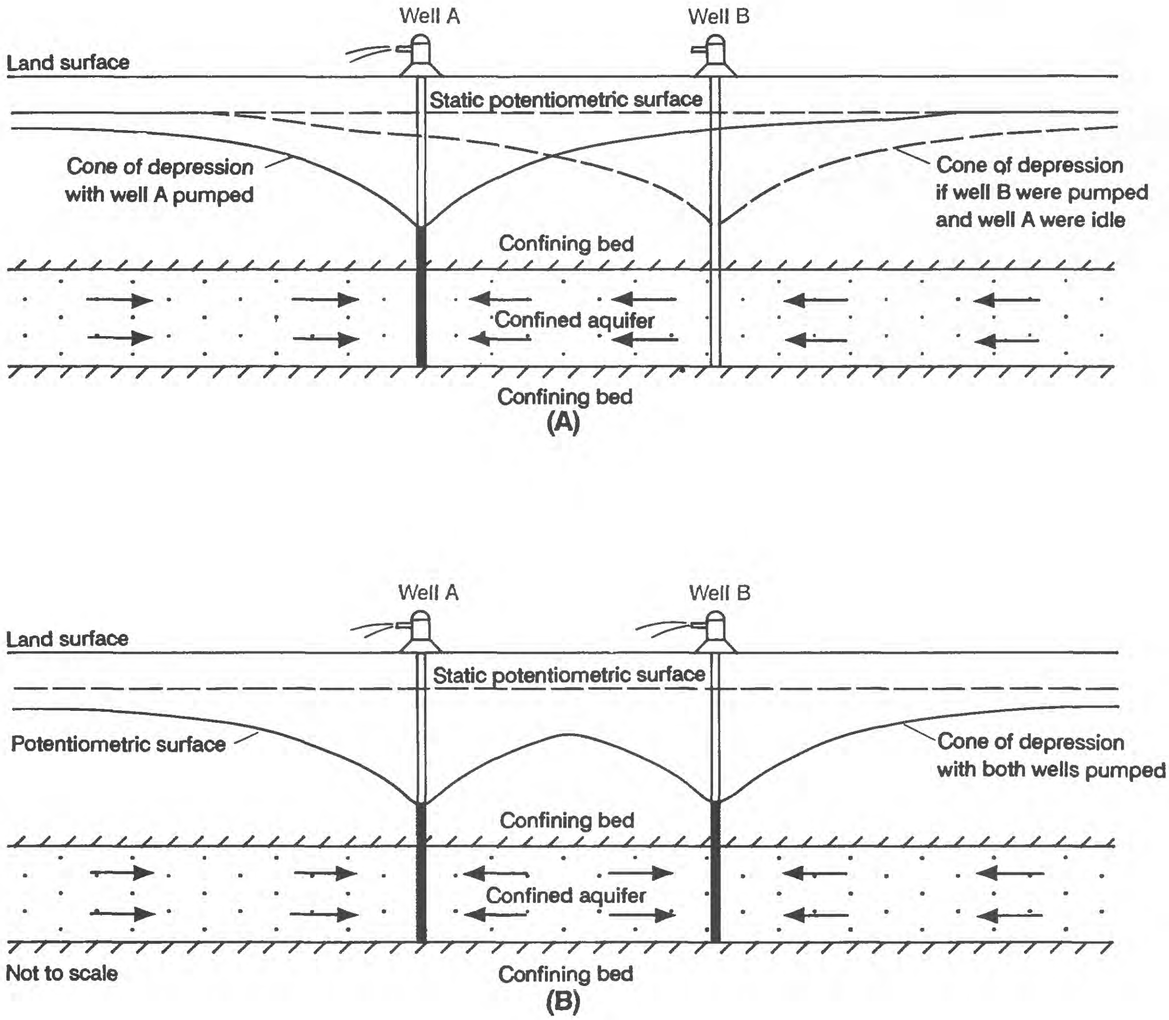


Figure 11.-- Well interference in a confined aquifer (modified from Heath, 1983, page 44)

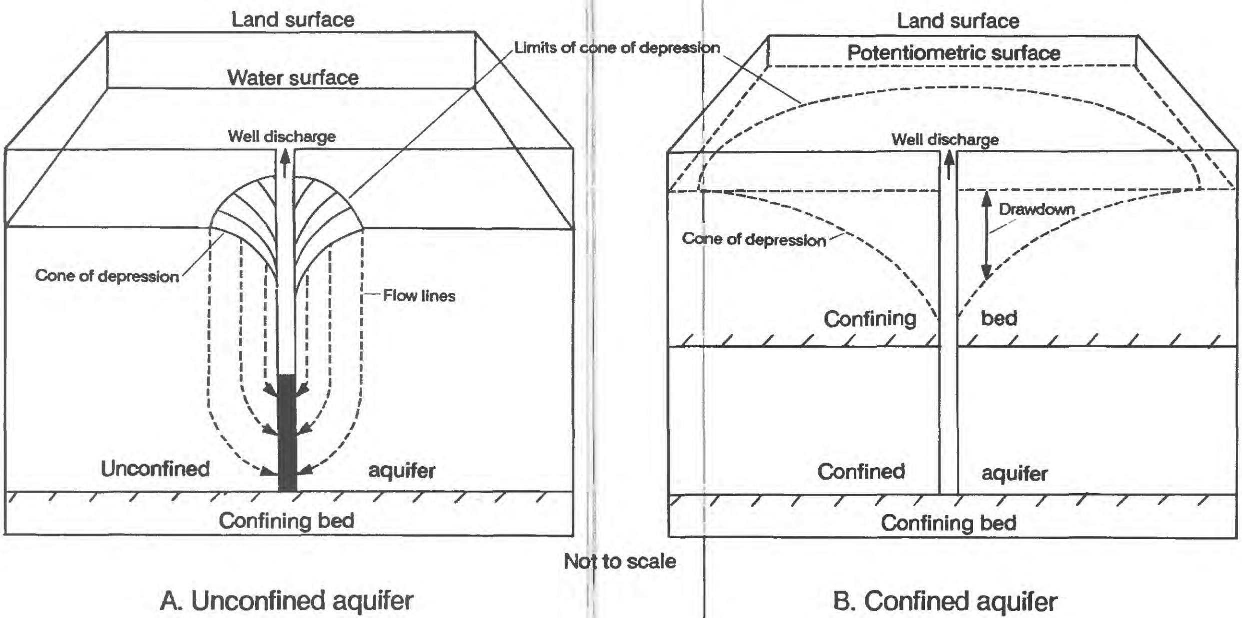


Figure 12.–Cones of depression for wells, pumping at the same rate, completed in (A) unconfined and (B) confined aquifers (modified from Heath, 1983, page 30)

Well interference reduces the amount of available drawdown, resulting in increased pumping costs and decreased well yield. Domestic wells may be dewatered because of well interference from a nearby high-capacity well. This problem usually can be corrected by screening the domestic well near the bottom of the confined aquifer rather than near the top. The potential for well interference should be considered prior to drilling a well.

Well interference also may occur near areas where confined and unconfined aquifers coalesce. Where confined and unconfined aquifers are separated by till (fig. 13a), water levels in the unconfined aquifer are relatively unaffected by pumping from the confined aquifer. However, where confined and unconfined aquifers coalesce, ground water can flow freely from one aquifer to the other. Therefore, if the aquifers are connected, pumping from a confined aquifer can cause drawdown in a nearby well completed in a unconfined aquifer (fig. 13b). A similar relation holds for two confined aquifers that coalesce. Because well logs indicate that the drift aquifers are connected in many places throughout the study area, interference between wells is a potential problem.

Based on results of an aquifer test northwest of Belgrade conducted for this study, drawdown may occur in overlying and underlying confined aquifers when a confined aquifer is pumped. An irrigation well completed in aquifer zone C was pumped at a rate of 800 gal/min for 48 hours. Water levels were monitored in 11 wells completed in aquifer zones C and D, the unconfined aquifer, and till separating the aquifer zones. Confined aquifers in zones C and D are separated by approximately 80 ft of till in this area. Areas where aquifers coalesce are not evident locally. The aquifer system generally responded to the pumping as expected. Drawdowns of 11.7 and 4.5 ft were measured in the pumped aquifer, zone C, at distances of 1,200 and 4,000 ft, respectively. Less than 3 ft of drawdown occurred in the unconfined aquifer in the immediate vicinity of the pumping well. However, drawdown of 2.3 ft was measured in the underlying confined aquifer, zone D, 3,600 ft from the pumping well. Although this may seem extraordinary, it is the expected response of the drift system in the Bonanza valley. Thus, well interference may occur even in areas unaffected by aquifer coalescing.

The location of a well near a physical boundary can affect drawdown also. Close proximity of a well to a sand-till boundary, for example, will increase drawdown in the well. Conversely, close proximity to lakes, streams, and swamps may induce infiltration of water to the aquifer, resulting in less drawdown.

Other potential problems caused by ground-water withdrawals from confined aquifers are relatively low rates of recharge to confined aquifers compared to unconfined aquifers, and areal discontinuity of the confined aquifers. Because of these factors, confined aquifers initially may yield sufficient quantities of water for irrigation but may not sustain these yields for an entire irrigation season.

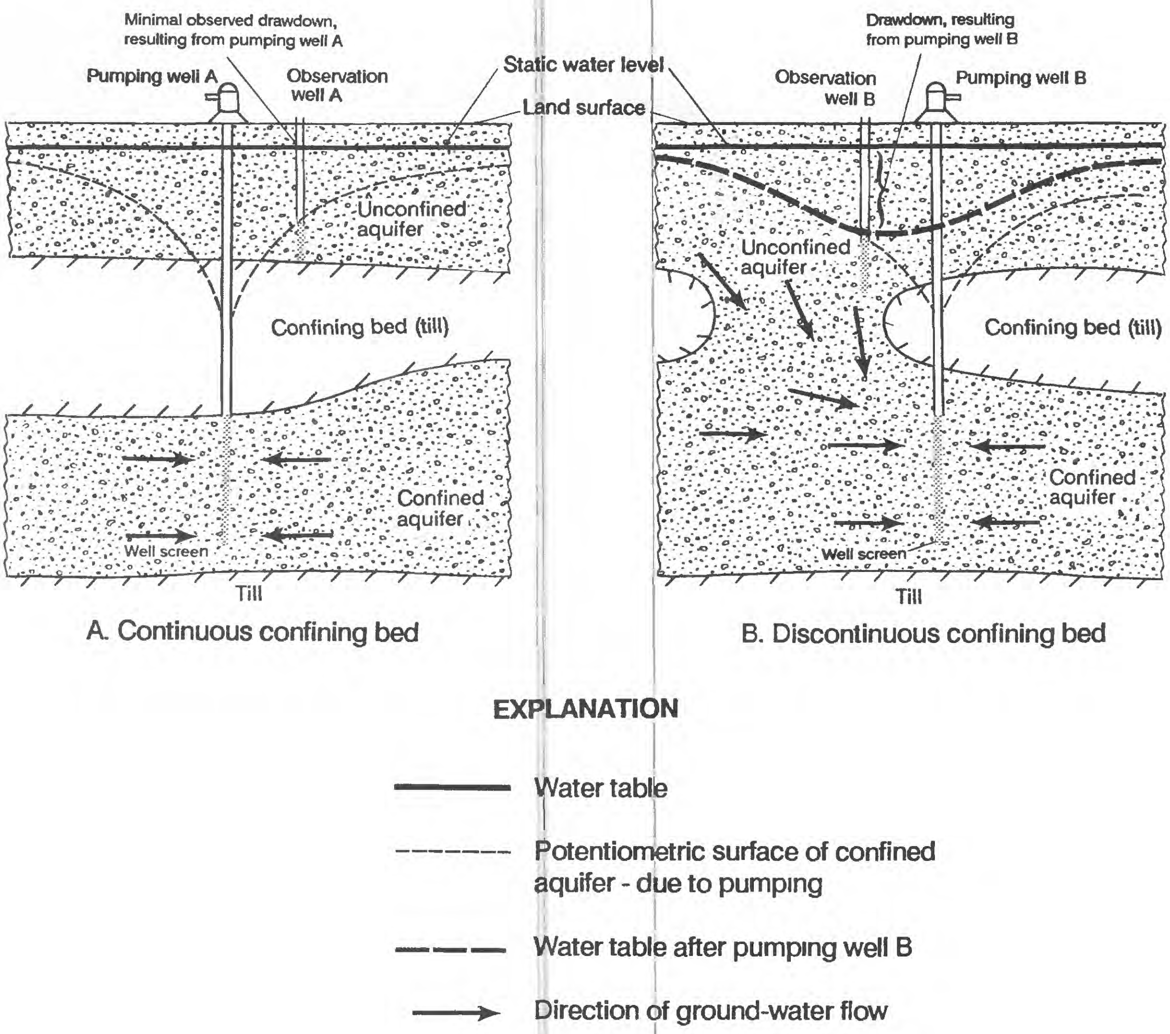


Figure 13.--Potential well interference near where confined and unconfined aquifers coalesce (from Delin (1983a, figure 22)

Simulation of Ground-Water Flow and Effect of Ground-Water Development

A ground-water-flow model was constructed to improve an understanding of the movement of water in the complicated drift system. Models are useful tools for management of ground-water systems because they can help assess possible water-level response to estimated climatic changes and pumping stresses. The modeled area covers approximately 2,500 mi^2 including parts of Douglas, Kandiyohi, Meeker, Pope, Stearns, Swift, and Todd Counties (fig. 14). An area covering approximately 1,300 mi^2 within the modeled area was the focus of the modeling effort. Modeling objectives were to (1) determine the vertical head gradient between the drift aquifers, and (2) determine the probable effects of future ground-water development and drought on water levels and storage of water in the aquifers. A detailed description of the model, including steady-state calibration, is provided by Delin (1988).

The computer code of McDonald and Harbaugh (1988) was used to simulate ground-water flow in three-dimensions. Several simplifying assumptions were made in constructing the model. The assumptions are:

1. Based on water-level data, ground-water flow in the drift aquifers is primarily horizontal and flow in the till-confining units separating them is primarily vertical;

2. The aquifers and confining units simulated are continuous, homogeneous, and isotropic;

3. Due to lack of accurate field data, streambeds are assumed to be 1 ft thick and composed of permeable material with lower hydraulic conductivity than that of the aquifers;

4. Ground-water discharge to minor streams and ditches is insignificant and is ignored;

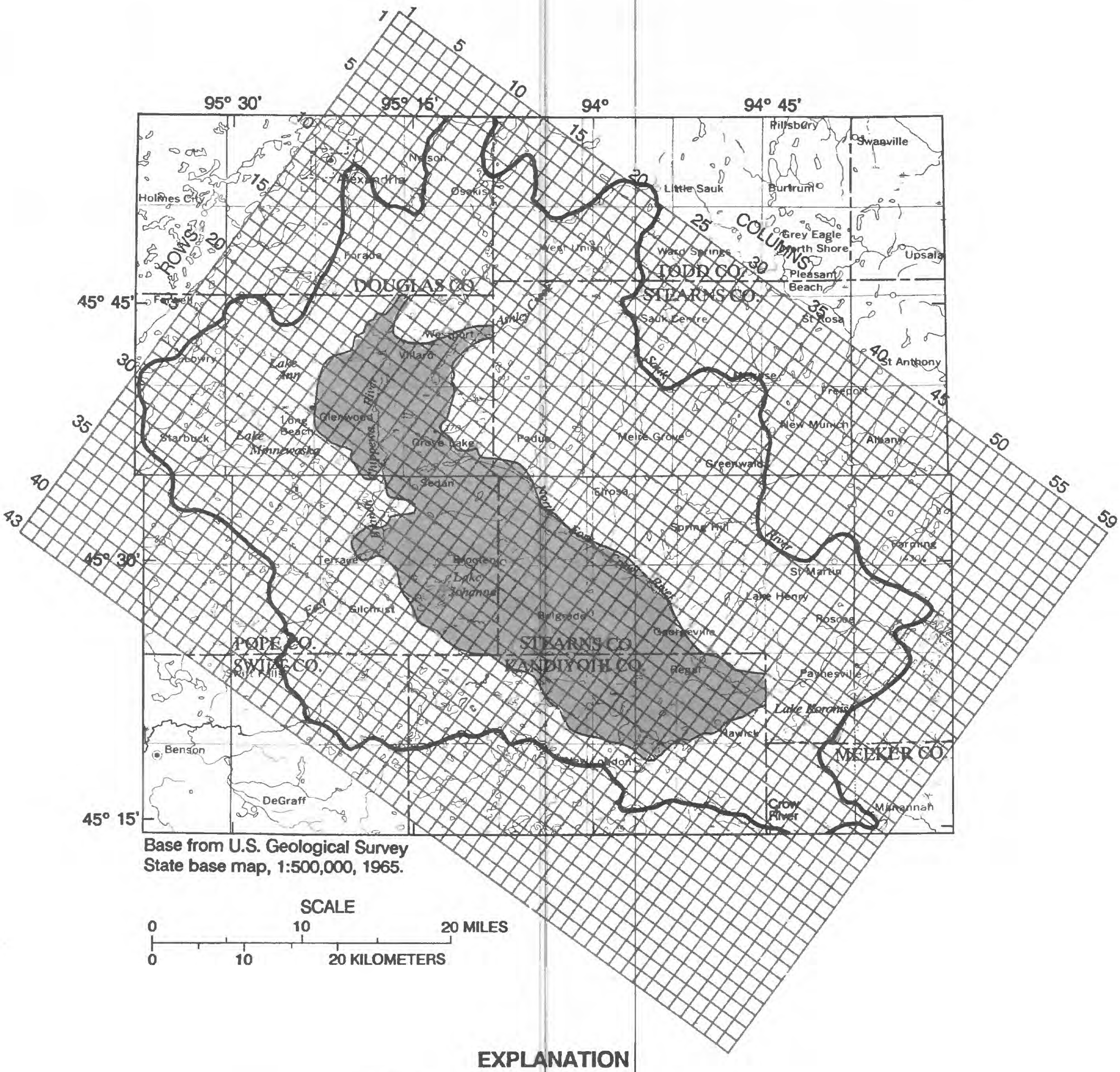
5. Areal recharge to the water table is from precipitation and occurs primarily from April through June and secondarily from October through December;

6. Where till is present at land surface, vertical leakage through till is constant and does not fluctuate seasonally;

7. The rate of evapotranspiration declines linearly to zero at a depth of 5 ft below land surface; and

8. Ground water used for irrigation is consumed by evapotranspiration and, therefore, return flow to the aquifer system is negligible.

The drift system was divided into seven model layers: layer 1 (the top layer) represents the unconfined aquifer; layer 2 represents confined aquifers in zone A; layer 3 represents confined aquifers in zone B; layer 4 represents confined aquifers in zone C; layer 5 represents confined aquifers in zone D; layer 6 represents confined aquifers in zone E; and layer 7 represents confined aquifers in zone F. Horizontal ground-water flow was simulated in each aquifer zone. Vertical flow in the ground-water system was simulated by allowing leakage between model layers.



EXPLANATION

Brooten-Belgrade sand plain

Hydrologic boundary of study area

Figure 14.--Finite-difference grid for the ground-water-flow model

The model was calibrated to assure that the hydrologic properties and boundaries selected were reasonable for the simulation of flow in the ground-water system. The model was calibrated for steady-state conditions by comparing measured water levels and calculated ground-water discharge to rivers with corresponding values computed by the model. Calibration of the model was achieved by successively adjusting hydrologic input values until model-computed water levels and ground-water discharge rates acceptably matched corresponding measured values. Calibration results were acceptable, with the exception that the model generally underestimated discharge to the rivers. This is because the measurements used to estimate ground-water discharge to rivers were not made during a period of low flow, which would be a better representation of the average (steady-state) conditions simulated by the model. However model results are considered to be a reasonable estimate of ground-water discharge to streams. If low-flow measurements are made in the future, the model could be recalibrated and run to determine if the recalibrated input affects results of the simulations described in this report.

A water budget is an accounting of the inflow to, outflow from, and storage in the ground-water system. For steady-state conditions, the inflow (sources) to the system, equal the outflow (discharges) from the system. A general equation of the steady-state water budget in the modeled area can be written as:

Precipitation + ground-water flow into the modeled area = evapotranspiration + ground-water discharge to rivers + ground-water pumpage

The steady-state water budget for the calibrated model is shown in table 5. Precipitation is the major inflow to the system, whereas ground-water discharge to the principal streams is the major outflow.

Following calibration, the model was used to simulate the effects of pumping in 1984, potential effects of hypothetical increases in ground-water development, and the potential effects of below-normal precipitation (drought). Results of these simulations, described in detail by Delin, (1988), can be used to estimate regional aquifer response to future stress.

The effects on the ground-water system of historical and 1984 pumping (simulation A) were evaluated using the model. According to the model's computations, pumping has lowered water levels between 5 and 10 ft regionally in all aquifer zones (table 6). Water-level declines have been greatest near Belgrade. Ground-water discharge to the East Branch Chippewa and North Fork Crow Rivers has been reduced by approximately 25 percent compared to predevelopment conditions.

Table 5.--*Steady-state water budget for the calibrated ground-water-flow model*

Sources	Rate (million gallons per year)	Percent
Recharge from precipitation	16,895	95.6
Ground-water discharge from the East Branch Chippewa and North Fork Crow Rivers	775	4.4
Total inflow	17,670	100.0

Discharges	Rate (million gallons per year)	Percent
Ground-water discharge to the East Branch Chippewa and North Fork Crow Rivers	11,090	62.6
Ground-water pumpage	6,010	34.0
Discharge directly to Lakes Minnewaska and Koronis	350	2.0
Springs surrounding Lake Minnewaska and along the Sauk River	255	1.4
Total outflow	17,705	100.0
Inflow - outflow	-35	-0.2

The model was used to simulate the potential effects of a hypothetical drought (simulation B) of 25-percent-less recharge for 3 years, accompanied by a 50-percent increase in pumpage. According to the model's computations, increased pumping during the hypothetical drought probably would lower water levels 2 to 10 ft regionally in each aquifer zone and as much as 20 ft locally in the unconfined aquifer. Ground-water discharge to the North Fork Crow, Middle Fork Crow, and East Branch Chippewa Rivers in the modeled area would be reduced by 47 percent of 1984 conditions. Discharge from confined aquifers to Lakes Minnewaska and Koronis would be reduced by about 11 percent and discharge to springs around Lake Minnewaska and along the Sauk River would be reduced by about 9 percent.

Based on simulations of hypothetical development (simulations C1, C2, C3, C4 and C5), the confined aquifers in the Brooten-Belgrade area are capable of supporting additional pumping. Hypothetical development was simulated in aquifer zones A, B, C, D, and E. The hypothetical wells were located throughout each aquifer zone in areas of sandy soils where future ground-water development is likely and were spaced to minimize well-interference problems. The average pumping rate for irrigation wells in the modeled area, 12.3 Mgal/yr

Table 6.--*Summary of results of hypothetical model simulations A, B, C1, C2, C3, C4, and C5*

Simulation	Conditions of simulation	Model results
A	Predevelopment: 1984 pumping removed to determine effects of historical pumpage Average areal recharge	Water levels have declined between 5 and 10 feet regionally in all aquifer zones. Declines have been greatest near Belgrade. Ground-water discharge to rivers has decreased 25 percent since predevelopment.
B	Present well development (344 wells) Pumping stress: actual (1984) X 1.5 Drought: 25-percent less recharge for 3-year duration	Water levels decline between 2 and 5 ft regionally in each aquifer zone and as much as 20 feet locally. Ground-water discharge to rivers is reduced by 47 percent of 1984 conditions.
C1	Present + hypothetical well development: 10 in aquifer zone A (354 wells total) Pumping stress: actual + estimated* Average areal recharge	Water levels decline between 0.2 and 0.4 feet regionally and as much as 1.4 feet locally in aquifer zone A. Water levels decline as much as 1.4 feet in overlying surficial aquifer and as much as 0.8 feet in underlying aquifer zone B.
C2	Present + hypothetical well development: 15 in aquifer zone B (359 wells total) Pumping stress: actual + estimated* Average areal recharge	Water levels decline between 0.1 and 0.5 feet regionally and as much as 2.7 feet locally in aquifer zone B. Water levels decline as much as 0.7 feet in overlying aquifer zone A and as much as 0.9 feet in underlying aquifer zone C.
C3	Present + hypothetical well development: 20 in aquifer zone C (364 wells total) Pumping stress: actual + estimated* Average areal recharge	Water levels decline between 0.1 and 1.0 feet regionally and as much as 2.0 feet locally in aquifer zone C. Water levels decline as much as 0.9 feet in overlying aquifer zone B and as much as 0.4 feet in underlying aquifer zone D.
C4	Present + hypothetical well development: 20 in aquifer zone D (364 wells total) Pumping stress: actual + estimated* Average areal recharge	Water levels decline between 0.1 and 0.5 feet regionally and as much as 1.2 feet locally in aquifer zone D. Water levels decline as much as 0.5 feet in overlying aquifer zone C and as much as 0.7 feet in underlying aquifer zone E.
C5	Present + hypothetical well development: 20 in aquifer zone E (364 wells total) Pumping stress: actual + estimated* Average areal recharge	Water levels decline between 0.5 and 1.0 feet regionally and as much as 5.0 feet locally in aquifer zone E. Water levels decline as much as 2.8 feet in overlying aquifer zone D and as much as 0.4 feet in underlying aquifer zone F.

* Pumping rate for each hypothetical well is 12.3 Mgal/yr

(million gallons per year), was simulated for each hypothetical well. All model-computed water-level declines mentioned in the remainder of this section are in addition to the historical declines that occurred prior to 1984. It must be emphasized that the hypothetical simulations were allowed to reach equilibrium conditions, whereas the ground-water system probably would not reach equilibrium during a given pumping season. The projected declines represent average declines over model grid blocks that cover 1 mi^2. Actual water-level declines in wells will differ from computed values, and declines in or near individual high-capacity wells generally will be greater.

According to the model's computations, the addition of 10 hypothetical high-capacity wells in aquifer zone A, (simulation C1) pumping a total of 123 Mgal/yr, would lower water levels in the aquifer zone about 0.2 to 0.4 ft regionally and reduce discharge to the East Branch Chippewa and North Fork Crow Rivers by about 123 Mgal/yr (100 percent of the hypothetical pumpage) (table 6); the addition of 15 hypothetical wells in aquifer zone B (simulation C2), pumping a total of 184.5 Mgal/yr, would lower water levels in the aquifer zone 0.1 to 0.5 ft regionally and reduce discharge to rivers by about 117 Mgal/yr (63 percent of the hypothetical pumpage); the addition of 20 hypothetical wells in aquifer zone C (simulation C3), pumping a total of 246 Mgal/yr, would lower water levels in the aquifer zone 0.1 to 1 ft regionally and reduce discharge to rivers by about 104 Mgal/yr (42 percent of the hypothetical pumpage); the addition of 20 hypothetical wells in aquifer zone D (simulation C4), pumping a total of 246 Mgal/yr, would lower water levels in the aquifer zone 0.1 to 0.5 ft regionally and reduce discharge to rivers by about 83 Mgal/yr (34 percent of the hypothetical pumpage); and the addition of 20 hypothetical wells in aquifer zone E (simulation C5), pumping a total of 246 Mgal/yr, would lower water levels in the aquifer zone 0.1 to 1 ft regionally and reduce discharge to rivers by about 186 Mgal/yr (76 percent of the hypothetical pumpage). These results indicate that water-level declines would be greatest in zones C and E (as a result of the hypothetical pumping) and that the greatest reduction in streamflow would occur in zones A, B, and E.

According to the model's computations, significant volumes of water are exchanged between the drift aquifers. The approximate model-computed leakage from overlying deposits to the confined aquifers are: aquifer zone A--2,200 Mgal/yr; aquifer zone B--2,700 Mgal/yr; aquifer zone C--2,800 Mgal/yr; aquifer zone D--2,500 Mgal/yr; aquifer zone E--70 Mgal/yr; and aquifer zone F--40 Mgal/yr.

Caution should be used in making ground-water-management decisions based on the model simulations. Model-computed water-level declines reflect simplified assumptions and should be considered only in assessing regional water-level changes. The projected declines represent average declines over model grid blocks. Actual water-level declines in wells will differ from computed values, and declines in or near individual high-capacity wells generally will be greater than those shown in this report. A detailed description of all model results is provided by Delin (1988).

WATER QUALITY

Chemical constituents dissolved in ground water are derived mainly from the materials (soil, drift, etc.) through which the water moves. Ground-water quality varies due to changes in residence time, length of flow path, temperature, rainfall, land use, and chemical reactions with minerals and aquifer materials.

Water from 17 domestic or municipal wells was sampled for chemical analysis in 1985; 13 wells were sampled in 1986. All the samples were from wells completed in confined aquifers. In addition, water-quality data from 9 wells sampled by U.S. Geological Survey personnel between 1965 and 1975 also were used in interpreting the quality of ground water in the area. The median, standard deviation, and range in chemical-constituent concentrations for the six aquifer zones are given in table 7, including data for the unconfined aquifer for comparison. Water-quality data for the unconfined aquifer (table 7) were collected during a previous U.S. Geological Survey study. Anderson (1987) provides a detailed analysis of the quality of water in the unconfined aquifer. Water-quality data for the confined aquifers sampled in this study are insufficient to determine chemical-constituent variations within each aquifer zone.

Calcium and bicarbonate are the predominant ions in water from the confined aquifers (fig. 15). Calcium and bicarbonate are derived primarily from contact with carbonate rocks as the water moves slowly through the ground-water reservoir.

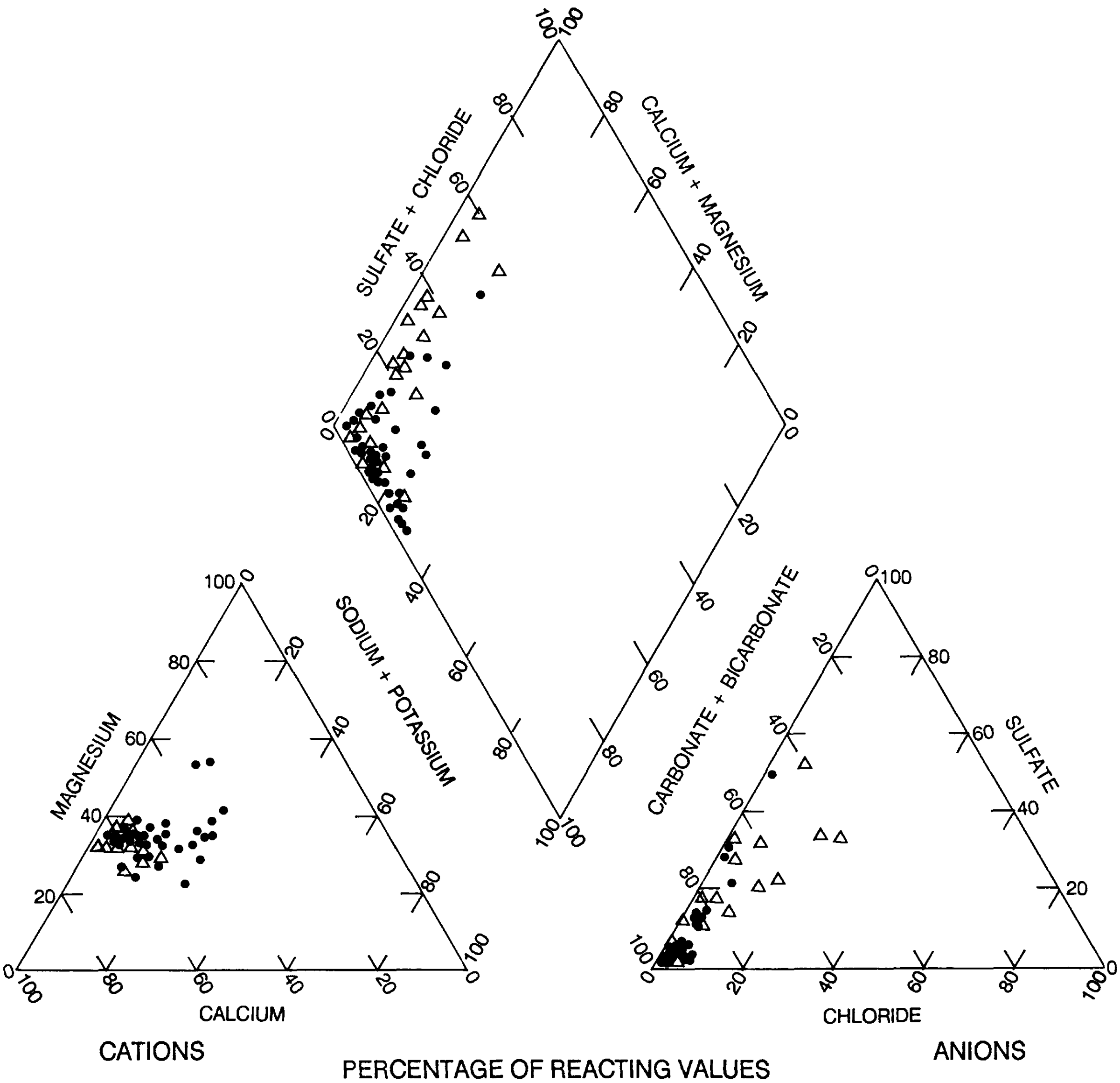
Water from confined aquifers in the study area is hard, but it generally is suitable for domestic consumption and for irrigation. However, concentrations of manganese, iron, and dissolved solids locally exceed limits recommended by the Minnesota Pollution Control Agency (MPCA) (1978) for domestic consumption. Table 8 lists the recommended limits for domestic consumption and table 9 lists the recommended limits for use by agriculture and wildlife. Also included in the tables is the percentage of analyses that exceeded the recommended limits.

The suitability of water for irrigation commonly is determined by relating conductivity of the water to the sodium-adsorption ratio (fig. 16), which can be used to classify the water in terms of its sodium and salinity hazards (Allred and Machmeier, 1961). This classification system was developed by the U.S. Salinity Laboratory (1954). The sodium-adsorption ratio is a measure of the amount of sodium with respect to calcium and magnesium. High values of the sodium-adsorption ratio can be an indication of tendency for ground water to destroy soil structure and thereby reduce permeability. High salinity concentrations endanger plants by reducing the amount of water absorbed by roots. Salinity is directly related to the specific conductance of water. Water from the confined aquifers generally has a low sodium hazard and a medium to high salinity hazard (fig. 16). Dissolved iron and manganese are essential to plants and animals, but, in high concentrations, may cause objectionable taste, odors, and staining of plumbing fixtures. Concentrations of dissolved iron and manganese in water from confined aquifers generally exceed limits recommended by the MPCA (1978) for domestic use. The concentrations (table 8) should not adversely affect plants, but treatment of the water may be desirable prior to domestic use.

Table 7.--*Comparison of water quality in confined and unconfined aquifers in the Brooten-Belgrade area, west-central Minnesota*

[μS/cm), microsiemens per centimeter at 25 degrees celsius; mg/L, milligrams per liter; μg/L, micrograms per liter]

Chemical constituent or property	Confined aquifers: Number of analyses	Mean	Median	Range	Standard deviation	Unconfined aquifers: Number of analyses	Mean	Median	Range	Standard deviation
Specific conductance (μS/cm)	41	661	640	420-990	33.5	114	639	620	290-1,070	128
pH (standard units)	41		7.5	6.7-8.4	.3	115		7.4	6.4-8.5	.3
Calcium, dissolved (mg/L as Ca)	40	79.4	83.0	44-120	17.0	26	82.6	76.0	40-130	17.5
Magnesium, dissolved (mg/L as Mg)	40	30.0	30.0	17-53	8.4	26	26.5	26.0	13-40	5.5
Sodium, dissolved (mg/L as Na)	40	18.1	17.5	2.5-48	24.6	27	6.3	2.5	1.0-36	8.3
Potassium, dissolved (mg/L as K)	40	2.5	2.4	1.4-3.8	.6	27	5.2	2.0	0.9-35.0	7.3
Alkalinity (lab) (mg/L as $CaCO_3$)	40	365	345	246-799	92	17	292	292	180-439	84.3
Sulfate, dissolved (mg/L as SO_4)	40	17.4	5.0	2-160	29.4	55	27.0	24.0	2-100	20.9
Chloride, dissolved (mg/L as Cl)	39	1.8	1.5	.5-7.9	1.3	55	17.2	10.0	1.6-49	15.4
Fluoride, dissolved (mg/L as F)	40	.3	.3	.1-0.5	.1	27	.1	.1	.0-0.3	.1
Silica, dissolved (mg/L as SiO_2)	40	25.1	25.0	16-32	3.1	26	22.4	21.5	13-31	4.0
Solids, sum of constituents, dissolved (mg/L)	36	385	360	270-650	79	26	344	320	190-500	74.9
Nitrogen, NO_2+NO_3, dissolved (mg/L as N)	29	.2	.2	0-0.32	.02	106	9.6	4.0	.0-44	1.7
Phosphorus, ortho, dissolved (mg/L as P)	28	.07	.06	.01-0.20	.05	36	.02	.01	.01-0.07	.01
Boron, dissolved (μg/L as B)	40	91	110	0-220	56	26	68	30	10-330	89.5
Iron, dissolved (μg/L as Fe)	34	2,807	1,800	300-9,000	2,068	21	1,220	1,100	10-6,400	1,893
Manganese, dissolved (μg/L as Mn)	34	127	175	20-480	102.3	21	139	250	10-580	165



EXPLANATION

- • Confined aquifer
- △ Unconfined aquifer

Figure 15.--Trilinear diagram showing chemical character of water in the confined and unconfined aquifers

Table 8.--*Recommendations of the Minnesota Pollution Control Agency (1978) for concentrations of selected chemical constituents in drinking water*

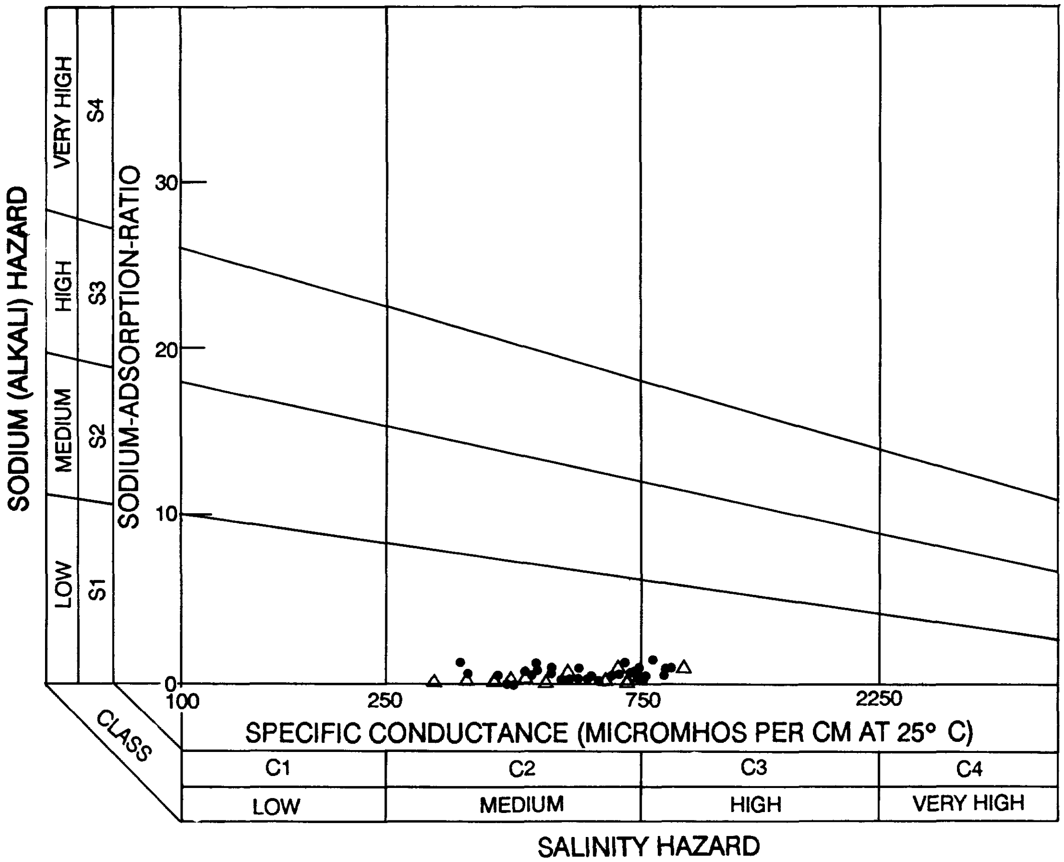
[mg/L, milligrams per liter; µg/L, micrograms per liter]

Chemical constituent	Recommended limit	Percentage of analyses exceeding limit
Chloride	250 mg/L	0
Fluoride	1.5 mg/L	0
Iron	300 µg/L	95
Manganese	50 µg/L	71
Nitrate as nitrogen	10 mg/L	0
Sulfate	250 mg/L	0
Dissolved solids	500 mg/L	3

Table 9.--*Recommendations of the Minnesota Pollution Control Agency (1978) for concentrations of selected chemical constituents in water for agricultural use and consumption by wildlife*

[mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 degrees celsius]

Chemical constituent	Recommended limit	Percentage of analyses exceeding limit
Boron	500 mg/L	0
pH	6.0-8.5 units	0
Specific conductance	1,000 µS/cm	0



EXPLANATION

- • Confined aquifer
- △ Unconfined aquifer

Figure 16.--Diagram showing suitability of water from confined and unconfined aquifers for irrigation in terms of sodium and salinity hazards. (U.S. Salinity Laboratory, 1954)

High concentrations of some dissolved solids in ground water can cause well-screen incrustation and reduced well yield. Dissolved-solids concentrations in water from confined aquifers (table 7) generally are within the recommended limits for domestic use.

Chemical-constituent concentrations generally are similar in water from the unconfined and confined aquifers, as shown in tables 7 and 10 and in figures 15 and 16. Manganese concentrations, for example, fluctuate somewhat with depth in the drift system (fig. 17) but the fluctuation is insignificant. The similarity in major-ion concentrations probably is a reflection of the similarities in aquifer material composing the unconfined and confined aquifers. Locally, however, mixing of ground water may occur. Mixing is highly probable where the unconfined and confined aquifers coalesce. In these areas, chloride concentrations in both aquifers should be similar because chloride ions are mobile and readily flow with the ground water. Although this similarity in chloride concentration was not observed, ground-water mixing probably occurs locally. The similarity of water from the unconfined and confined aquifers is shown also in figure 16. Water from both aquifers generally has a low sodium hazard and medium to high salinity hazard to soils.

There are several differences in the quality of water from the confined and unconfined aquifers. Although median concentrations of constituents are similar in the aquifer zones (table 10), concentrations of many constituents increase with depth in the drift system. Specific conductance and pH, and concentrations of dissolved solids, alkalinity, phosphorus, magnesium, fluoride, silica, and boron were, in general, slightly higher in water from confined aquifers than from unconfined aquifers (table 10). Aquifer zones E and F (representing the lowermost confined aquifers in the area) had the highest concentrations of most chemical constituents determined in the analyses. This relation also is illustrated in figures 17 and 18. Although median concentrations of calcium and magnesium do not vary significantly, the concentrations do increase slightly with depth. Median sodium and iron concentrations (figs. 17 and 18) clearly increase with depth in the drift system.

The increase in chemical-constituent concentrations with depth reflects an increase in ground-water residence times in the confined aquifers compared to the unconfined aquifers. Ground water leaches chemical constituents from the soil and rock material through which it passes. The longer that water remains in the ground before discharging to a lake, stream, wetland, or well, the greater the concentration of most chemical constituents. The length of residence time results primarily from the low permeability of till in intermediate and regional flow systems that hinders ground-water flow. Water in unconfined aquifers generally does not flow through till and, thus, has short residence times and correspondingly low chemical-constituent concentrations. Because aquifer zones E and F are confined by an average of 135 and 220 feet of till, respectively, high chemical-constituent concentrations in water from these aquifers are unexpected. Work on age-dating of water in drift aquifers near Park Rapids, Minnesota, supports the above relation of length of residence time to depth of the confined aquifers (Dr. Calvin Alexander, University of Minnesota, written commun., 1987).

Table 10.--*Median concentration of selected chemical constituents in water from drift aquifers in the Brooten-Belgrade area, west-central Minnesota*

[µs/cm, microsiemens per centimeter at 25 degrees celsius; mg/L, milligrams per liter; µg/L, micrograms per liter]

Chemical constituent or property	Unconfined aquifer	All confined aquifers	Confined-aquifer zone					
			A	B	C	D	E	F
Specific conductance (µs/cm)	639	661	612	607	666	638	703	740
pH (standard units)	7.4	7.5	7.4	7.2	7.4	7.6	7.7	7.6
Calcium, dissolved (mg/L as Ca)	82.6	79.4	78.8	75.4	81.4	73.6	83.8	84.8
Magnesium, dissolved (mg/L as Mg)	26.5	30.0	25.8	25.4	30.3	29.2	33.6	35.4
Sodium, dissolved (mg/L as Na)	6.3	18.1	11.2	12.4	15.4	25.9	18.4	20.5
Potassium, dissolved (mg/L as K)	5.2	2.5	2.9	2.5	2.5	2.2	2.4	2.5
Alkalinity (mg/L as $CaCO_3$)	292	365	335	335	367	353	355	448
Sulfate, dissolved (mg/L as SO_4	27.0	17.4	15.0	5.3	7.9	13.3	46.9	29.3
Chloride (mg/L as Cl)	17.2	1.8	1.0	1.5	2.0	1.6	1.8	2.0
Fluoride, dissolved (mg/L as F)	0.1	0.3	0.2	0.2	0.3	0.3	0.2	0.2
Silica, dissolved (mg/L as SiO_2	22.4	25.1	25.5	25.8	25.1	24.9	24.6	26.0
Solids, sum of constituents, dissolved (mg/L)	344	385	365	350	390	380	447.50	376.67
Nitrogen, dissolved NO_2+NO_3 (mg/l as N)	9.6	0.2	<0.1	0.3	<0.1	0.3	0.1	<0.1
Phosphorus, ortho dissolved (mg/L as P)	0.02	0.07	0.05	0.04	0.07	0.05	0.08	0.12
Boron, dissolved (µg/L as B)	68	91	78	76	101	87	106	90
Iron, dissolved (µg/L as Fe)	1220	2807	2975	2525	3802	1382	2770	3120
Manganese, dissolved (µg/L as Mn)	139	127	255	192	120	43	125	77

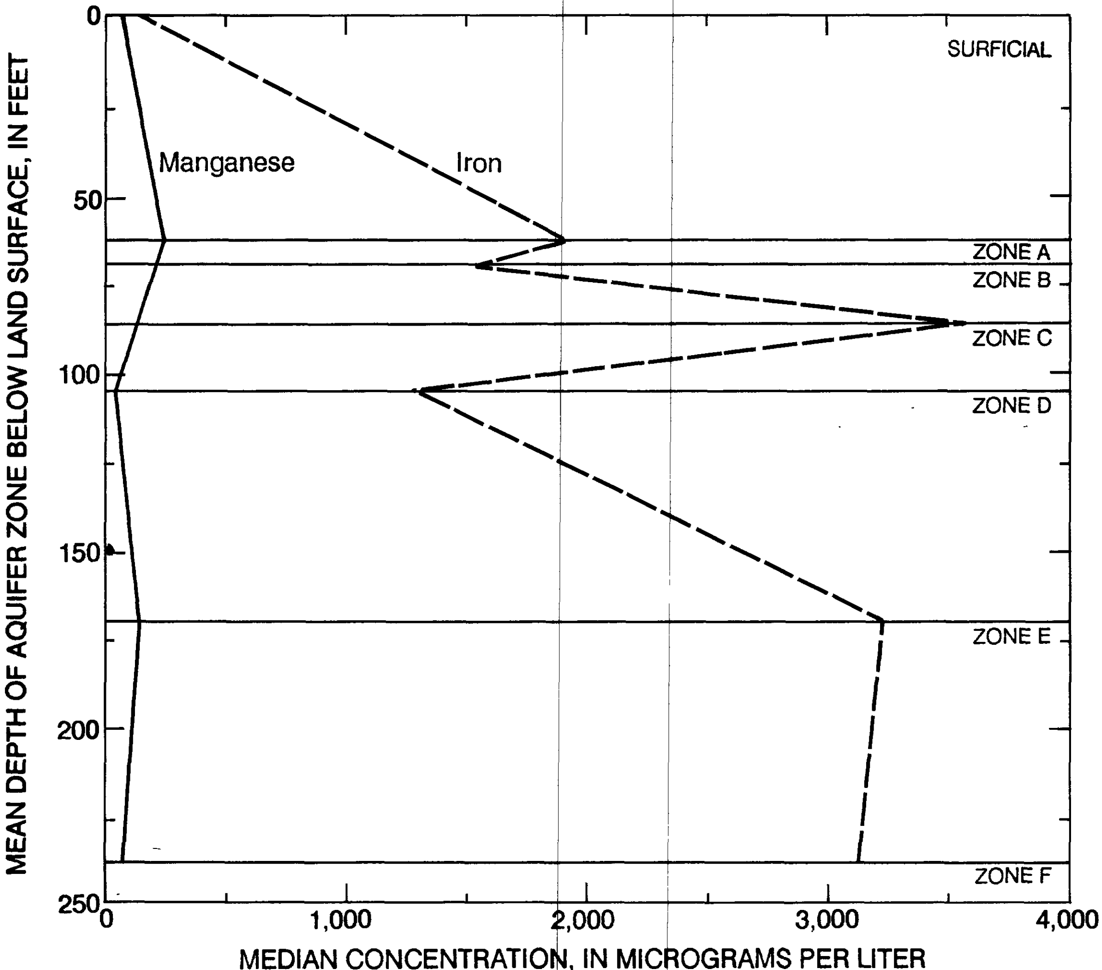


Figure 17.-- Comparison of median concentrations of manganese and iron with mean depth in the drift system

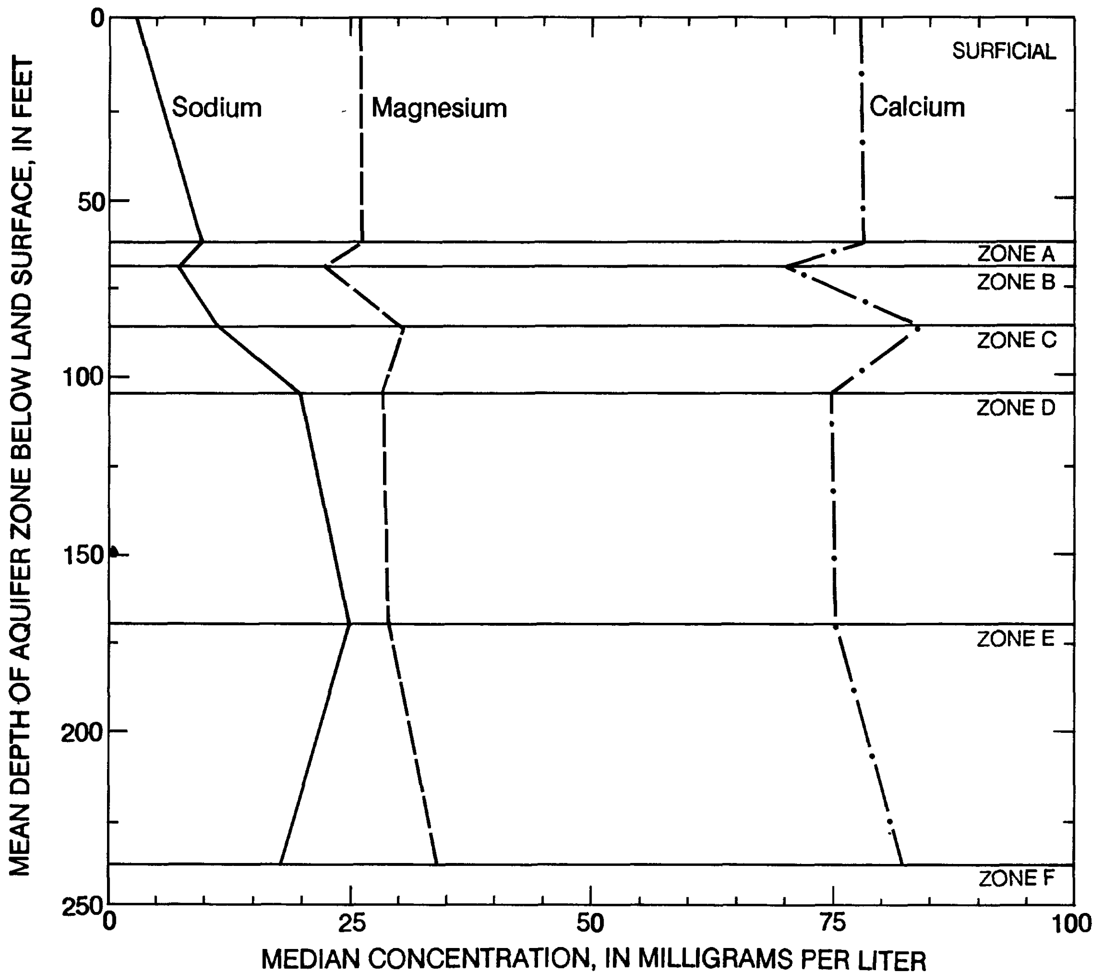


Figure 18.--Comparison of median concentrations of sodium, magnesium, and calcium with mean depth in the drift system

Increased concentrations of chemical constituents in water from confined aquifers also may result from migration of water from underlying deposits of Cretaceous age. Data from drift aquifers in Big Stone County, Minnesota, (Soukup, 1980) indicate that the pH, sodium-adsorption ratio, specific conductance, and concentrations of boron, iron, sodium, sulfate, chloride, fluoride, and dissolved solids generally increase with depth and are highest in water from the Cretaceous deposits. Because of the relative absence of Cretaceous deposits in the Brooten-Belgrade area, however, migration of water from these deposits is an unlikely cause of the higher constituent concentrations determined by the chemical analyses.

Although most constituent concentrations increase with depth (table 10), concentrations of nitrate (NO_2+NO_3 as N), sulfate, potassium, and chloride generally were 2 to 15 mg/L higher in water from the unconfined aquifer than from the confined aquifers (fig. 19). Mean concentrations of nitrate in the unconfined aquifer, for example, were 9.6 mg/L compared to 0.2 mg/L in confined aquifers. Results of a study in the area by Anderson (1987) and a study near Staples, Minnesota by Myette (1984) also indicate that concentrations of nitrate and chloride generally are greatest in samples from the shallowest part of the unconfined aquifer, near the water table.

The relatively high concentrations of nitrate in the unconfined aquifer probably result from infiltration of runoff from feedlots, seepage from domestic septic systems, or leaching of fertilizers. It should be noted that many of the samples collected from the unconfined aquifer were purposely located in areas where higher nitrate concentrations were expected. Background levels throughout most of the unconfined aquifer are between 1 and 3 mg/L (Anderson, 1987). The decrease in concentrations of nitrate with depth results in part from denitrification, a process in which nitrate is reduced to nitrogen gas, bicarbonate, hydrogen ions, and water.

Increased mean concentrations of chloride, sulfate, and potassium in the unconfined aquifer may result from use of fertilizers containing these chemical constituents. Increased concentrations of chloride and potassium also may result from the use of salt as a road deicer. Confined aquifers generally are less affected by these sources, primarily because the overlying till confining units prevent rapid leakage of water to the confined aquifers. The plot of sulfate concentrations with depth (fig. 19) is unique in that the concentrations decrease through the upper 100 ft of drift and then increase below this depth. Data indicate that the higher concentrations in the unconfined and shallower aquifer zones are the result of man's activities, listed above. The increase in concentration of sulfate below the 100-ft depth is probably caused by the increased residence time for this ground water; this increase with depth is similar to that measured for other constituents.

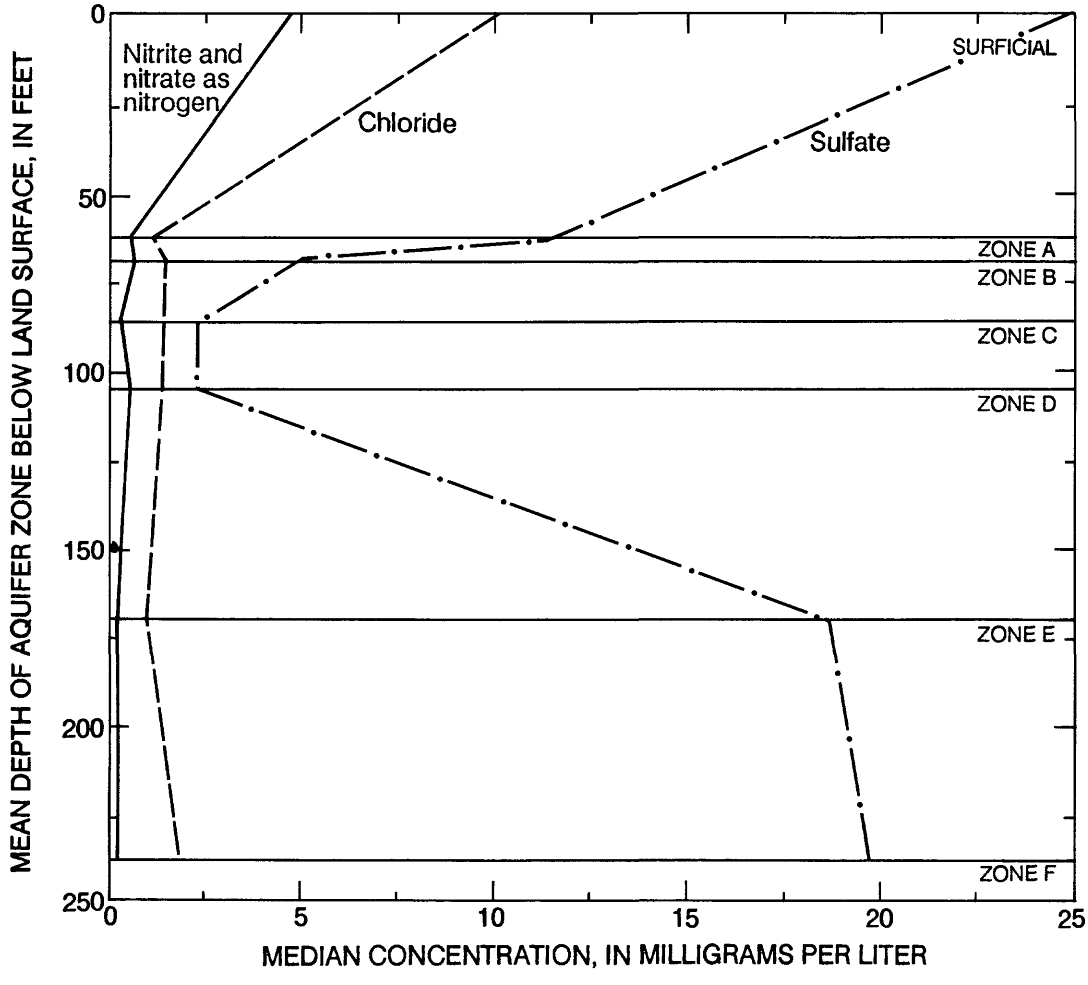


Figure 19.--Comparison of median concentrations of nitrate, chloride, and sulfate with mean depth in the drift system

Six of the wells sampled in 1985-86 had been sampled between 1965 and 1975 during previous U.S. Geological Survey ground-water investigations (Van Voast, 1971, and Wolf, 1976). Results from both sets of analyses were compared to determine if any water-quality degradation has occurred in the area during the past two decades. All samples were analyzed at U.S. Geological Survey laboratories. Analyses from wells completed in aquifer zones B, C, and D were compared (table 11). Results of this comparison indicate that chemical-constituent concentrations have remained fairly constant over the past two decades. Concentrations of several constituents increased slightly over the time period. Concentrations of sulfate, for example, increased between 2.3 and 5.0 mg/L over the past two decades in two of the resampled wells. Conversely, the concentrations of several constituents decreased over the time period. Concentrations of chloride, for example, decreased between 0.7 and 1.6 mg/L in four of the resampled wells. Some of the differences in chemical-constituent concentrations shown in table 11 may be the result of changes in laboratory procedures over the past 20 years.

One of the most significant advantages of developing water supplies from confined aquifers, rather than unconfined aquifers, is the lower susceptibility of confined aquifers to ground-water contamination. Till confining units greatly impede the migration of contaminants from or near land surface to confined aquifers. Conversely, unconfined aquifers are vulnerable to contamination from a variety of sources, including fertilizer applications and drainage from feedlots and septic systems. Although confined aquifers are less susceptible to contamination than unconfined aquifers, an increase in withdrawals from confined aquifers could degrade the quality of water in the aquifers by inducing migration of poorer quality water from overlying and underlying deposits.

Table 11.--*Chemical-quality changes in water from confined aquifers between 1965-75 and 1985-86*

[na, not analyzed; µS/cm, microsiemens per centimeter at 25 degrees celsius; mg/L, milligrams per liter; µg/L, micrograms per liter]

Chemical constituent or property — Well Location:	123.35.28ADB		126.37.24ABD		126.36.32CBC		124.37.6AAD		123.34.19BB		122.34.12ACB	
Aquifer Zone:	B		C		C		D		D		D	
Date Sampled:	8/67	5/86	6/71	5/86	5/75	5/86	8/65	5/86	1/72	5/86	5/75	6/85
Specific conductance (µS/cm)	670	840	774	790	630	660	582	640	543	539	700	710
pH (standard units)	na	7.0	7.3	7.5	7.6	7.5	8.4	7.5	7.4	7.6	7.4	7.3
Calcium, dissolved (mg/L as Ca)	249	100	91	88	86	83	44	58	66	68	87	86
Magnesium, dissolved (mg/L as Mg)	155	35	35	35	31	29	29	28	21	20	33	34
Sodium, dissolved (mg/L as Na)	na	5.9	26	22	8.5	8.8	31	35	17	17	19	20
Potassium, dissolved (mg/L as K)	na	3.1	2.7	2.5	2.4	2.2	1.8	1.8	2.2	2.1	3.0	2.4
Alkalinity (lab) (mg/L as $CaCO_3$)	448	428	426	431	357	352	na	348	303	296	na	387
Sulfate, dissolved (mg/L as SO_4)	2.0	9.1	30.0	5.7	2.3	2.3	1.2	3.5	2.9	.8	12	17
Chloride, dissolved (mg/L as Cl)	1.5	1.9	1.6	0.9	1.5	.7	2.0	1.1	1.1	1.1	1.8	.2
Fluoride, dissolved (mg/L as F)	na	.1	.3	.3	.3	.3	.4	.4	.4	.3	.3	.3
Silica, dissolved (mg/L as SiO_2)	na	32	24	24	23	24	na	24	28	26	na	25
Solids, sum of constituents, dissolved (mg/L)	na	450	382	450	363	370	317	360	324	319	na	na
Nitrogen, NO_2+NO_3, dissolved (mg/L as N)	1.0	.1	na	.1	2.3	.1	1.5	.1	na	.1	na	.1
Phosphorus, ortho, dissolved (mg/L as P)	na	.02	.4	.02	.08	.08	na	.1	.09	.03	.03	.03
Boron, dissolved (µg/L as B)	na	40	120	130	50	60	150	160	110	120	100	110
Iron, dissolved (µg/L as Fe)	3500	6000	9000	5000	1200	1600	1300	680	1600	2000	1300	1200
Manganese, dissolved (µg/L as Mn)	250	350	130	80	210	200	100	75	30	29	10	89

SUMMARY AND CONCLUSIONS

Ground-water withdrawals from confined aquifers in western Minnesota has increased during the last decade. These aquifers are the main source of ground-water supplies where the unconfined aquifer is absent. A study of confined aquifers in the Brooten-Belgrade area was done to determine their areal distribution, thickness, hydraulic properties, well-yield capabilities, and water quality.

Areally extensive confined aquifers were identified in six aquifer zones with thicknesses ranging from less than 5 to 110 ft. Depth below land surface to the top of the confined aquifers ranges from about 5 to 300 ft. Typical aquifer transmissivities range from about 500 to 10,000 ft^2/d. Theoretical maximum well yields range from about 100 to 900 gal/min. Results of an aquifer test northwest of Belgrade indicate that drawdown is to be expected in overlying and underlying drift aquifers when a confined aquifer is pumped. Thus, well interference is expected even in areas where the aquifers are separated by confining beds. About 2 ft of drawdown was observed in aquifer zone D at a distance of 3,600 ft from the pumping well after 48 hours of pumping at 800 gal/min from aquifer zone C.

Ground water in confined aquifers generally flows from northwest to southeast through the Brooten-Belgrade area and discharges to streams, lakes, wetlands, and pumped wells. Head in each confined aquifer generally is higher than in the underlying aquifer(s), indicating downward flow. However, the head increases with depth near rivers and the ground-water flow is upward. Areal recharge from precipitation averages 10.7 in/yr where the unconfined aquifer is present, but generally is less than 1.6 in/yr where till is present at land surface.

Confined aquifers in zones C and D have been most intensely developed for water supplies. Pumpage from wells completed in the confined aquifers generally decreased during 1981, compared to 1980, and remained fairly constant from 1981 to 1983 before increasing again in 1984. Pumpage from unconfined aquifers exceeded total pumpage from all confined aquifers for each of these years.

Water levels in wells completed in confined aquifers generally fluctuate 5 to 40 ft annually near high-capacity pumping wells during an average climatic year, compared to annual fluctuations of 1 to 3 ft in unconfined-aquifer wells. During periods of below-normal precipitation, however, water-level declines of greater than 40 ft were measured in some confined-aquifer wells in the vicinity of Brooten and Belgrade. Water levels in confined aquifers recover to prepumping levels following each irrigation season. Thus, although water levels in confined aquifers decline significantly during years of intense pumping for irrigation, such as in 1987, the water levels return to prepumping levels.

Well interference occurs when wells completed in confined aquifers are relatively close together. Well interference reduces the amount of available drawdown, resulting in increased pumping costs and decreased maximum well yield. Domestic wells may be dewatered because of interference from a nearby high-capacity well. This problem usually can be corrected by screening the domestic well near the bottom of the confined aquifer rather than near the top.

Based on results from a ground-water-flow model constructed for this study, confined aquifers in the area are capable of supporting additional ground-water withdrawals. According to the model's computations, regional water-level declines of less than 1 ft generally would result from the addition of 20 hypothetical wells pumping a total of 246 Mgal/yr. Based on model results, an extended drought could lower water levels 2 to 10 ft regionally in each aquifer zone and as much as 20 ft locally in the unconfined aquifer. Ground-water discharge to the East Branch Chippewa and North Fork Crow Rivers in the modeled area during the simulated drought would be reduced by 38 percent of 1984 conditions.

Based on the results of hypothetical simulations, expanded development of water supplies from aquifer zone D probably would cause the least water-level drawdown in the aquifer system. Southeast of Belgrade, zone D is the uppermost confined-aquifer zone, which would facilitate the drilling of relatively inexpensive wells compared to completing wells in the deeper aquifers. According to the model's computations, aquifer zones E and F receive considerably less leakage, or recharge, than the other zones and are more susceptible to long-term water-level declines than aquifers in the other zones.

According to the model's computations, expanded development of water supplies from aquifer zone E would produce the greatest drawdown compared to the other zones, primarily because of a reduction in leakage to the zone. In most locations, however, overlying aquifers are present for development of water supplies.

Water from confined aquifers is hard but generally is suitable for domestic consumption and irrigation of crops. However, locally large concentrations of some chemical constituents may require treatment of the water. Concentrations of dissolved-iron range from about 300 to 9,000 $\mu g/L$. Concentrations of several chemical constituents are slightly higher in water from the confined aquifers than in water from unconfined aquifers. These higher concentrations probably result from longer residence time of water in the confined aquifer's. Concentrations of nitrate are notably greater in the unconfined aquifer than in the confined aquifers. Based on these data, confined aquifers are less susceptible to contamination than the unconfined aquifers.

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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, consisting mainly of ground-water discharge.

Beach-ridge deposit--sand and gravel deposited by wave action on the shores of former large glacial lakes.

Cone of Depression--a depression in the potentiometric surface of an aquifer. Has the shape of a cone around a well from which water is being withdrawn.

Confined aquifer--an aquifer bounded above and below by confining beds. An aquifer containing confined ground water. Synonymous with buried aquifer.

Confined ground water--ground water under pressure significantly greater than atmospheric and whose upper surface is the bottom of a confining bed.

Confining bed--a body of material with low vertical permeability stratigraphically adjacent to one or more aquifers. Replaces the terms "aquiclude," "aquitard," and "aquifuge."

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

Drift--a general term applied to all material (clay, sand, gravel, and boulders) transported and deposited by glacial ice or melt water issuing therefrom.

Equipotential line--line connecting points of equal static head. (Head is a measure of the potential.)

Esker--a long, narrow ice-contact ridge composed of stratified drift. The drift was deposited in glacial streams flowing over glacial ice masses.

Evapotranspiration--water discharged to the atmosphere by evaporation from water surfaces and moist soil and by transpiration by plants.

Flow line--the idealized path followed by particles of water.

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

Head, static--the height above a standard datum of the surface of a column of water that can be supported by the static pressure at a given point.

Hydraulic conductivity--capacity of porous material to transmit water under pressure. It is the rate of flow of water passing through a unit section of area under a unit hydraulic gradient.

<u>Hydraulic gradient</u>--the rate of change of pressure head per unit distance of flow at a given point and in a given direction. Synonymous with potentiometric gradient.

<u>Kame</u>--mound-like hill of ice-contact stratified drift, of any size.

<u>Outwash</u>--washed, sorted, and stratified drift deposited beyond the melting glacial ice front by melt-water streams.

<u>Permeability</u>--a measure of the relative ease with which a porous medium can transmit a fluid under a potential gradient.

<u>Potentiometric surface</u>--surface that represents the static head of water in an aquifer; it is defined by the levels to which water will rise in tightly cased wells from a given point in an aquifer.

<u>Saturated zone</u>--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.

<u>Specific yield</u>--the ratio of the volume of water that a saturated aquifer will yield by gravity drainage to the volume of the aquifer material.

<u>Steady-state flow</u>--flow at any point in a flow field when the magnitude of the flow velocity and the hydraulic head are constant with time.

<u>Storage coefficient</u>--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.

<u>Surficial aquifer</u>--the saturated zone between the water table and the first lower confining bed; synonymous with unconfined aquifer.

<u>Till</u>--unsorted, unstratified drift deposited directly by glacial ice.

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

<u>Unconfined aquifer</u>--an aquifer that has a water table; the saturated zone between the water table and the first lower confining bed; synonymous with surficial aquifer.

<u>Water table</u>--that surface in a ground-water body at which the water pressure is atmospheric. Generally, this is the upper surface of the zone of saturation.

APPENDIX I - GEOLOGIC LOGS OF TEST HOLES

Test hole number: BB01 Location: 123.36.15DDDDD County: Pope

Township: Lake Johanna Land Surface Altitude: 1,300 feet

Geologic log	Depth (feet)	Thickness (feet)
Topsoil	0-2	2
Gravel, fine to coarse, and fine to coarse sand, light brown	2-54	52
Till, sandy, gray; some cobbles	54-86	32
Boulder, granite	86-87	1
Till, sandy, gray	87-99	12
Sand, medium, brown	99-100	1
Till, silty, light gray	100-110	10
Sand, fine to coarse, light brown	110-140	30
Gravel, fine to medium, brown	140-154	14
Till, sandy, gray	154-156	2
Sand, medium to coarse, gray, silty	156-169	13
Clay, silty, gray; some sand lenses	169-215	46
Sand, fine, light brown, silty	215-249	34
Sand, medium to coarse, light brown	249-280	31
Sand, coarse to very coarse, brown	280-285	5
Gravel, fine to medium, brown; some cobbles	285-289	4
Till, sandy, gray; some gravel, hard	289-315	26
Crystalline rock, black; very hard	315-317	2

Observation Well Information

Two-inch diameter black steel: 0-284 feet
Stainless steel 30-slot screen: 284-287 feet

Height of casing above land surface: 1.3 feet

Static Water Level: 9.28 feet below top of casing (8/23/85)

Test hole number: BB02 Location: 123.35.33CCCCD County: Stearns

Township: Crow Lake Land surface altitude: 1,275 feet

Geologic log	Depth (feet)	Thickness (feet)
Topsoil	0-1	1
Sand, medium to coarse, and fine to coarse gravel, multicolored to gray	1-58	57
Till, sandy, gray	58-81	23
Sand, medium to coarse, and fine to coarse gravel, gray	81-92	11
Till, sandy, gray; some gravel	92-156	64
Gravel, fine to medium, brown	156-158	2
Till, sandy, gray; some gravel	158-162	4
Sand, fine to coarse, and fine to medium gravel, gray	162-173	11
Boulder, white	173-174.5	1.5
Till, sandy, gray; more silt and clay with depth	174.5-272	97.5
Sand, fine to coarse, light gray	272-278	6
Till, sandy, gray; tight	278-300	22
Sand, brown	300-300.5	0.5
Till, sandy, gray; some sand lenses	300.5-320	19.5
Clay, brownish-gray, soft; harder from 357-360 feet	320-384	64
Sand, brown	384-385	1

Observation Well Information

Two-inch diameter black steel: 0-167 feet
Stainless steel 30-slot screen: 167-170 feet

Height of casing above land surface: 2.1 feet

Static Water Level: 8.00 feet below top of casing (8/23/85)

Test hole number: BB03 Location: 122.35.23BBBCC County: Kandiyoi

Township: Colfax Land surface altitude: 1,250 feet

Geologic log	Depth (feet)	Thickness (feet)
Topsoil	0-1	1
Sand, medium to coarse, and fine to coarse gravel, brown to multicolored	1-31	30
Till, sandy, clayey, gray; soft, harder with depth	31-77	46
Till, sandy, yellowish-brown; hard	77-85	8
Till, sandy, brownish-gray; hard	85-100	15
Clay, gray, sticky	100-120	20
Sand, brown	120-122.5	2.5
Till, sandy, gray	122.5-126	3.5
Boulder, white	126-127	1
Till, sandy, gray	127-145	18
Sand and gravel, brown	145-147.5	2.5
Till, sandy, gray; some interbedded sand lenses	147.5-158	10.5
Sand, fine to coarse, and fine gravel, brown	158-161	3
Till, sandy, clayey, gray; soft	161-216	55
Sand, brown	216-218	2
Till, sandy, gray	218-233	15
Sand, medium to coarse, and fine gravel, brown	233-244	11
Till, sandy, gray	244-254.5	10.5
Sand, medium to coarse, brown	254.5-256	1.5
Till, sandy, gray; some sand lenses	256-326	70
Sand, medium to coarse, gray; some fine gravel	326-331	5
Till, sandy, gray	331-355	24
Sand, fine to medium, gray; coarser with depth	355-367	12
Sand, medium to coarse, and, fine to medium gravel, gray	367-434	67
Sand, silty, gray	434-440	6
Sand, medium to coarse, gray	440-478	38
Clay, gray, sticky	478-480	2
Sand, fine to very coarse, gray	480-504.5	24.5
Highly weathered granite, white with green specks; soft	504.5-505	0.5

<u>Observation Well Information</u>

Two-inch diameter black steel: 0-235 feet
Stainless steel 30-slot screen: 235-238 feet

Height of casing above land surface: 2.0 feet

Static Water Level: 10.22 feet below top of casing (8/28/85)

Test hole number: BB04 Location: 122.34.31CBCBBC County: Kandiyohi

Township: Burbank Land surface altitude: 1,270 feet

Geologic log	Depth (feet)	Thickness (feet)
Sand, fine to very coarse, and fine to medium gravel, brown	0-35	35
Gravel, medium to coarse, brown; some coarse sand and cobbles	35-76	41
Till, sandy, clayey, gray; hard, some silt	76-125	49
Till, sandy, clayey, light gray	125-130	5
Till, sandy, dark gray	130-139	9
Sand, brown	139-140	1
Till, sandy, dark gray; some sand and gravel lenses	140-180.5	39.5
Sand, fine to coarse, gray	180.5-215	34.5
Sand, fine, brown; silty	215-225	10
Till, sandy, clayey, gray	225-265	40
Till, clayey, brown; some sand lenses	265-296	31
Till, clayey, sandy, dark gray; sticky	296-360	64
Sand, medium to coarse, and fine gravel, brown	360-368	8
Till, clayey, sandy, dark gray	368-378	10
Sand, fine to medium, brown	378-505	127

Observation Well Information

Two-inch diameter black steel: 0-189 feet
Stainless steel 30-slot screen: 189-192 feet

Height of casing above land surface: 2.0 feet

Static Water Level: 49.88 feet below top of casing (9/03/85)

Test hole number: BB05 Location: 122.34.28ADDBB County: Kandiyohi

Township: Burbank Land surface altitude: 1,208 feet

Geologic log	Depth (feet)	Thickness (feet)
Sand, medium to very coarse, and fine to coarse gravel, brown; some cobbles	0-45	45
Sand, fine to medium, gray	45-52	7
Till, sandy, clayey, gray	52-57	5
Sand, medium to very coarse, brown; some fine gravel	57-72	15
Till, sandy, clayey, gray	72-85	13
Till, gray, with sand lenses	85-90	5
Till, sandy, clayey, gray	90-97	7
Clay, silty, light brown	97-113	16
Sand, fine, brown	113-118	5
Till, sandy, clayey, gray	118-125	7
Sand, brown	125-129	4
Till, sandy, gray	129-132	3
Sand, fine to coarse, multicolored	132-137	5
Till, sandy, clayey, gray	137-142	5
Sand, coarse to very coarse, brown	142-157	15
Till and interbedded sand	157-160	3
Sand, coarse to very coarse, and fine to medium gravel, brown	160-172	12
Till, sandy, gray	172-174	2
Sand, coarse to very coarse, brown	174-175.5	1.5
Till, clayey, sandy, gray; sticky	175.5-195	19.5
Till, silty, clayey, light brown	195-237	42
Sand, fine to coarse, brown; coarser with depth	237-260	23
Sand, coarse to very coarse, brown	260-269	9
Till, sandy, clayey, light brown; interbedded with brown coarse to very coarse sand	269-273	4
Sand, medium to very coarse, brown	273-281	8
Till, gray	281-282	1
Gneiss or schist, mafic, soft to hard	282-285	3
Gneiss or schist, felsic, very hard	285-288	3

Observation Well Information

Two-inch diameter black steel: 0-241 feet
Stainless steel 30-slot screen: 241-244 feet

Height of casing above land surface: 2.0 feet
Static Water Level: 2.70 feet below top of casing (9/06/85)

Test hole number: BB06 Location: 122.33.05DDADAA County: Kandiyohi

Township: Roseville Land surface altitude: 1,208 feet

Geologic log	Depth (feet)	Thickness (feet)
Topsoil	0-1	1
Sand, medium to very coarse, and fine to coarse gravel, brown; some interbedded till lenses	1-15	14
Till, clayey, sandy, dark gray; sticky	15-37	22
Sand, brown	37-38	1
Till, sandy, clayey, gray	38-92	54
Till, sandy, clayey, light gray	92-148.5	56.5
Sand, brown	148.5-150	1.5
Till, sandy, clayey, gray	150-165	15
Till, clayey, sandy, reddish-brown	165-192	27
Till, clayey, sandy, light gray; hard	192-197	5
Weathered granite, greenish gray; hard, some mica	197-207	10

Test hole number: BB07 Location: 123.36.20BDBAB County: Pope

Township: Lake Johanna Land surface altitude: 1,350 feet

Geologic log	Depth (feet)	Thickness (feet)
Topsoil	0-1	1
Sand, fine to very coarse; some gravel, brown	1-14	13
Sand, medium to very coarse, and fine to medium gravel, brown	14-16	2
Boulder	16-17	1
Till, sandy, clayey, light brown	17-18	1
Sand, medium to very coarse, and fine to coarse gravel, brown	18-20	2
Gravel, fine to very coarse, brown; some cobbles	20-52	32
Sand, medium to very coarse, and fine gravel, brown	52-90	38
Till, clayey, sandy, dark gray	90-117	27
Sand, medium to very coarse, and fine to medium gravel, brown	117-133	16
Till, sandy, clayey, gray	133-139	6
Sand, brown	139-142	3
Till, sandy, gray; interbedded sand lenses	142-148	6
Boulder	148-149.5	1.5
Till, sandy, gray	149.5-160	10.5
Sand, brown	160-163	3
Till, gravely, gray; hard	163-169	6
Till, sandy, clayey, gray; interbedded sand lenses	169-186	17
Sand, medium to very coarse, and fine gravel, brown	186-200.5	14.5
Till, gravely, gray; hard	200.5-205	4.5
Gravel, fine to medium, and medium to very coarse sand, brown	205-211	6
Till, sandy, clayey, gray	211-245	34
Boulder	245-246	1
Till, clayey, sandy, gray; some cobbles	246-328	82
Till, sandy, clayey, gray; hard	328-335	7
Sand, fine to coarse, brown; coarser with depth	335-351	16
Till, silty, clayey, gray; sparsely interbedded sand lenses	351-370	19
Till, sandy, gray; some interbedded sand lenses	370-385	15

Observation Well Information

Two-inch diameter black steel: 0-338 feet
Stainless steel 30-slot screen: 338-341 feet
Height of casing above land surface: 1.9 feet
Static Water Level: 77.08 feet below top of casing (9/06/85)

Test hole number: BB08 Location: 123.35.30DBAAAA County: Stearns

Township: Crow Lake Land surface altitude: 1,310 feet

Geologic log	Depth (feet)	Thickness (feet)
Topsoil, black	0-2	2
Sand, fine, and silt, brown	2-6	4
Sand, medium to very coarse, and fine to very coarse gravel, with some cobbles, brown	6-46	40
Sand, medium to very coarse with sparse gravel, brown	46-67	21
Till, sandy, clayey, gray, soft	67-87	20
Sand, medium to very coarse, brown	87-89	2
Till, sandy, clayey, gray	89-106	17
Sand, medium to coarse, brown	106-107	1
Till, sandy, brown	107-114	7
Sand, medium to very coarse, and fine to medium gravel, brown	114-116	2
Till, sandy, light gray	116-120	4
Till, sandy, gray, with lenses of sand	120-124	4
Sand, coarse to very coarse, and fine to medium gravel, brown	124-131	7
Till, sandy, gray, hard, with lenses of sand 174-177 ft.	131-178.5	47.5
Sand, medium to very coarse, and fine to medium gravel, brown	178.5-182	3.5
Till, sandy, gray	182-220	38
Till, sandy, brown	220-223	3
Sand, medium to coarse, brown	223-226	3
Till, sandy, brown	226-228	2
Sand, medium to very coarse with interbedded till lenses	228-239	11
Till, sandy, brown to light-brown, hard	239-254	15
Till, sandy, gray, hard, with lenses of sand 262-267 ft.	254-267	13
Till, sandy, clayey, olive, hard	267-276	9
Sand, medium to coarse, brown	276-282	6
Till, sandy, clayey, brown to olive	282-288	6
Till, clayey, sandy, dark gray	288-299	11
Sand, medium to coarse, and fine gravel, brown	299-304	5
Till, clayey, dark gray	304-308	4
Till, clayey, grayish-brown	308-311	3
Till, sandy, clayey, dark gray, with lenses of sand 315-326 ft.	311-353	42
Clay, sandy, grayish-brown, very soft, sticky	353-432	79
Sand, medium to coarse, brown	432-438	6
Clay, sandy, gray, soft	438-440	2
Boulder, granite, black and pink	440-441	1
Weathered granite, light gray to gray, very hard, harder with depth	441-480	39

Test Hole BB08 -- Continued

Observation Well Information

Two-inch diameter black steel: 0-235 feet
Galvanized steel 10-slot screen: 235-237 feet

Height of casing above land surface: 2.8 feet

Static water level: 28.91 feet below top of casing (7/23/86)

Test hole number: BB09 Location: 126.36.20ACDBA County: Pope

Township: Westport Land surface altitude: 1,355 feet

Geologic log	Depth (feet)	Thickness (feet)
Topsoil, black	0-1	1
Till, sandy, brown	1-3	2
Gravel, fine to coarse, and some medium to very coarse sand, brown	3-27	24
Till, sandy, clayey, light brown	27-29	2
Sand, coarse to very coarse, and fine to coarse gravel, brown	29-33	4
Till, gray, sandy, silty	33-36	3
Gravel	36-37	1
Till, sandy, clayey, silty, gray	37-58	21
Sand, medium, brown	58-59	1
Till, sandy, clayey, silty, gray	59-61	2
Sand, medium to coarse, and fine to coarse gravel, brown	61-64	3
Till, sandy, silty, greenish-gray	64-71	7
Till, sandy, silty clayey, brownish-gray	71-77	6
Sand, medium to coarse, and fine to medium gravel, light-brown, with till lenses at 85 and 110 feet	77-120	43

Observation Well Information

Two-inch diameter black steel: 0-102 feet
Galvanized steel 30-slot screen: 102-105 feet

Height of casing above land surface: 2.4 feet

Static water level: 17.53 feet below top of casing (7/22/86)

Test hole number: BB10 Location: 126.37.34DDDDD County: Pope

Township: Leven Land surface altitude: 1,375 feet

Geologic log	Depth (feet)	Thickness (feet)
Gravel, fine to very coarse, and medium to very coarse sand, brown	0-45	45
Sand, medium to very coarse, some gravel, brown	45-56	11
Till, sandy, clayey, gray	56-61	5
Sand, medium to very coarse, brown	61-69	8
Sand, medium to very coarse with interbedded till, brown	69-84	15
Till, sandy, brown	84-86	2
Sand, medium to very coarse, brown	86-88	2
Till, sandy, silty, brown	88-98	10
Till, sandy, clayey, gray, tight	98-104	6
Sand, medium to very coarse, brown	104-120	16

Observation Well Information

Two-inch diameter black steel: 0-109 feet
Galvanized steel 30-slot screen: 109-112 feet

Height of casing above land surface: 2.4 feet

Static water level: 31.45 feet below top of casing (7/23/86)

Test hole number: BB11 Location: 124.36.36CBBBD County: Pope

Township: Bangor Land surface altitude: 1,312 feet

Geologic log	Depth (feet)	Thickness (feet)
Topsoil, black	0-1	1
Till, brown	1-3	2
Gravel, fine to medium, and medium to coarse sand, brown	3-27	24
Till, sandy, clayey, gray	27-43	16
Sand, medium to very coarse, brown	43-44	1
Till, sandy, silty, grayish-brown	44-45	1
Sand, medium to very coarse, brown	45-85	40
Till, sandy, silty, brownish-gray	85-89	4
Sand, medium to very coarse, brown	89-91	2
Till, sandy, gray, soft, with lenses of sand	91-95	4
Till, sandy, clayey, brownish-gray, harder	95-105	10
Till, sandy, clayey, gray, soft	105-117	12
Sand, medium to very coarse, and fine to medium gravel, brown	117-124	7
Till, sandy, clayey, gray	124-136	12
Sand, medium to very coarse, and fine to medium gravel, light brown	136-162	26
Till, sandy, clayey, gray	162-165	3

Observation Well Information

Two-inch diameter black steel: 0-148 feet
Galvanized steel 30-slot screen: 148-151 feet

Height of casing above land surface: 2.7 feet

Static water level: 16.65 feet below top of casing (7/22/86)

Test hole number: BB12 Location: 123.36.04ADDDCB County: Pope

Township: Lake Johanna Land surface altitude: 1,328 feet

Geologic log	Depth (feet)	Thickness (feet)
Topsoil, black	0-1	1
Sand, medium to very coarse, and fine to coarse gravel, brown	1-27	26
Till, sandy, clayey, light brown	27-30	3
Sand, fine to medium, brown	30-58	28
Sand, medium to coarse, and fine to medium gravel, brown	58-65	7
Till, sandy, clayey, gray, hard	65-105	40
Till and interbedded sand	105-117	12
Gravel, fine to coarse, and medium to very coarse sand, brown, till lense at 139 feet	117-141	24
Till, sandy, clayey, gray	141-145	4
Sand, medium to very coarse, brown	145-146	1
Till, sandy, clayey, gray	146-188	42
Sand, fine to medium, brown	188-190	2
Till, sandy, clay, gray	190-225	35
Till grading to soft clay	225-235	10
Clay, light green, soft, sand lense at 239 feet	235-248	13
Sand, medium to very coarse, brown	248-250	2
Till, clayey, sandy, brown, green, and gray, hard	250-255	5
Till, sandy, clayey, brown, hard	255-288	33
Sand, medium to coarse, brown	288-290	2
Sand and interbedded till	290-295	5
Sand, medium to coarse, brown	295-303	8
Till, clayey, sandy, light to hard brown	303-312	9
Till, clayey, sandy, hard, gray	312-326	14
Boulder, black	326-327	1
Sand, medium to very coarse, brown	327-330	3
Till, clayey, sandy, dark gray, sticky	330-368	38
Sand, coarse to very coarse, and fine to medium gravel, brown	368-375	7
Clay, sandy, light gray, soft with sand lenses 442-458 feet	375-463	88
Sand, medium to very coarse with some gravel, brown	463-469	6
Clay, sandy, grayish-brown	469-478	9
Boulder	478-479	1
Clay, sandy, grayish-brown, soft	479-516	37
Granite, greenish-black, very hard	516-517.5	1.5

Test Hole BB12 -- Continued

Observation Well Information

Two-inch diameter black steel: 0-123 feet
Galvanized steel 30-slot screen: 123-126 feet

Height of casing above land surface: 1.8 feet

Static water level: 27.40 feet below top of casing (7/22/86)

Test hole number: BB13 Location: 124.35.33AAACAC County: Stearns

Township: North Fork Land surface altitude: 1,292 feet

Geologic log	Depth (feet)	Thickness (feet)
Topsoil, black	0-1	1
Sand, medium to very coarse, and fine to coarse gravel, brown	1-19	18
Till, sandy, clayey, gray, soft	19-33	14
Till, sandy, gray, hard	33-37	4
Boulder, white	37-38	1
Till, sandy, gray, hard	38-67	29
Till, sandy, silty, brown	67-84	17
Gravel, fine to medium, brown	84-85	1
Till, sandy, silty, clayey, gray, sand lense at 86 feet	85-90	5
Till, sandy, brown	90-93	3
Till, sandy, clayey, gray, hard	93-109	16
Sand, medium to very coarse, and fine to medium gravel, brown	109-111	2
Till, sandy, clayey, gray	111-115	4
Sand, coarse, and fine to very coarse gravel, light brown	115-135	20

Observation Well Information

Two-inch diameter black steel: 0-123 feet
Galvanized steel 10-slot screen: 123-125 feet

Height of casing above land surface: 2.9 feet

Static water level: 14.89 feet below top of casing (7/23/86)

Test hole number: BB14 Location: 122.33.28BAABBA County: Kandiyohi

Township: Roseville Land surface altitude: 1,242 feet

Geologic log	Depth (feet)	Thickness (feet)
Topsoil, black	0-2	2
Sand, medium to very coarse, and fine to medium gravel, brown; some clay lenses	2-34	32
Gravel, fine to coarse, some sand, brown	34-45	11
Till, sandy, gray, hard	45-113	68
Sand, medium to very coarse, some gravel, brown	113-114	1
Till, sandy, clayey, gray	114-118	4
Sand, medium to very coarse, and fine to medium gravel, brown	118-120	2
Till, clayey, sandy, gray, soft	120-127	7
Till, sandy, gray, hard	127-134	7
Sand, medium to coarse, brown	134-138	4
Till, sandy, gray	138-140	2
Till, sandy, silty, light, gray	140-153	13
Boulder	153-154	1
Till, sandy, gray	154-177	33
Till, sandy, clayey, brown	177-193	16
Till, sandy, clayey, greenish-gray	193-196	3
Sand, medium to coarse, brown	196-197	1
Till, sandy, gray	197-200	3
Sand, medium to very coarse, brown	200-202	2
Till, sandy, gray	202-213	11
Gravel, medium to coarse, brown	213-214	1
Till, sandy, gray	214-222	8
Till and sand interbedded	222-225	3
Sand, coarse to very coarse, and gravel, brown	225-228	3
Till, clayey, grayish-brown	228-240	12

Test hole number: BB15 Location: 123.34.22DADAAA County: Stearns

Township: Crow River Land surface altitude: 1,240 feet

Geologic log	Depth (feet)	Thickness (feet)
Topsoil, black	0-1	1
Sand, coarse to very coarse, and fine to coarse gravel, brown	1-23	22
Till, sandy, gray	23-25	2
Sand, medium to very coarse, and gravel, brown	25-28	3
Till, sandy, gray, some interbedded sand	28-31	3
Till, sandy, gray, sparse sand and gravel lenses, hard	31-116	85
Sand, medium to very coarse, and fine gravel, brown	116-129	13
Till, sandy, gray	129-135	6

Observation Well Information

Two-inch diameter black steel: 0-123 feet
Galvanized steel 10-slot screen: 123-125 feet

Height of casing above land surface: 3.4 feet

Static water level: 2.64 feet below top of casing (7/23/86)

Test hole number: BB16 Location: 123.35.07CABBAB County: Stearns

Township: Crow Lake Land surface altitude: 1,325 feet

Geologic log	Depth (feet)	Thickness (feet)
Topsoil, black	0-1	1
Sand, medium to very coarse, and fine to coarse gravel, brown	1-63	62
Till, sandy, gray	63-87	24
Sand, medium to very coarse, and gravel, brown	87-90	3
Sand and interbedded till	90-92	2
Till, sandy, gray	92-121	29
Sand, medium to very coarse, and fine to medium gravel, brown	121-134	13
Clay, sandy, brown	134-136	2
Till, sandy, gray	136-147	11
Sand, coarse to very coarse, and fine to medium gravel, brown	147-170	23
Gravel, fine to medium, and coarse to very coarse sand, brown, with some clay lenses	170-185	15
Till, sandy, gray	185-187	2
Sand, medium to very coarse, brown	187-190	3
Clay, sandy, gray, sticky	190-195	5
Till, sandy, gray, clayey, hard	195-220	25
Sand, medium to very coarse, brown	220-223	3
Till, sandy, gray	223-228	5
Sand, medium to very coarse, brown	228-229	1
Till, clayey, brown to grayish-brown, soft	229-243	14
Till, clayey, gray, soft	243-260	17
Till, clayey, dark gray, soft	260-267	7
Sand, coarse to very coarse, and fine to medium gravel, brown, silty	267-276	9
Till, clayey, dark brown	276-281	5
Sand, coarse to very coarse, brown	281-285	4
Till, clayey, dark grayish-brown	285-291	6
Sand, medium to very coarse, and gravel, brown	291-300	9
Till, clayey, dark brownish-gray, soft	300-308	8
Boulder, granite, black, pink	308-309	1
Till, clayey, dark brownish-gray, some sand lenses	309-342	33
Sand, medium to very coarse, light brown	342-348	6
Till, sandy, clayey, gray	348-357	9
Sand, medium to coarse, brown	357-358	1
Till, sandy, clayey, gray	358-361	3
Sand	361-362	1
Clay, green, soft, may be of Cretaceous age	362-370	8
Granite, black, pink, and red, very hard	370-371	1

Test Hole BB16 -- Continued

Observation Well Information

Two-inch diameter black steel: 0-151 feet
Galvanized steel 10-slot screen: 151-153 feet

Height of casing above land surface: 2.0 feet

Static water level: 32.49 feet below top of casing (7/22/86)

Test hole number: BB17 Location: 123.35.02AADDCA County: Stearns

Township: Crow Lake Land surface altitude: 1,279 feet

Geologic log	Depth (feet)	Thickness (feet)
Topsoil, black	0-1	1
Sand, medium to very coarse, and fine to medium gravel, brown; some cobbles, coarser toward bottom	1-17	16
Till, sandy, gray, soft	17-31	14
Till, sandy, gray, hard	31-62	31
Till, sandy, clayey, gray, soft	62-74	12
Till, sandy, gray	74-88	14
Clay, grayish-black	88-94	6
Sand, coarse to very coarse, and fine to medium gravel, light brown	94-107	13
Sand, coarse to very coarse with lenses of till	107-110	3
Sand, coarse to very coarse, and fine to medium gravel, light brown	110-118	8
Till, sandy gray, with some brown clay lenses	118-125	7
Clay, gray, hard	125-129	4
Till, sandy, clayey, light gray, hard	129-143	14
Sand, coarse to very coarse, and fine to medium gravel, dark brown	143-150	7
Till, sandy, clayey, light gray, hard	150-157	7
Sand, medium to very coarse, and fine to medium gravel, brown, with clay lenses below 172 feet	157-178	21
Boulder	178-179	1
Till, sandy, clayey, light to dark gray, hard	179-187	8
Till, clayey, brownish-gray, hard	187-197	10
Clay, black, soft	197-205	8
Till, clayey, light gray	205-209	4
Sand, medium to coarse, silty, brown	209-213	4
Till, clayey, light gray	213-215	2
Sand, medium to coarse, brown	215-216	1
Till, clayey, light gray	216-219	3
Sand, medium to coarse, and fine gravel, brown, with some clay lenses	219-222	3
Till, clayey, sandy, dark gray to brownish gray, soft	222-233	11
Clay, brown, soft	233-239	6
Granite, pink, hard	239-242	3

Test hole number: BB17 Location: 123.35.02AADDCA County: Stearns

Township: Crow Lake Land surface altitude: 1,279 feet

Geologic log	Depth (feet)	Thickness (feet)

Observation Well Information

Three-inch diameter black steel: 0-165 feet
Stainless steel four-inch diameter 10-slot screen: 165-170 feet
Height of casing above land surface: 2.2 feet
Static water level: 7.83 feet below top of casing (7/23/86)

Test hole number: BB18 Location: 123.34.04ABDCCB County: Stearns

Township: Crow River Land surface altitude: 1,253 feet

Geologic log	Depth (feet)	Thickness (feet)
Topsoil, black	0-2	2
Sand, coarse to very coarse, and fine to medium gravel, brown; with cobbles and boulders	2-8	6
Till, sandy, brown	8-10	2
Till, sandy, gray, hard, cobbles at 31 feet	10-65	55
Till, sandy, clayey, gray	65-86	21
Sand, medium, brown	86-87	1
Till, sandy, dark gray	87-90	3
Sand, medium to very coarse, and fine to medium gravel, silty, brown, with some clay lenses from 91 to 94 feet	90-106	16
Till, sandy, clayey, gray	106-110	4
Till, sandy, gray to brownish-gray, hard	110-138	28
Sand, medium to very coarse, and fine to medium gravel, brown	138-148	10
Till, clayey, sandy, gray, soft, some sand lenses last five feet	148-163	15
Sand, medium to coarse, and fine to medium gravel, brown	163-174	11
Till, sandy, clayey, brown	174-183	9
Sand, medium to coarse, brown	183-184	1
Till, sandy, clayey, brown	184-196	12
Sand, medium to very coarse, and fine gravel, brown	196-197	1
Till, sandy, brown	197-219	22
Sand, medium to coarse, brown	219-221	3
Till, sandy, brown	221-222	1
Sand, medium to very coarse, and fine to medium gravel, brown	222-230	8
Till, clayey, sandy, dark gray to grayish brown	230-241	11
Shale, Cretaceous age, green, fairly hard	241-243	2
Schist, black, very hard	243-245	2

Observation Well Information

Three-inch diameter black steel: 0-165 feet
Galvanized steel 10-slot screen: 165-167 feet

Height of casing above land surface: 7.1 feet

Static water level: 1.18 feet below top of casing (7/23/86)

Test hole number: BB19 Location: 122.34.07BBBDBB County: Kandiyohi

Township: Burbank Land surface altitude: 1,275 feet

Geologic log	Depth (feet)	Thickness (feet)
Topsoil, black	0-1	1
Sand, medium to very coarse, and fine to coarse gravel, brown, some cobbles	1-28	27
Till, clayey, sandy, gray, soft	28-60	32
Till, sandy, clayey, gray	60-75	15
Till, sandy, gray, hard	75-81	6
Till, silty, sandy, light gray, hard	81-84	3
Sand, medium to very coarse, brown	84-86	2
Till, silty, light gray	86-90	4
Till, silty, sandy, clayey, brownish gray	90-136	46
Boulder, black, hard	136-137	1
Till, clayey, gray, hard	137-148	11
Till, sandy, clayey, soft	148-157	9
Till, clayey, sandy, hard	157-167	10
Clay, dark gray, hard, sand lense at 174 feet	167-176	9
Sand, medium to very coarse, and fine to medium gravel, silty, brown, some clay lenses near top	176-198	22
Till, clayey, gray, hard	198-208	10
Boulder, black, hard	208-209	1
Till, clayey, gray, hard	209-245	36
Sand, fine to medium, brown	245-247	2
Sand, medium to very coarse, and fine to medium gravel, brown	247-252	5
Till, clayey, grayish green	252-260	8
Till, clayey, gray, sticky, hard	260-302	42
Sand, medium to very coarse, brown	302-303	1
Till, clayey, gray, sticky	303-320	17
Sand, fine to very coarse, and fine to medium gravel, brown, finer sand near top	320-377	57
Till, clayey, olive-brown to brownish-gray	377-421	44
Till, clayey, brownish-gray, soft	421-479	58
Sand, medium to very coarse, brown	479-480	1
Till, clayey	480-481	1
Weathered granite, white to green, hard	481-487	6

Test hole number: BB20 Location: 123.35.36ABCDA County: Stearns

Township: Crow Lake Land surface altitude: 1,267 feet

Geologic log	Depth (feet)	Thickness (feet)
Sand, medium to very coarse, and fine to coarse gravel, brown, some cobbles	0-43	43
Till, sandy, clayey, gray, soft	43-62	19
Till, sandy, gray	62-101	39
Till, sandy, silty, light gray	101-106	5
Sand, medium to very coarse, and fine gravel, brown	106-113	7
Till, sandy, gray	113-117	4
Sand, medium to very coarse, and fine gravel, brown	117-119	2
Till, sandy, gray	119-123	4
Sand, medium to very coarse, and fine gravel, brown	123-125	2
Till, sandy, silty, gray	125-132	7
Till, sandy, clayey, gray, soft	132-137	5
Gravel, fine to coarse, and cobbles, brown	137-141	4
Till, sandy, clayey, gray	141-183	42
Sand, medium to very coarse, and fine gravel, brown	183-186	3
Till, sandy, clayey, gray	186-193	7
Till, sandy, gray	193-295	102
Sand, medium to very coarse, brown	295-297	2
Till, sandy, gray	297-298	1
Sand, medium to very coarse, brown	298-299	1
Till, sandy, gray	299-308	9
Sand and interbedded till	308-311	3
Till, sandy, gray, sand lense at 312 feet	311-317	6
Sand, medium to very coarse, brown	317-318	1
Till, sandy, gray, hard	318-344	26
Sand, medium to very coarse, brown, with interbedded gray sandy till	344-356	12
Gravel, fine to very coarse, and cobbles, brown	356-357	1
Boulder, granite, pink and black, hard	357-361	4
Till, sandy, dark gray, hard	361-377	16
Sand, coarse to very coarse, and fine to medium gravel, brown	377-393	16
Till, sandy, clayey, brown, hard	393-399	6
Sand, coarse to very coarse, and fine to coarse gravel, brown, clay lense at 407 feet	399-412	13
Sand, fine to medium, brown	412-419	7
Till, sandy, clayey, grayish brown, hard	419-455	36
Till, sandy, clayey, gray, hard	455-486	31
Weathered granite, white and black, hard	486-489	3

Test hole number: BB21 Location: 122.35.11BBBDCC County: Kandiyohi

Township: Colfax Land surface altitude: 1,260 feet

Geologic log	Depth (feet)	Thickness (feet)
Topsoil, black	0-2	2
Sand, medium to very coarse, and fine to coarse gravel, brown, some clay lenses top 5 feet	2-36	34
Till, sandy, clayey, gray, soft	36-62	26
Sand, fine to coarse, and fine to medium gravel, brown	62-66	4
Till and interbedded sand	66-69	3
Till, sandy, gray	69-76	7
Sand, medium to very coarse, brown	76-77	1
Till, silty, sandy, light gray	77-85	8
Till, sandy, clayey, gray, hard	85-126	41
Sand, medium to very coarse, brown	126-128	2
Till, sandy, clayey, gray	128-130	2
Sand, medium to coarse, and fine to medium gravel, brown	130-135	5
Till, sandy, clayey, gray	135-140	5
Till and interbedded sand	140-142	2
Till, clayey, sandy, gray, hard, some brown clay lenses	142-165	23
Till, clayey, gray, hard	165-185	20
Till, sandy, clayey, greenish gray	185-192	7
Till, sandy, clayey, brown	192-195	3
Sand, medium to coarse, and fine to medium gravel, brown	195-201	6
Till, sandy, clayey, brown	210-210	9
Till, sandy, clayey, gray to brownish gray	210-221	11
Sand, coarse, and fine to medium gravel	221-222	1
Till, sandy, clayey, gray	222-227	5
Sand, fine to very coarse, brown	227-229	2
Till, sandy, gray to greenish gray	229-240	11
Till, sandy, clayey, brown, with some sand lenses	240-257	17
Till, clayey, brownish gray to dark gray	257-264	7
Sand, medium to very coarse, brown	264-265	1
Till, clayey, dark gray	265-269	4
Sand, fine to very coarse, brown	269-272	3
Till, clayey, gray	272-279	7
Sand, medium to coarse, brown	279-280	1
Till, clayey, dark gray, soft, with some sand lenses	280-290	10
Clay, sandy, light gray to brownish gray, soft	290-330	40
Sand, very fine to very coarse, brown to gray	330-343	13
Till, clayey, gray, soft	343-344	1
Sand, very fine to coarse, gray	344-346	2
Till, clayey, gray, soft	346-347	1

Test hole number: BB21 Location: 122.35.11BBBDCC County: Kandiyohi

Township: Colfax Land surface altitude: 1,260 feet

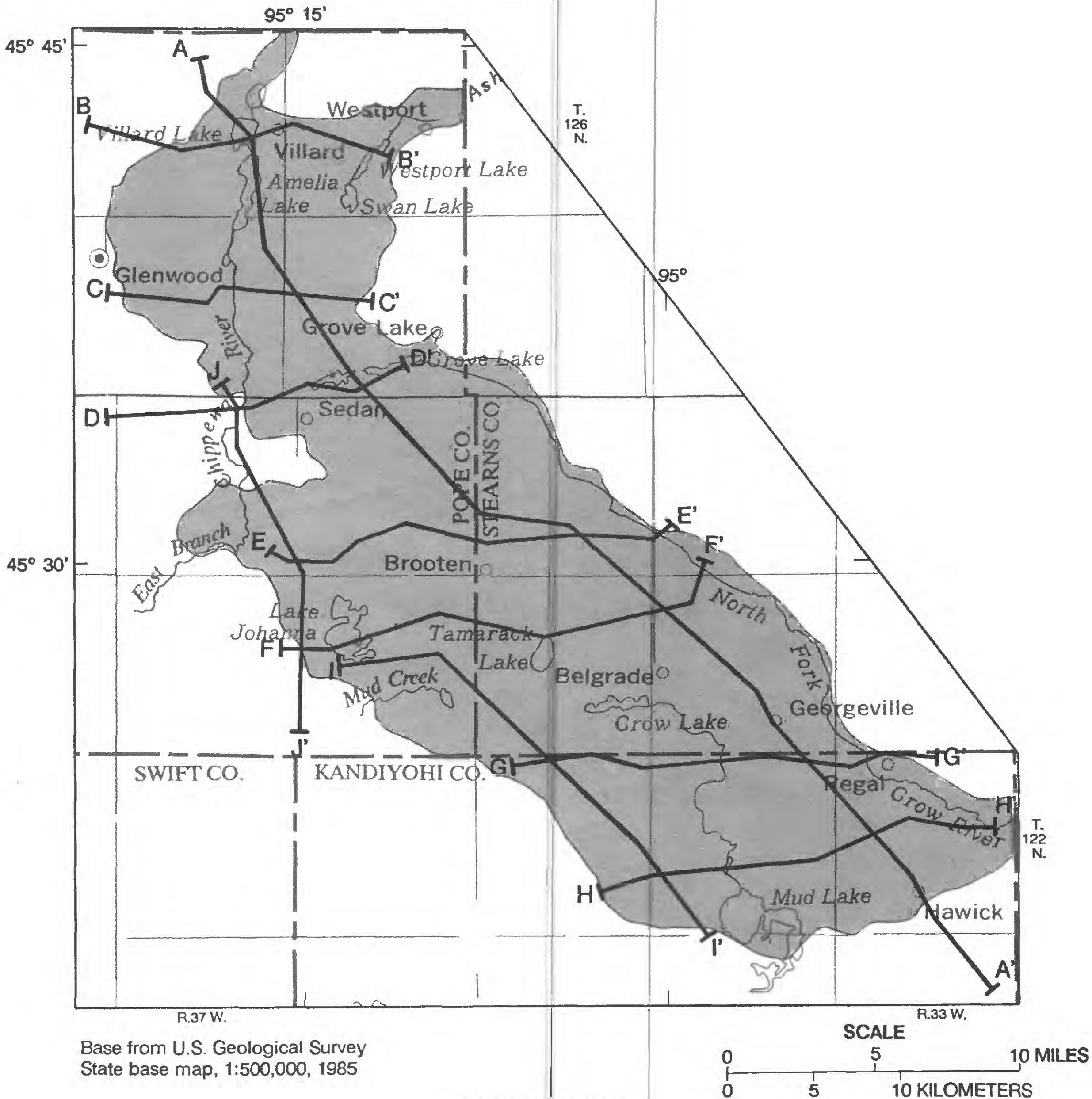
Geologic log	Depth (feet)	Thickness (feet)
Sand, very fine to coarse, gray	347-357	10
Till, clayey, gray	357-358	1
Sand, very fine to fine, some coarse, gray	358-360	2
Till, clayey, dark gray, soft	360-399	39
Bedrock, granitic, black, green, and white, hard	399-403	4

Test hole number: BB22 Location: 122.34.18ADCDBD County: Kandiyohi

Township: Burbank Land surface altitude: 1,224 feet

Geologic log	Depth (feet)	Thickness (feet)
Topsoil, black	0-1	1
Till, sandy, brown	1-2	1
Sand, medium to coarse, and fine to coarse gravel, brown	2-38	36
Till, sandy, clayey, gray, soft	38-54	16
Sand, medium to very coarse, and interbedded till	54-58	4
Till, sandy, clayey, gray, soft	58-67	9
Till, sandy, gray, harder	67-72	5
Till, sandy, brown	72-78	6
Sand and interbedded till	78-84	6
Till, sandy, light greenish gray	84-93	9
Till, sandy, brownish gray, with some sand lenses	93-100	7
Till, sandy, gray, hard, sand lense at 104 feet	100-110	10
Till, sandy, brownish gray, hard	110-112	2
Till, sandy, gray, hard	112-140	28
Sand, fine to coarse, brown	140-141	1
Till, clayey, gray, soft	141-150	9
Sand, medium to very coarse, and fine to medium gravel, brown, with some clay lenses	150-179	29
Till, sandy, gray	179-186	7
Sand, medium to very coarse, brown	186-189	3
Till, sandy, clayey, gray	189-250	61
Sand, fine to very coarse, and fine gravel, brown	250-285	35
Gravel, fine to medium, and medium to very coarse sand, brown	285-300	15
Sand, fine, brown	300-304	4
Sand, fine to coarse, and fine to medium gravel, brown	304-350	46
Sand, fine to coarse, and fine to medium gravel, gray	350-360	10
Till, sandy, gray, with some sand lenses	360-364	4
Till, sandy, clayey, gray, soft	364-400	36
Till, sandy, gray, hard	400-420	20
Till, clayey, gray, very soft	420-459	39
Boulder, granite, black, green, and white, very hard	459-461	2
Till, sandy, clayey, hard, brownish gray	461-465	4
Weathered granite, green and white, hard	465-477	12

APPENDIX II - HYDROGEOLOGIC SECTIONS



EXPLANATION

A ⊢——⊣ A' Trace of section

Figure II-1.--Location of the hydrogeologic sections in the Brooten-Belgrade area

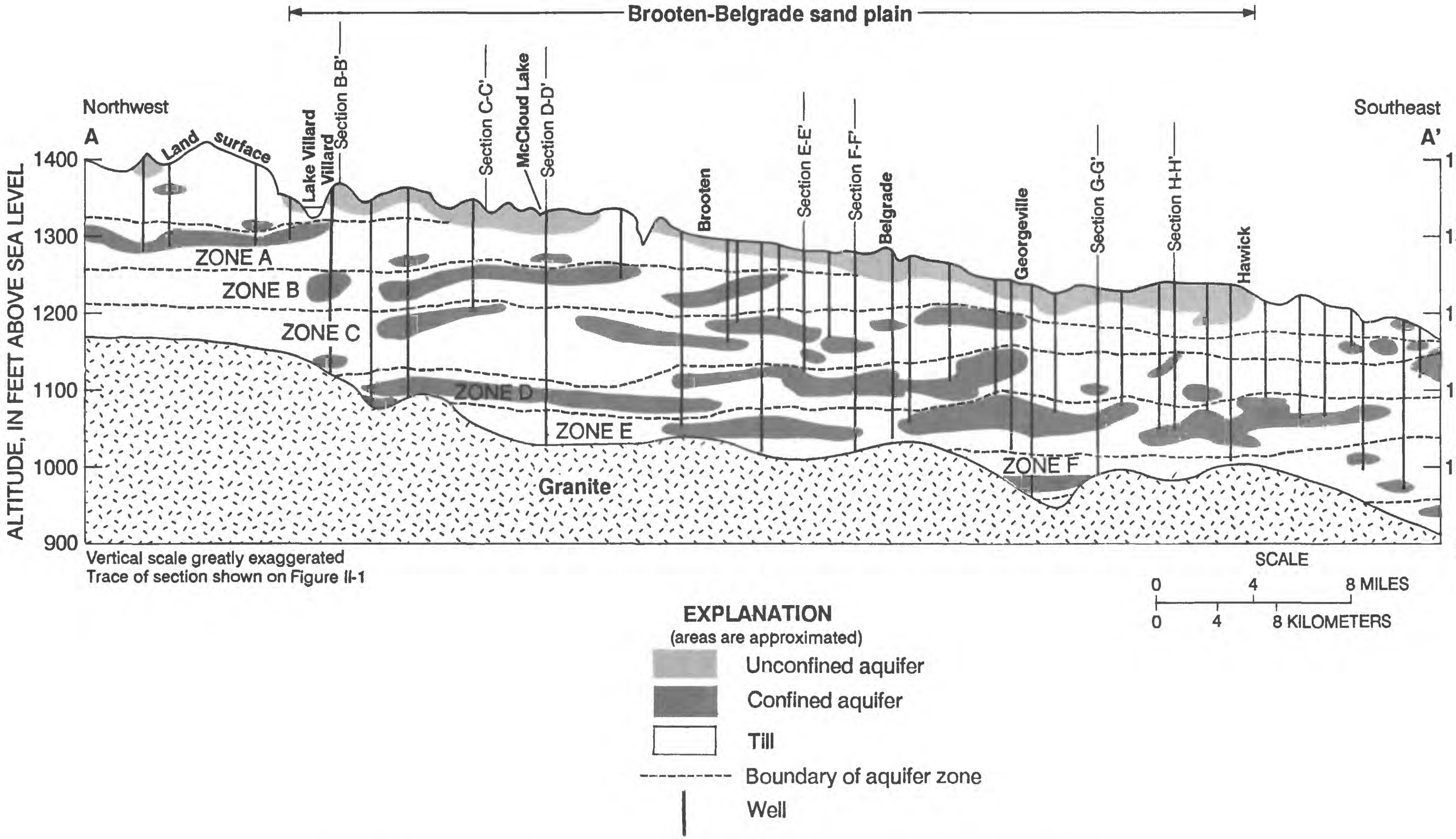


Figure II-2.-- Hydrogeologic section A-A' showing drift aquifers in the Brooten-Belgrade area

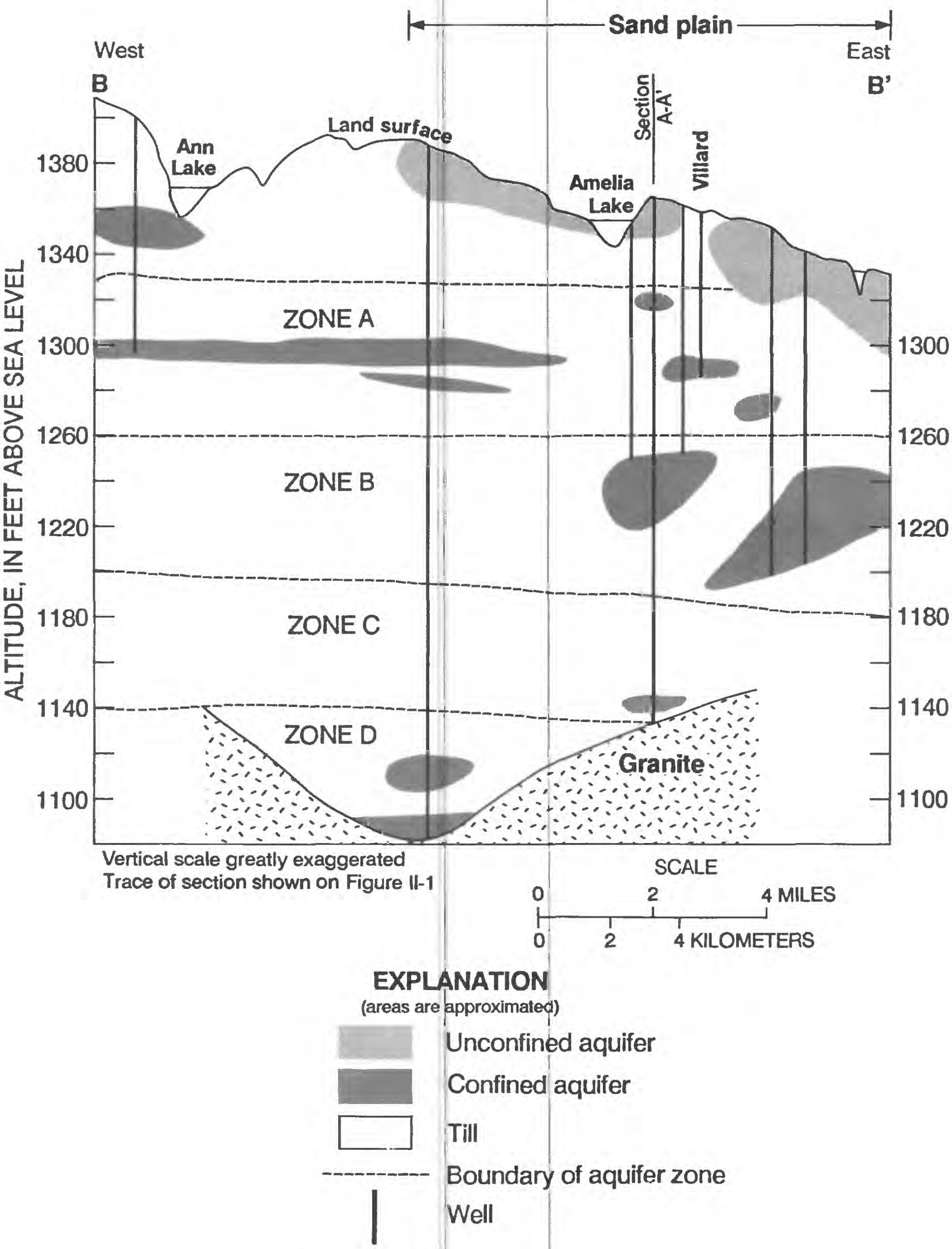


Figure II-3.--Hydrogeologic section B-B' near Villard.

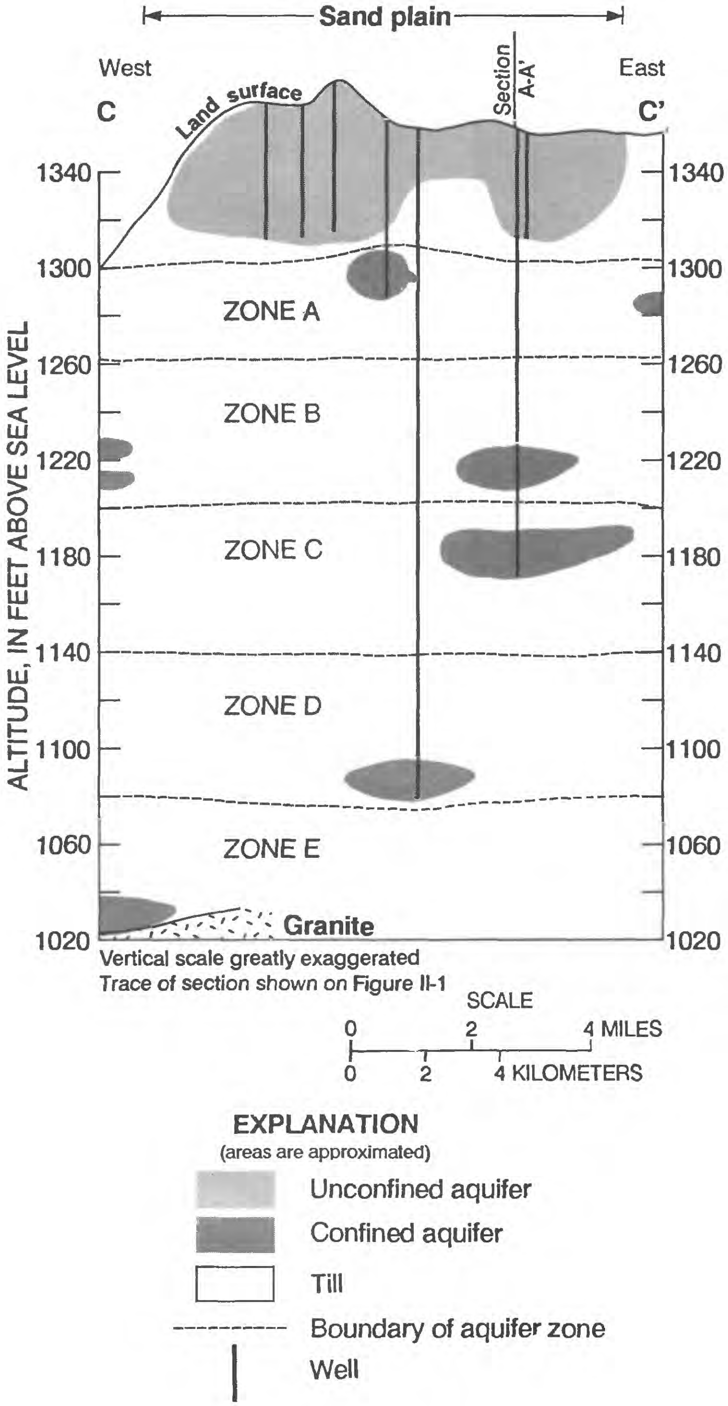


Figure II-4.--Hydrogeologic section C-C' southeast of Glenwood.

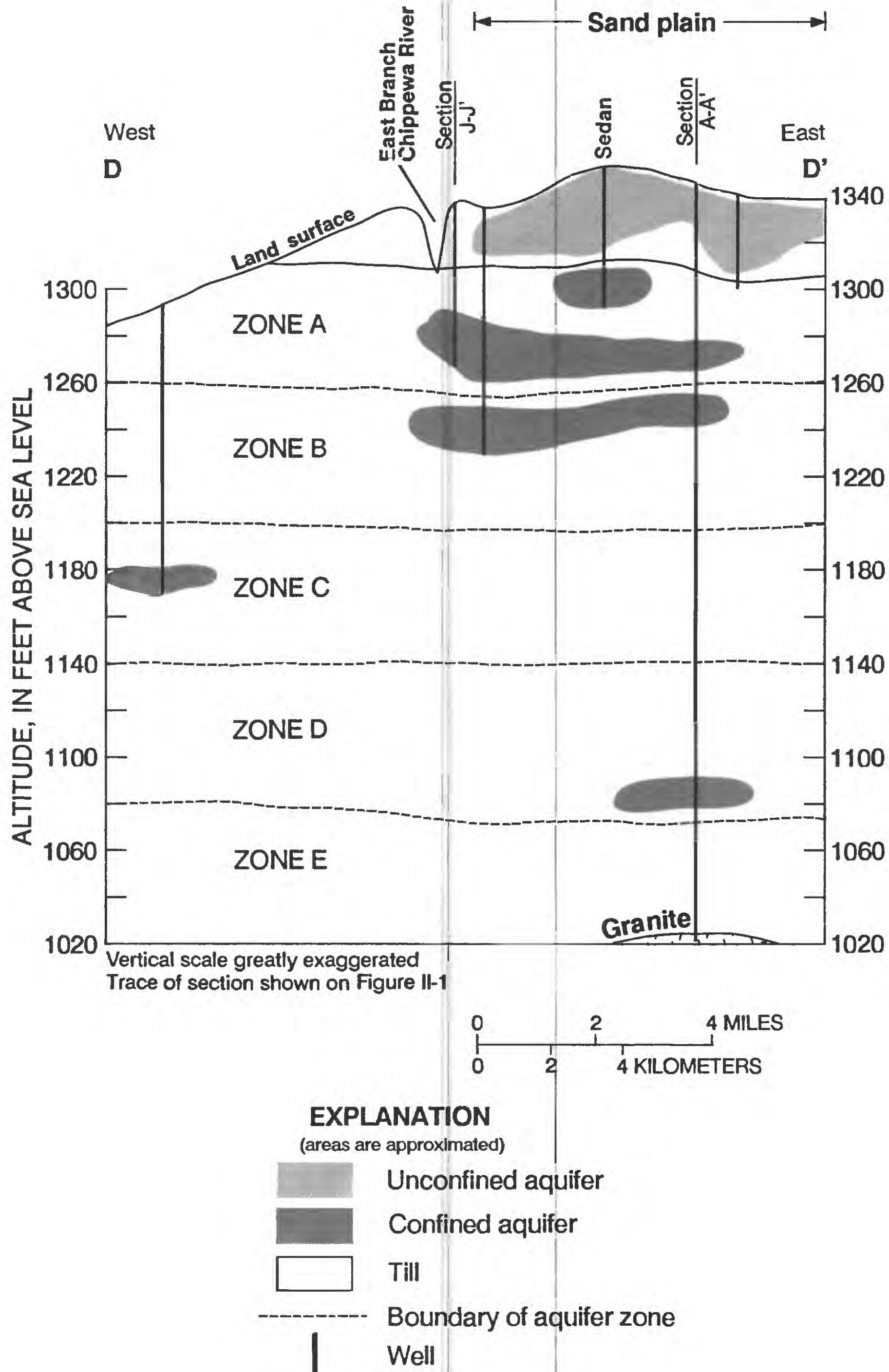


Figure II-5.--Hydrogeologic section D-D' near Sedan.

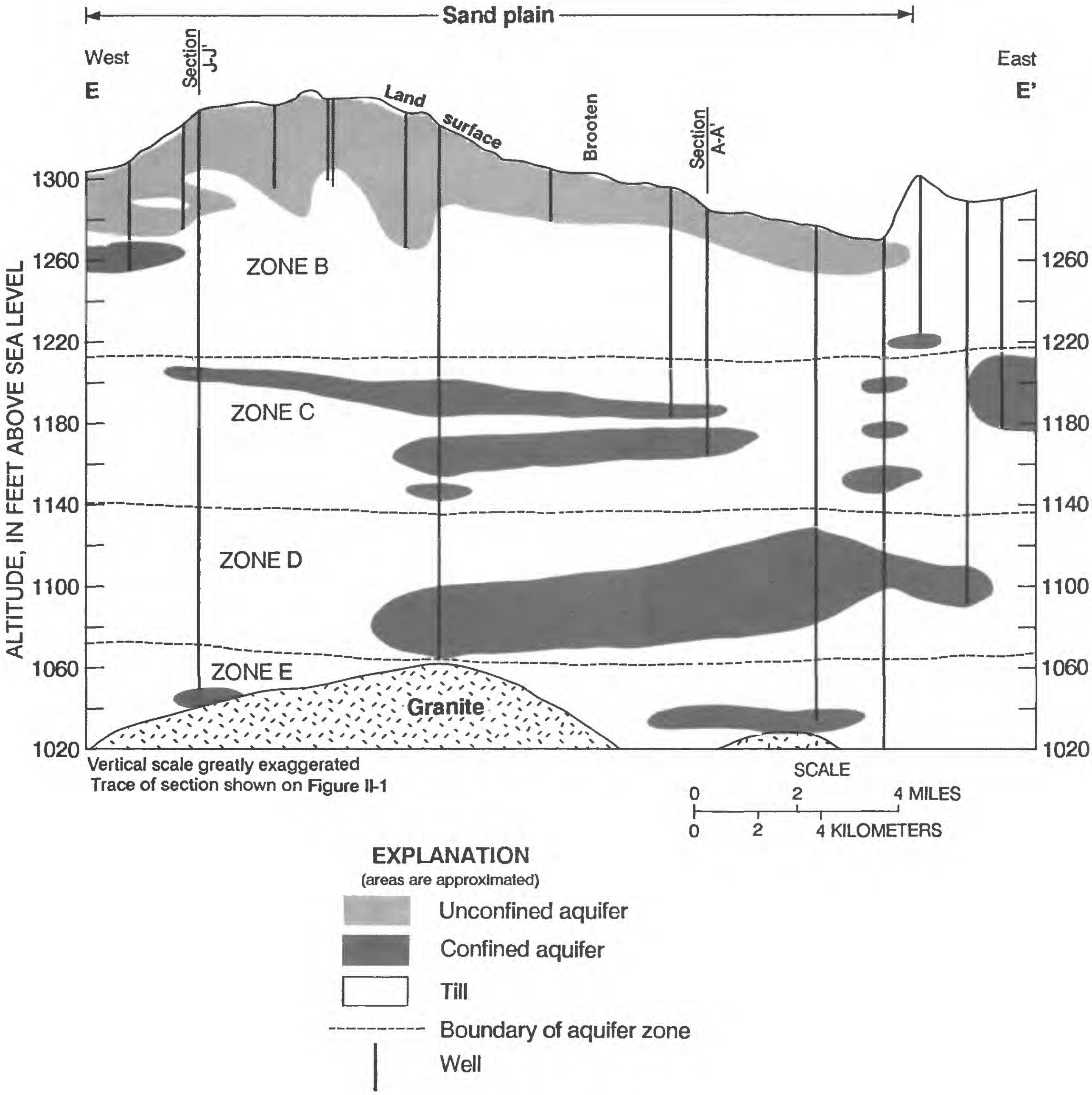


Figure II-6.--Hydrogeologic section E-E' near Brooten.

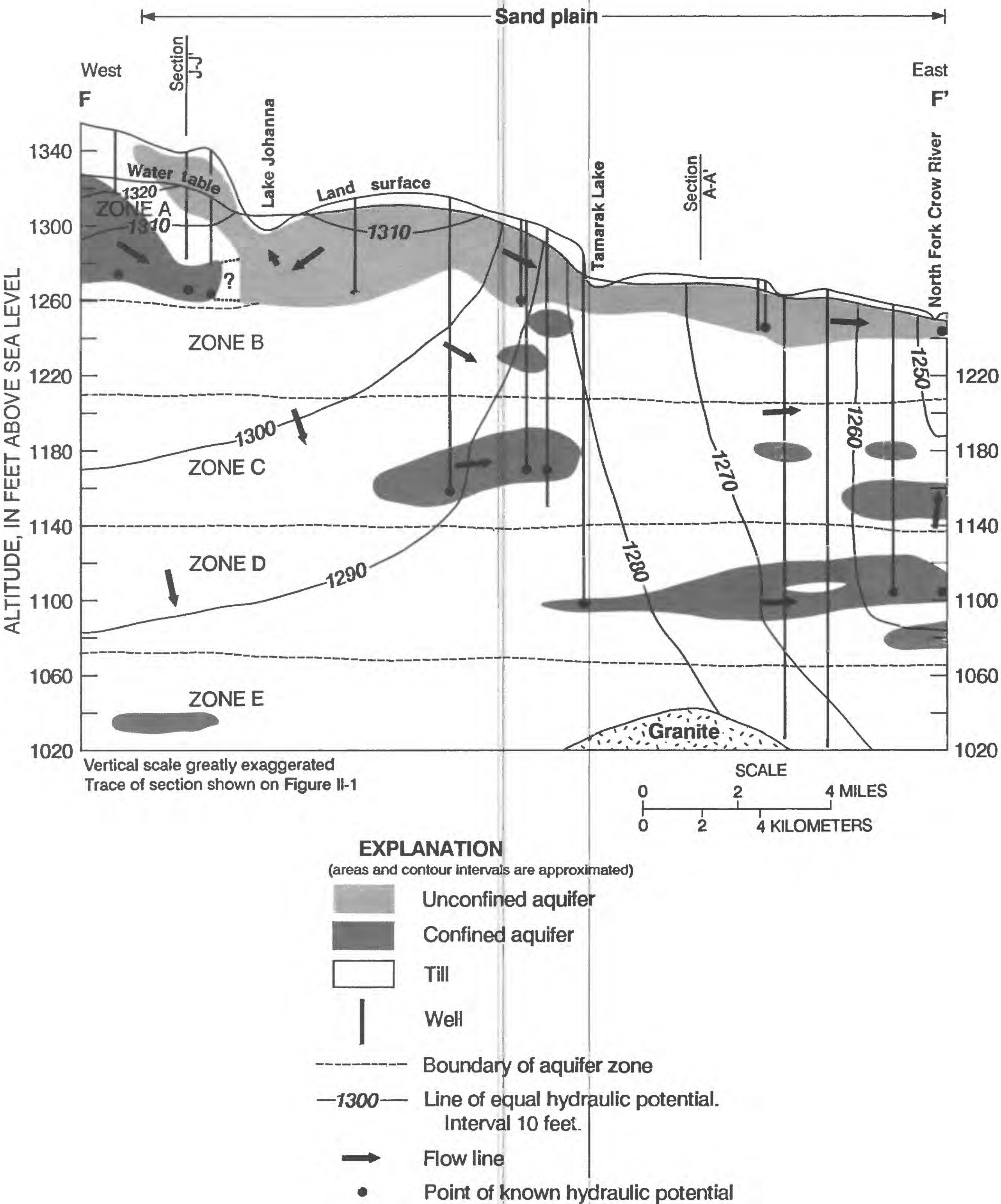


Figure II-7.--Hydrogeologic section F-F' north of Belgrade showing ground-water flow near the North Fork Crow River.

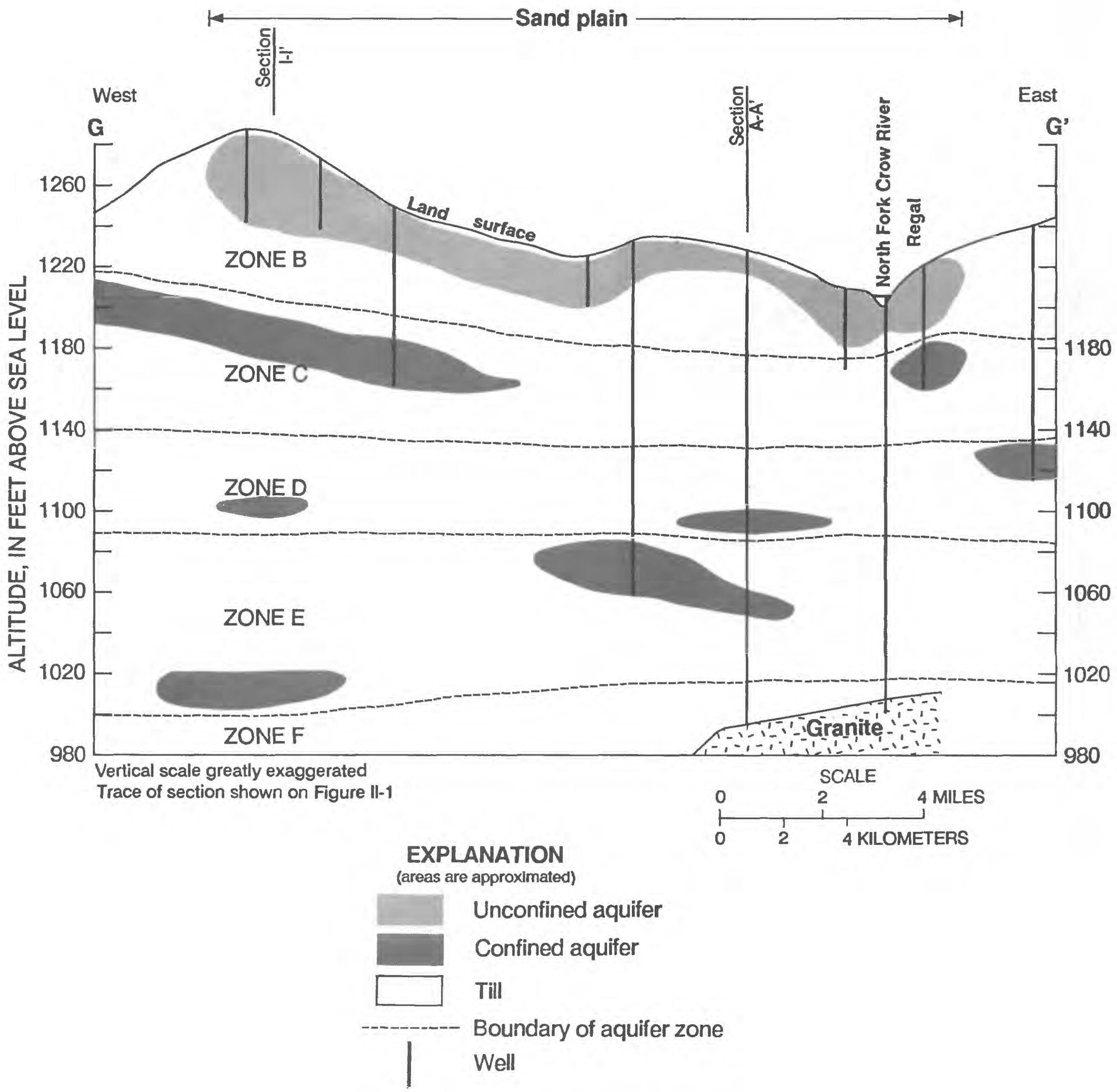


Figure II-8.-- Hydrogeologic section G-G' near Regal.

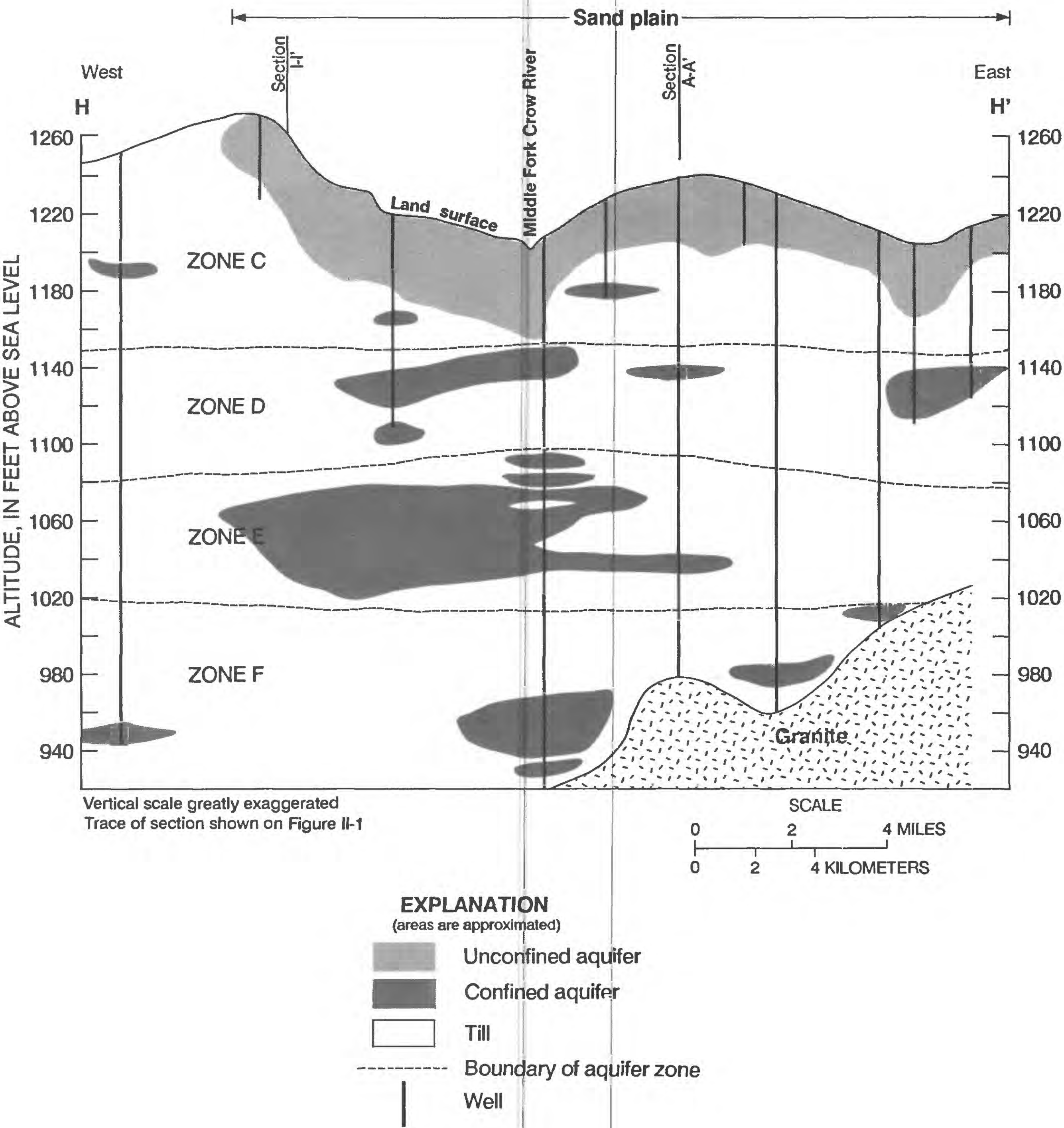


Figure II-9.--Hydrogeologic section H-H' near the Middle Fork Crow River.

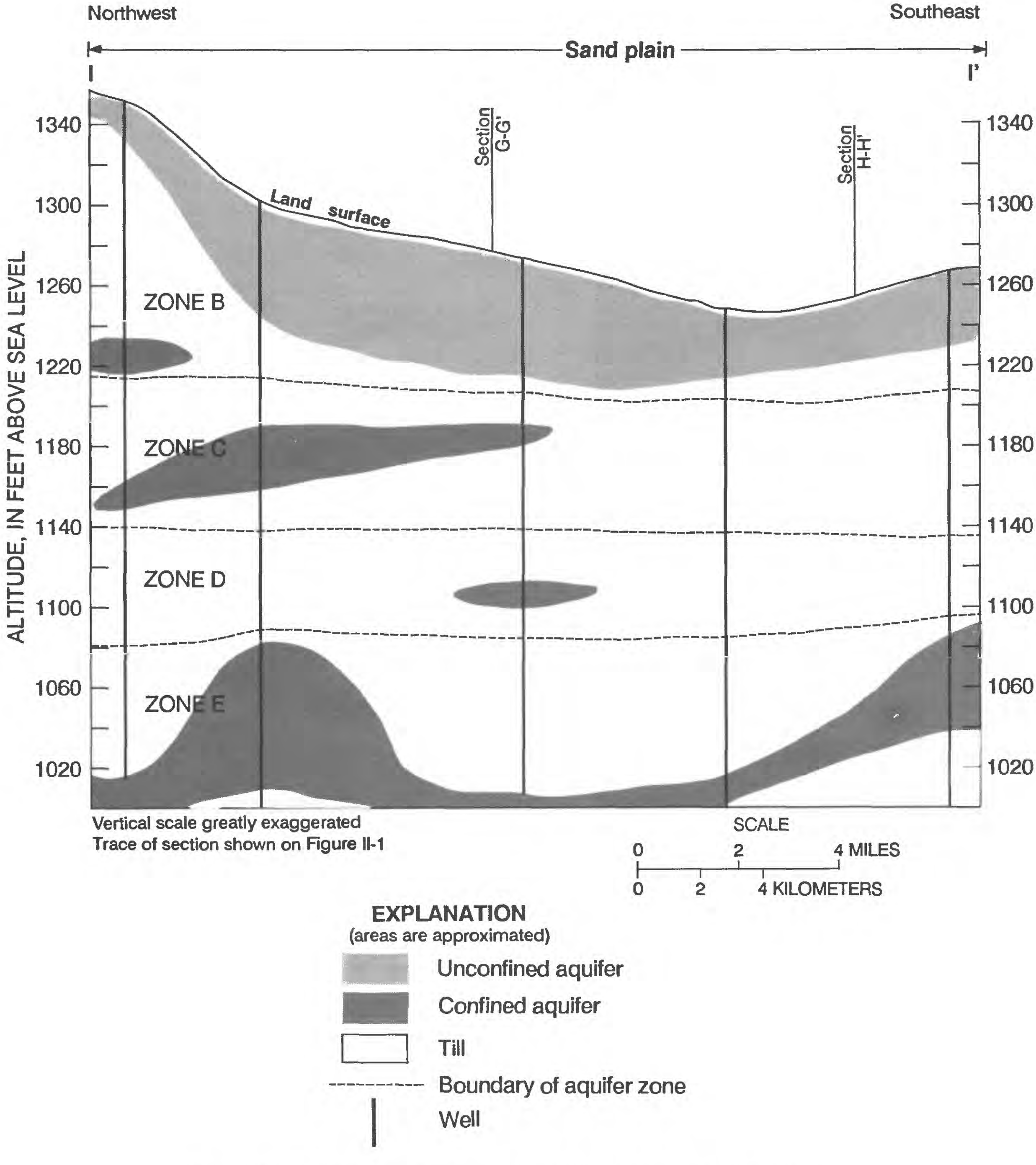


Figure II-10.--Hydrogeologic section I-I' southeast of Lake Johanna.

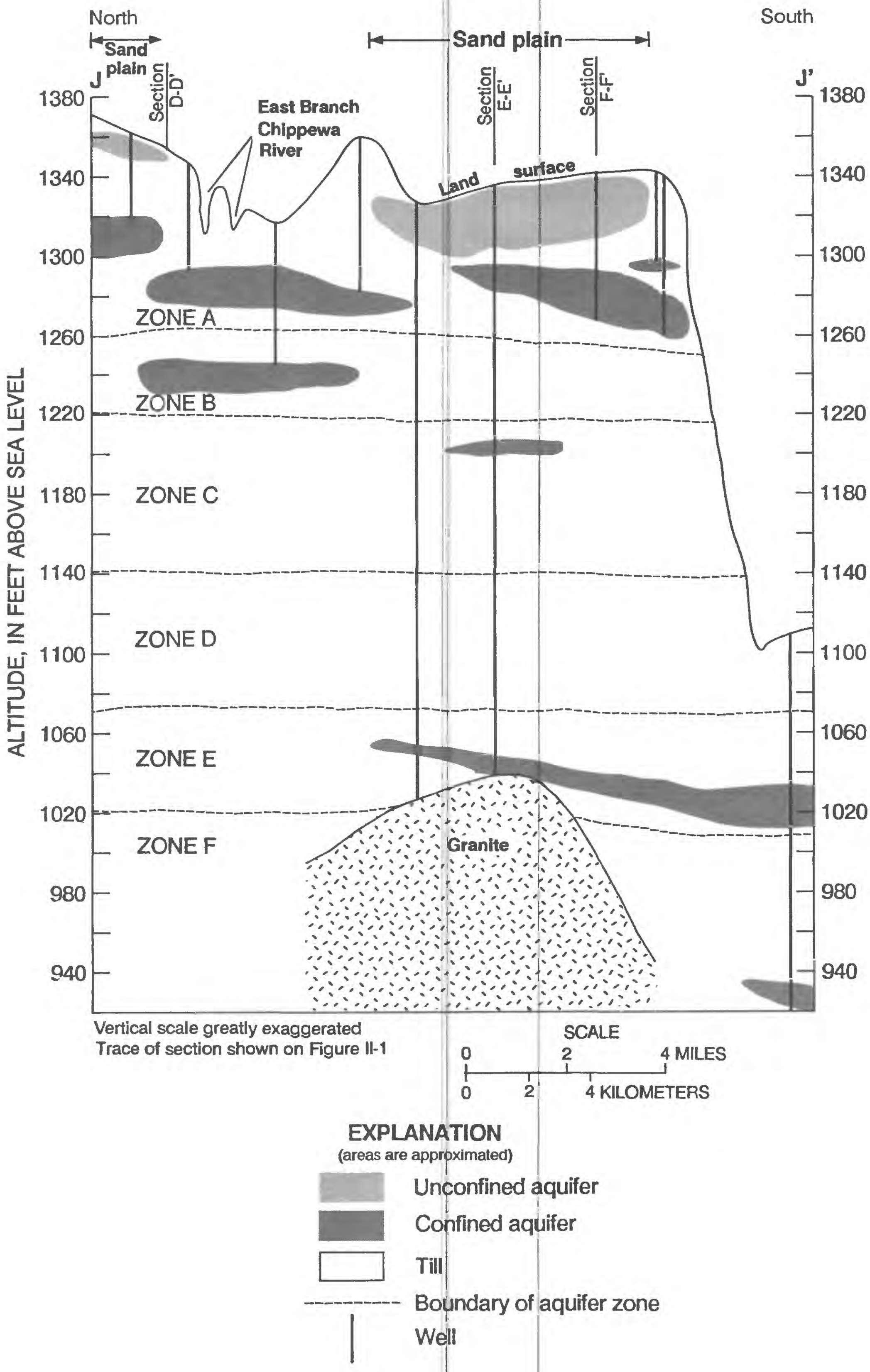
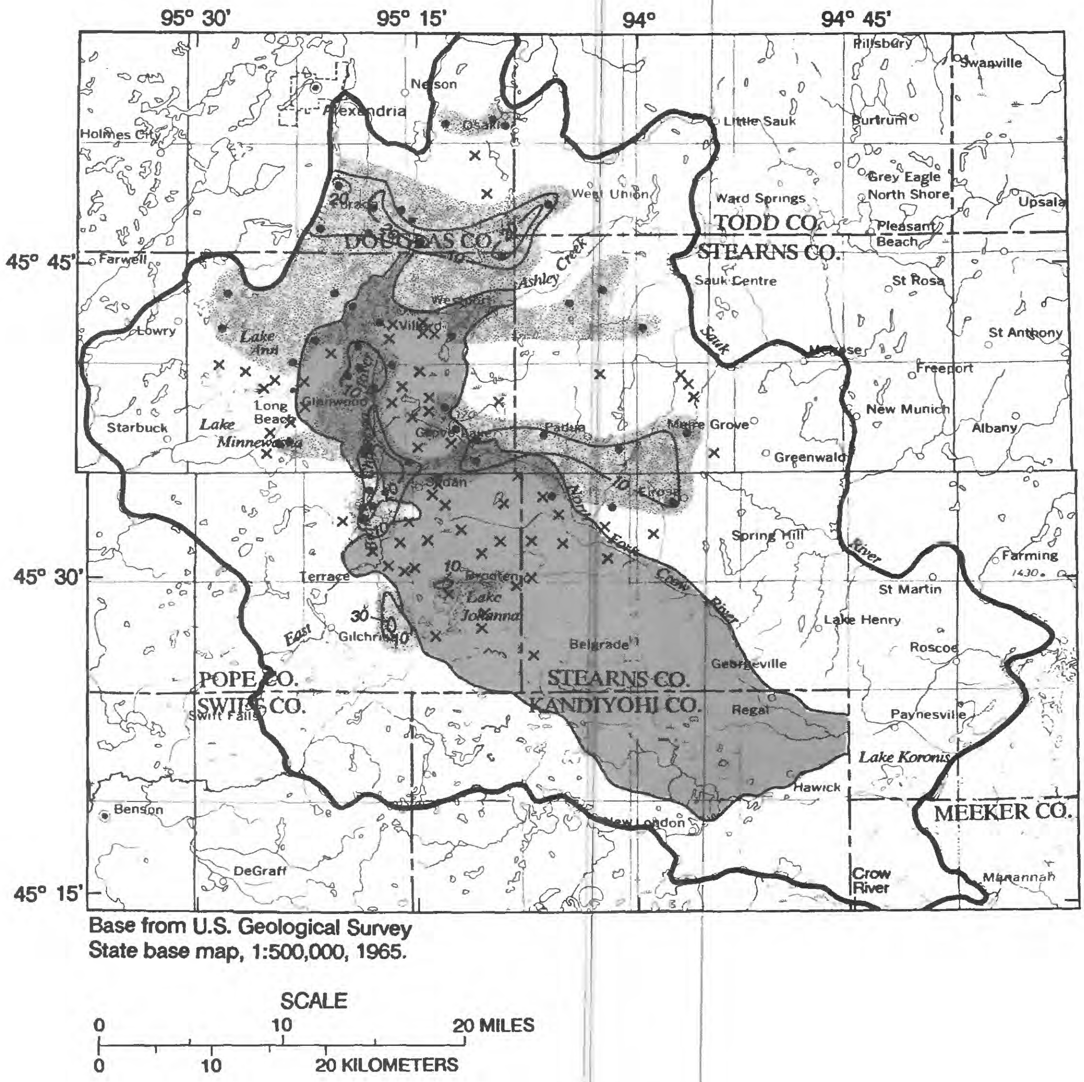


Figure II-11.--Hydrogeologic section J-J' northwest of Lake Johanna.

APPENDIX III - ZONE A

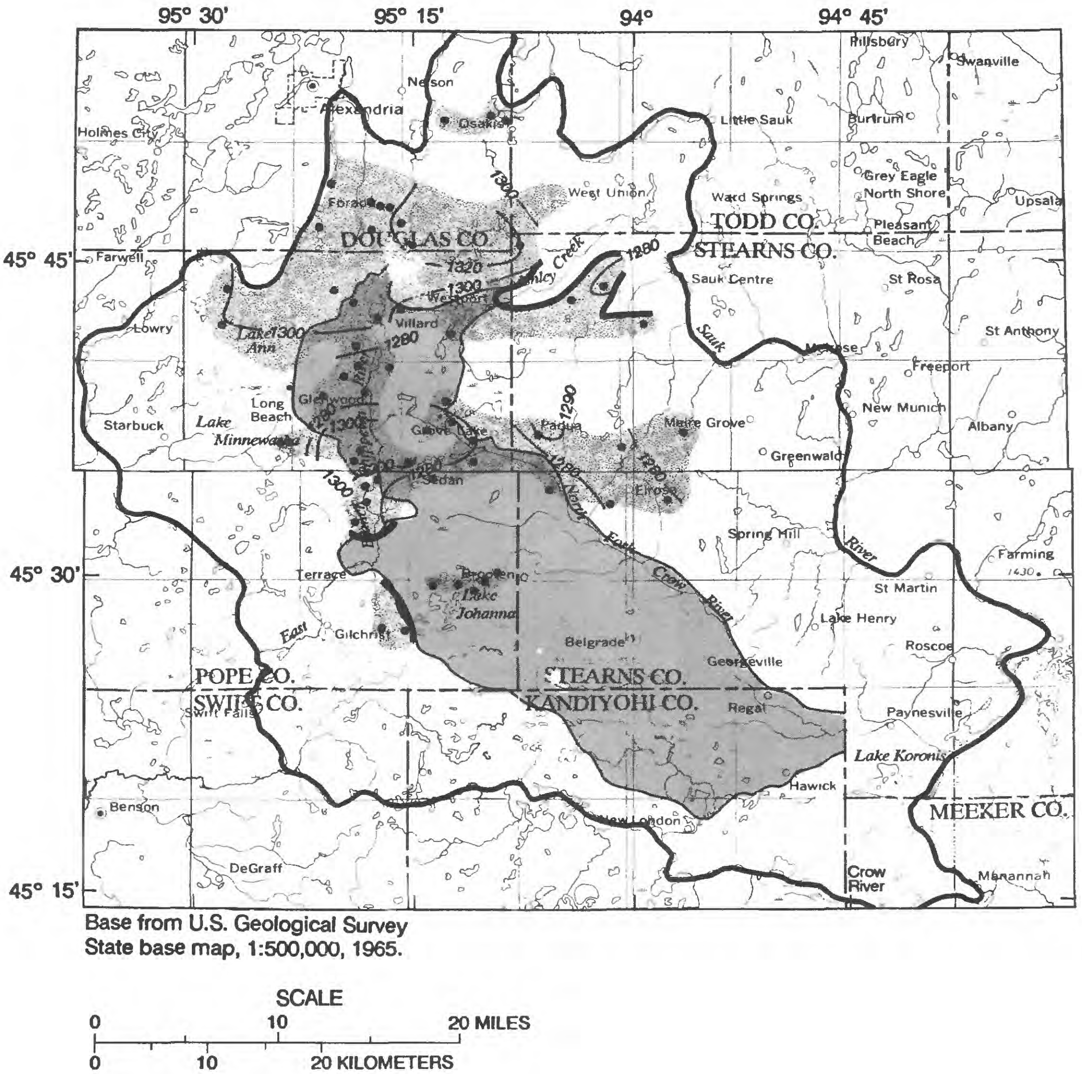
THICKNESS OF AQUIFERS,
CONFIGURATION OF TOP OF AQUIFERS,
TRANSMISSIVITY OF AQUIFERS,
POTENTIOMETRIC SURFACE OF CONFINED AQUIFERS,
AND THEORETICAL MAXIMUM YIELD OF WELLS IN AQUIFER



EXPLANATION

- Brooten-Belgrade sand plain
- Known areal extent of aquifers in zone A
- Hydrologic boundary of study area
- —10— Line of equal thickness. *Interval 10 and 20 feet.*
- • Well or test-hole location
- × Aquifer not present

Figure III-1.--Thickness of aquifers in zone A



EXPLANATION

Brooten-Belgrade sand plain

Known areal extent of aquifers in zone A

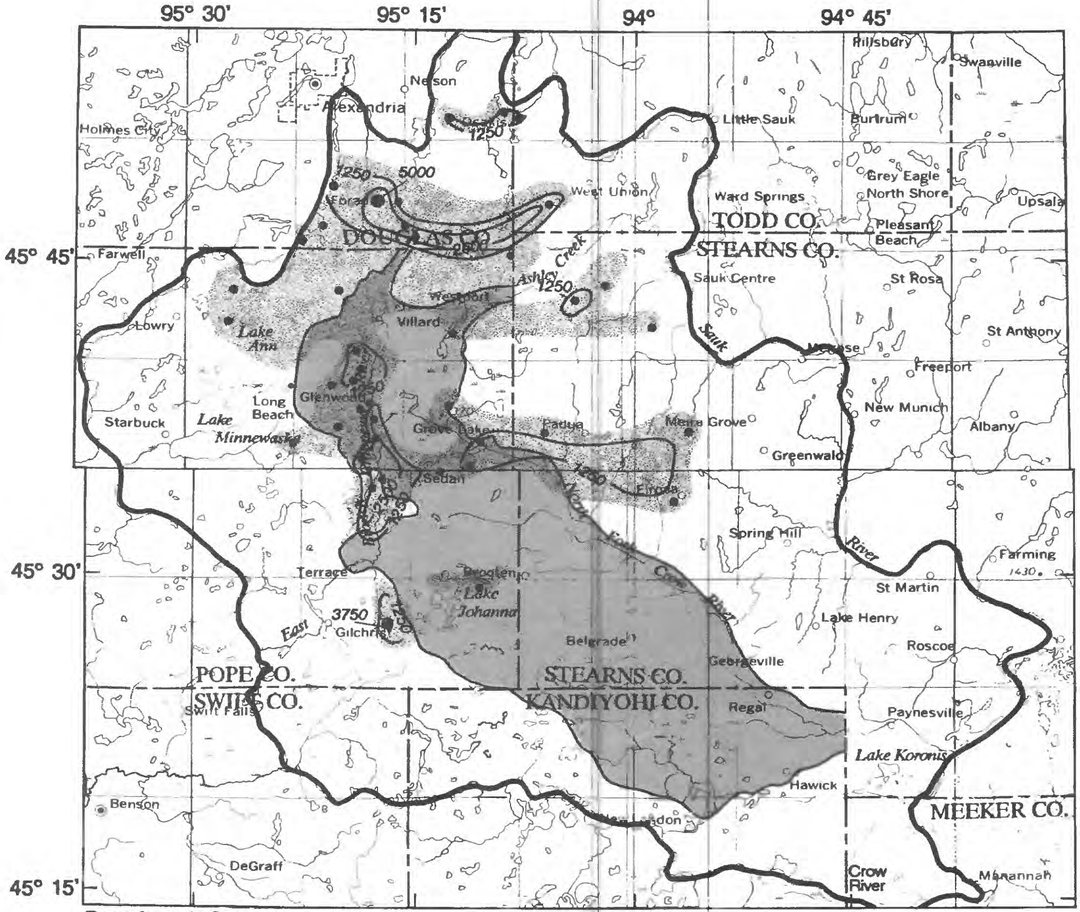
Hydrologic boundary of study area

—1280— Structure contour. *Shows altitude of top of aquifer. Interval 10 and 20 feet. Datum is sea level.*

Boundary between an unconfined aquifer and confined aquifers in zone A, where they coalesce.

• Well or test-hole location

Figure III-2.--Configuration of top of aquifers in zone A



Base from U.S. Geological Survey
State base map, 1:500,000, 1965.

SCALE

0 10 20 MILES

0 10 20 KILOMETERS

EXPLANATION

Brooten-Belgrade sand plain

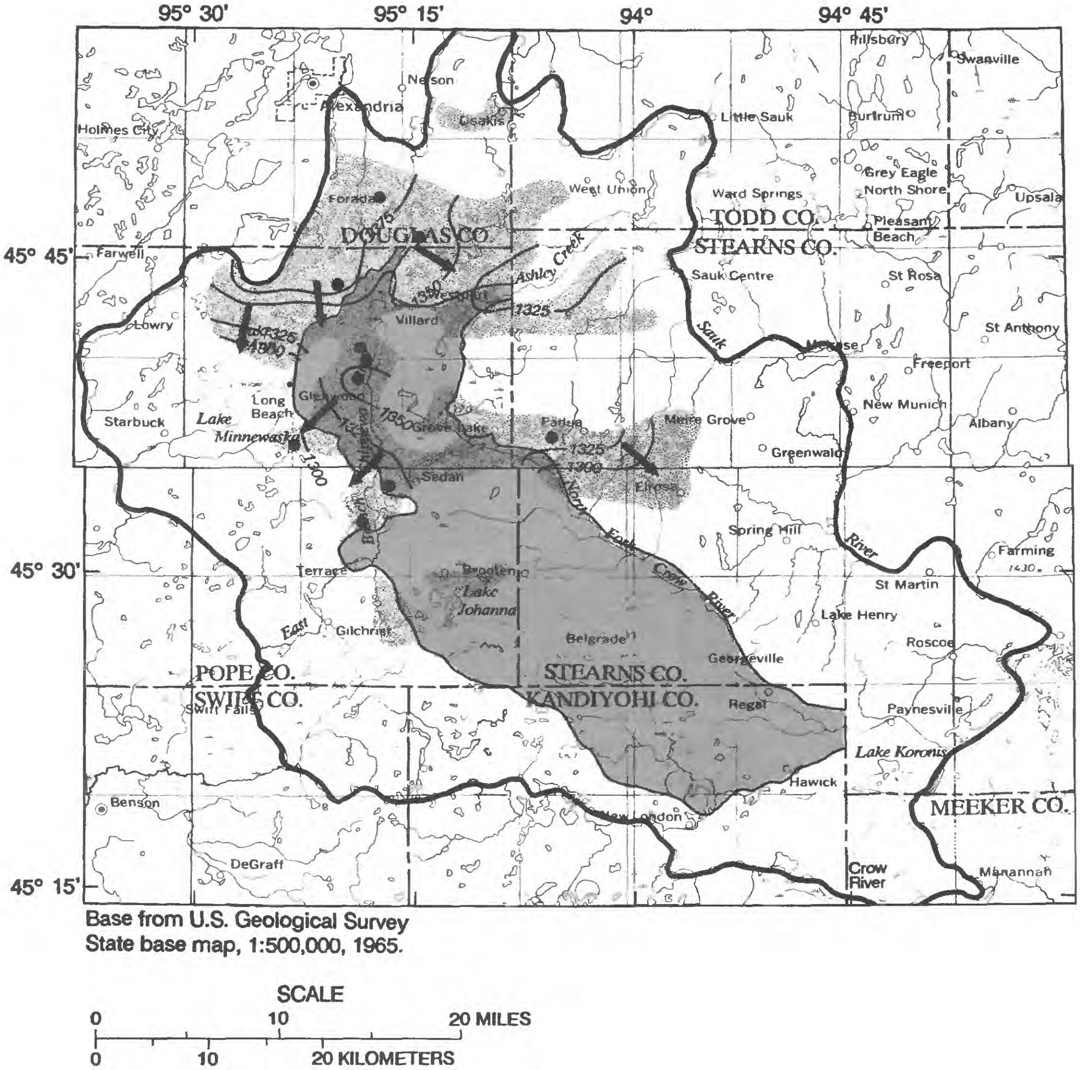
Known areal extent of aquifers in zone A

Hydrologic boundary of study area

— *1250* — Line of equal transmissivity. *Interval variable, in feet squared per day.*

• Transmissivity data point derived from specific-capacity or aquifer-test data

Figure III-3.--Transmissivity of aquifers in zone A



EXPLANATION

- Brooten-Belgrade sand plain
- Known areal extent of aquifers in zone A
- Hydrologic boundary of study area
- —1300— Potentiometric contour. *Interval 25 feet. Datum is sea level.*
- Direction of ground-water flow
- U.S. Geological Survey measured water level

Figure III-4.--Potentiometric surface of aquifers in zone A, 1985

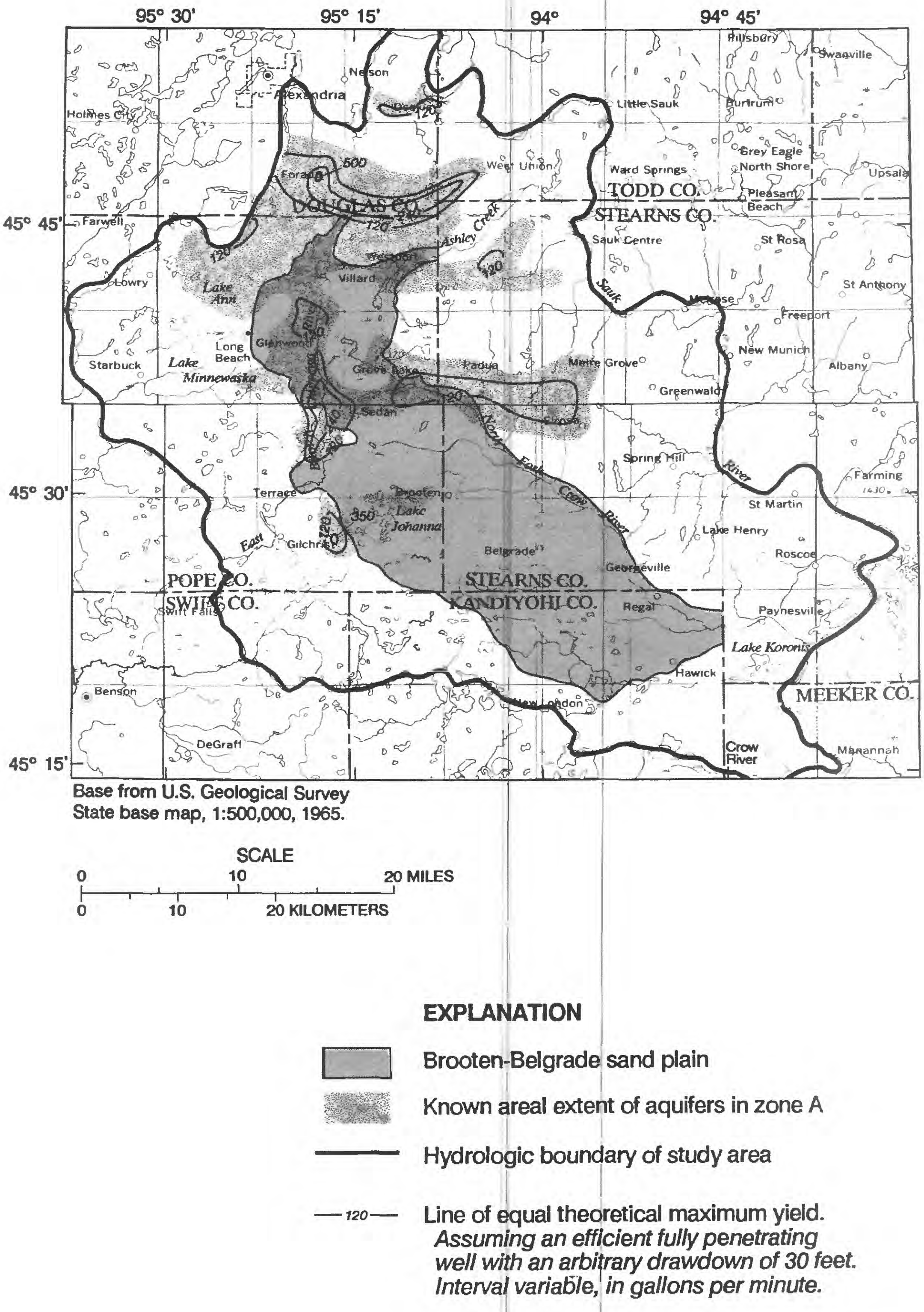
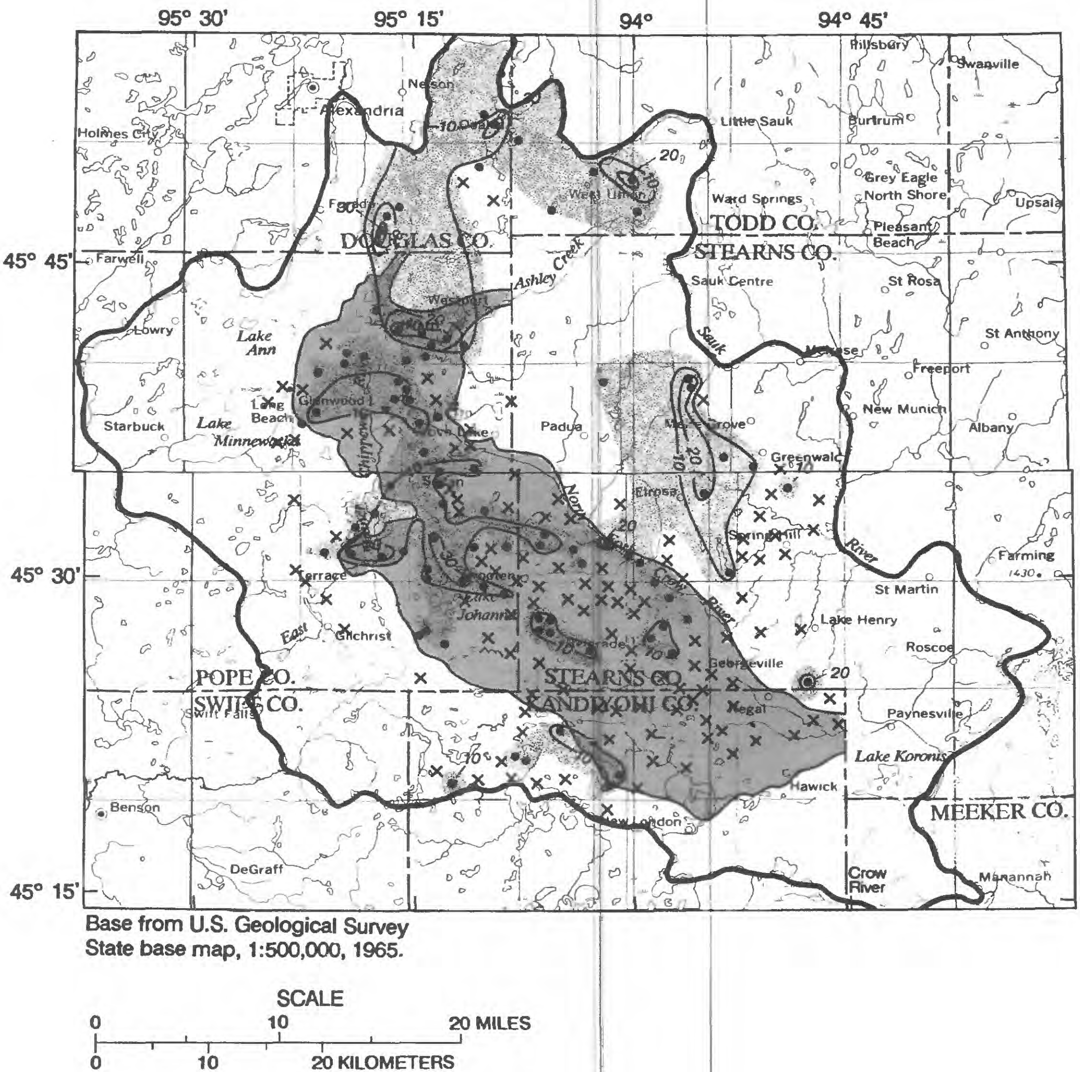


Figure III-5.--Theoretical maximum yield of wells in aquifer zone A

APPENDIX III - ZONE B

*THICKNESS OF AQUIFERS,
CONFIGURATION OF TOP OF AQUIFERS,
TRANSMISSIVITY OF AQUIFERS,
POTENTIOMETRIC SURFACE OF CONFINED AQUIFERS,
AND THEORETICAL MAXIMUM YIELD OF WELLS IN AQUIFER*



EXPLANATION

Brooten-Belgrade sand plain

Known areal extent of aquifers in zone B

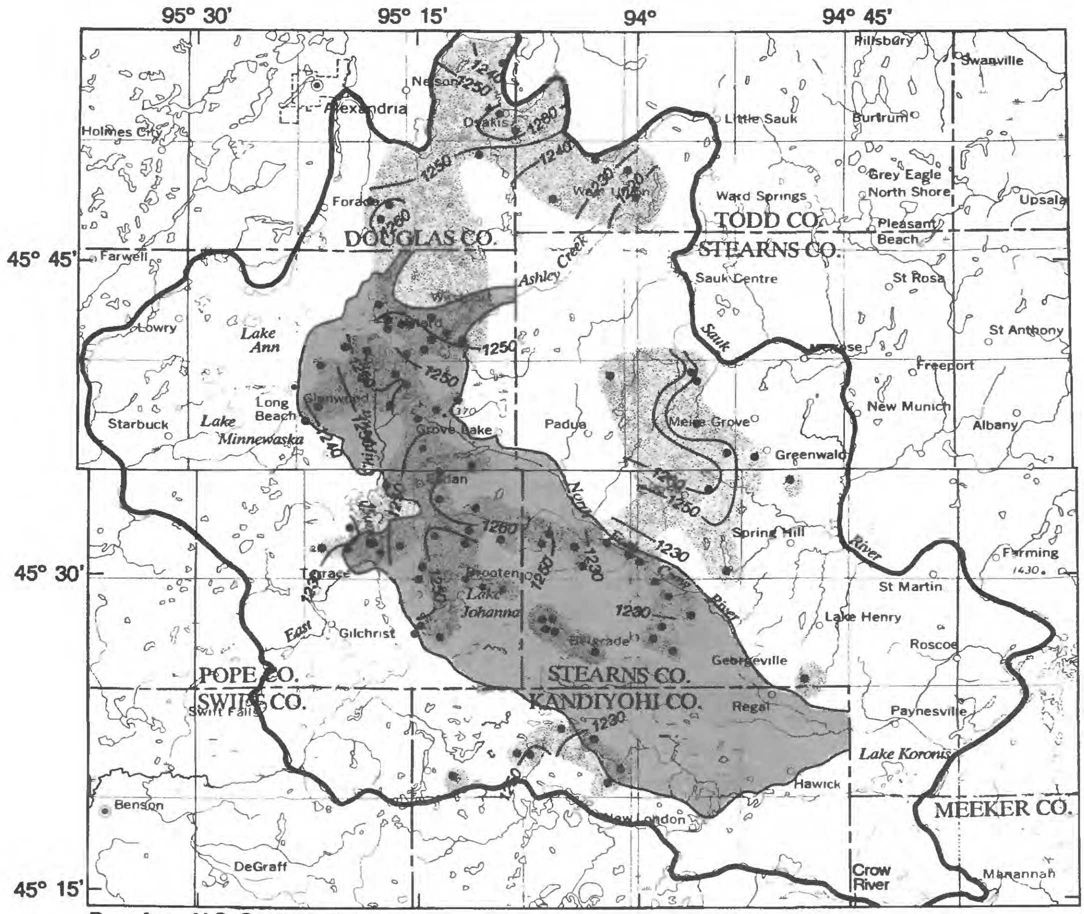
Hydrologic boundary of study area

—10— Line of equal thickness. *Interval 10 and 20 feet.*

• Well or test-hole location

× Aquifer not present

Figure III-6.--Thickness of aquifers in zone B



Base from U.S. Geological Survey
State base map, 1:500,000, 1965.

SCALE

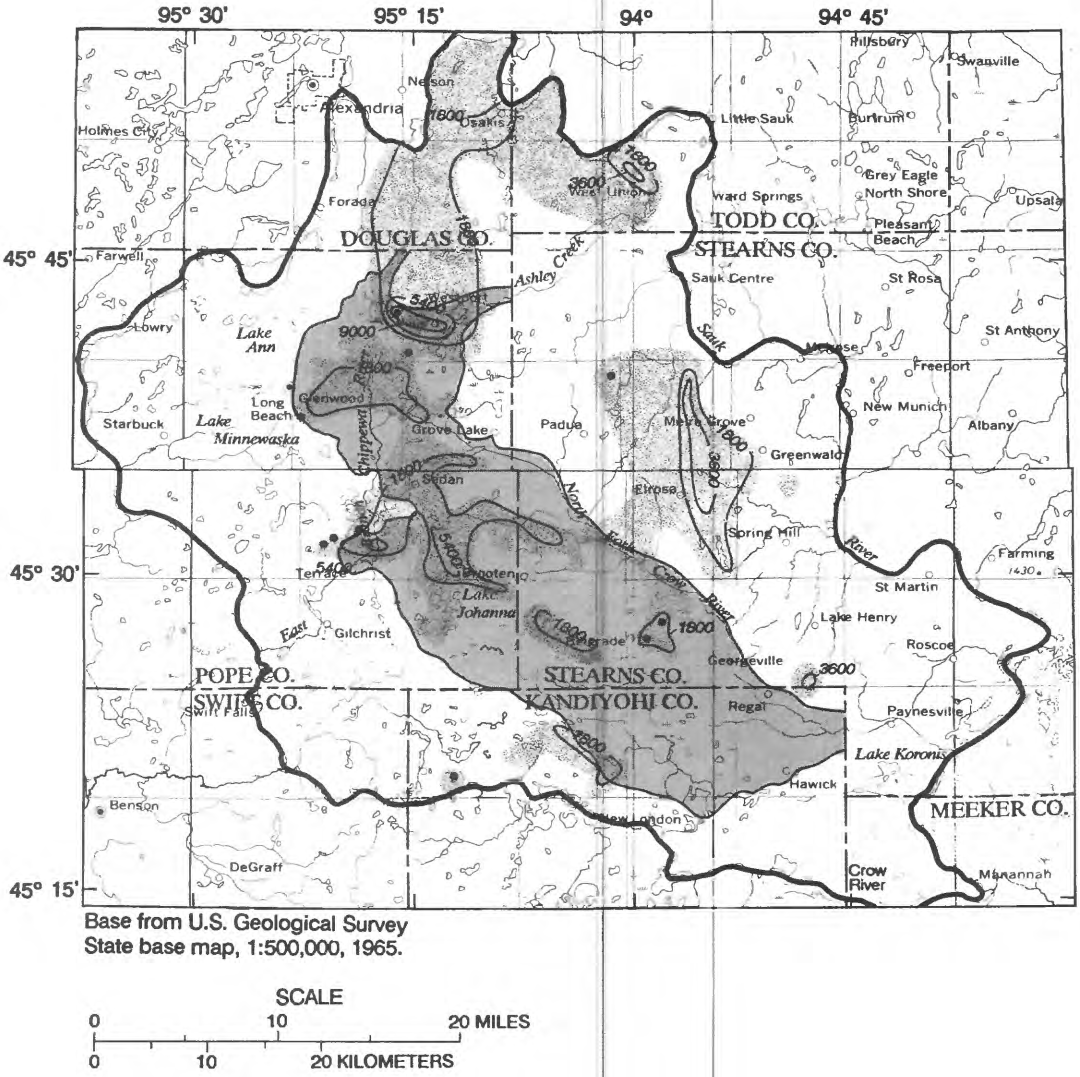
0 10 20 MILES

0 10 20 KILOMETERS

EXPLANATION

- Brooten-Belgrade sand plain
- Known areal extent of aquifers in zone B
- Hydrologic boundary of study area
- —1230— Structure contour. *Shows altitude of top of aquifer. Interval 10 and 20 feet. Datum is sea level.*
- • Well or test-hole location

Figure III-7.--Configuration of top of aquifers in zone B



EXPLANATION

Brooten-Belgrade sand plain

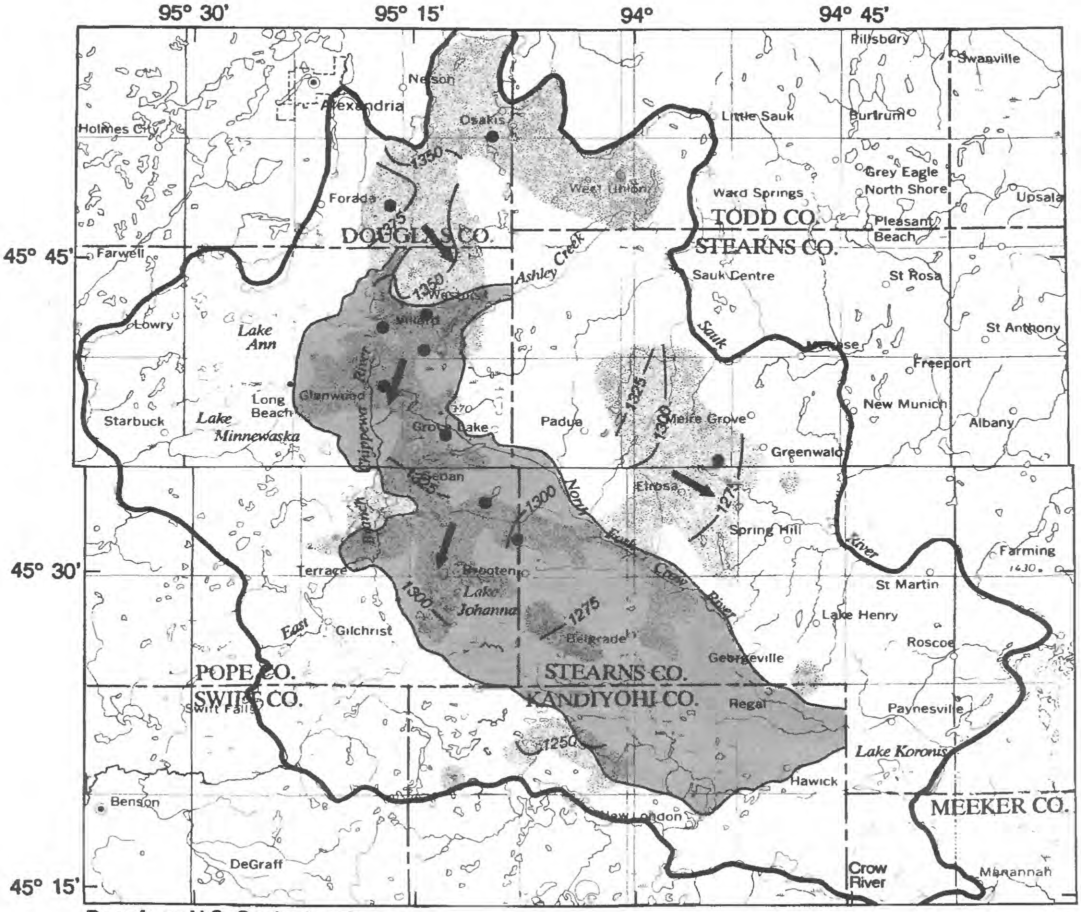
Known areal extent of aquifers in zone B

Hydrologic boundary of study area

— *1800* — Line of equal transmissivity. *Interval variable, in feet squared per day.*

• Transmissivity data point derived from specific-capacity or aquifer-test data

Figure III-8.--Transmissivity of aquifers in zone B



Base from U.S. Geological Survey
State base map, 1:500,000, 1965.

SCALE

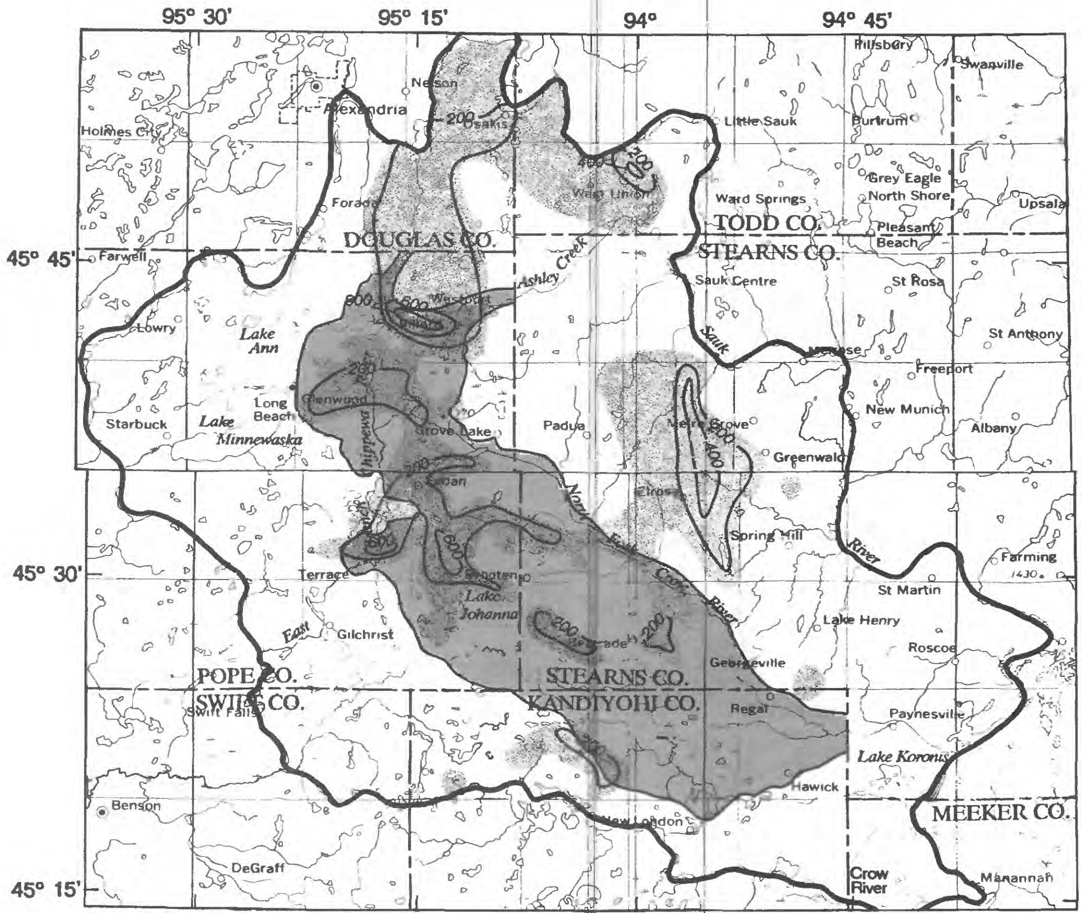
0 10 20 MILES

0 10 20 KILOMETERS

EXPLANATION

- Brooten-Belgrade sand plain
- Known areal extent of aquifers in zone B
- Hydrologic boundary of study area
- —1250— Potentiometric contour. *Interval 25 feet. Datum is sea level.*
- Direction of ground-water flow
- U.S. Geological Survey measured water level

Figure III-9.--Potentiometric surface of aquifers in zone B, 1985



Base from U.S. Geological Survey
State base map, 1:500,000, 1965.

SCALE

0 10 20 MILES

0 10 20 KILOMETERS

EXPLANATION

Brooten-Belgrade sand plain

Known areal extent of aquifers in zone B

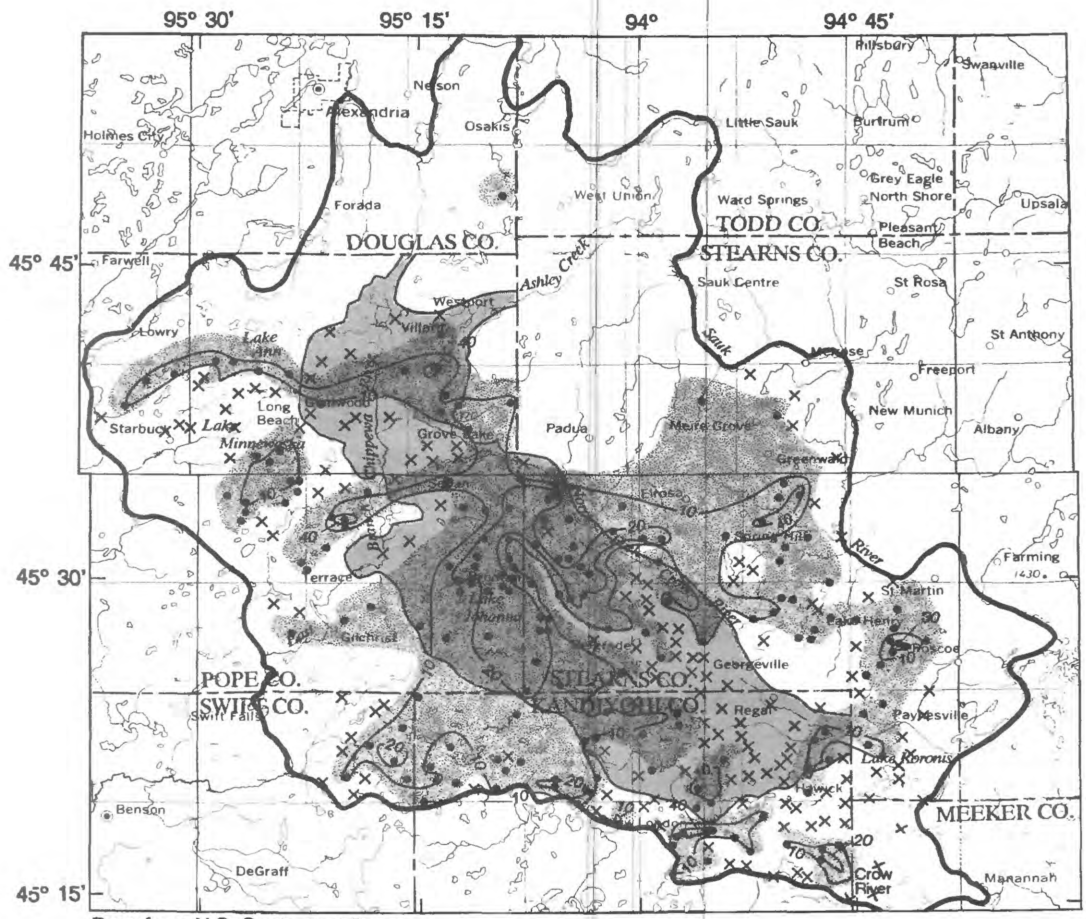
Hydrologic boundary of study area

—200— Line of equal theoretical maximum yield. *Assuming an efficient fully penetrating well with an arbitrary drawdown of 30 feet. Interval variable, in gallons per minute.*

Figure III-10.--Theoretical maximum yield of wells in aquifer zone B

APPENDIX III - ZONE C

THICKNESS OF AQUIFERS,
CONFIGURATION OF TOP OF AQUIFERS,
TRANSMISSIVITY OF AQUIFERS,
POTENTIOMETRIC SURFACE OF CONFINED AQUIFERS,
AND THEORETICAL MAXIMUM YIELD OF WELLS IN AQUIFER



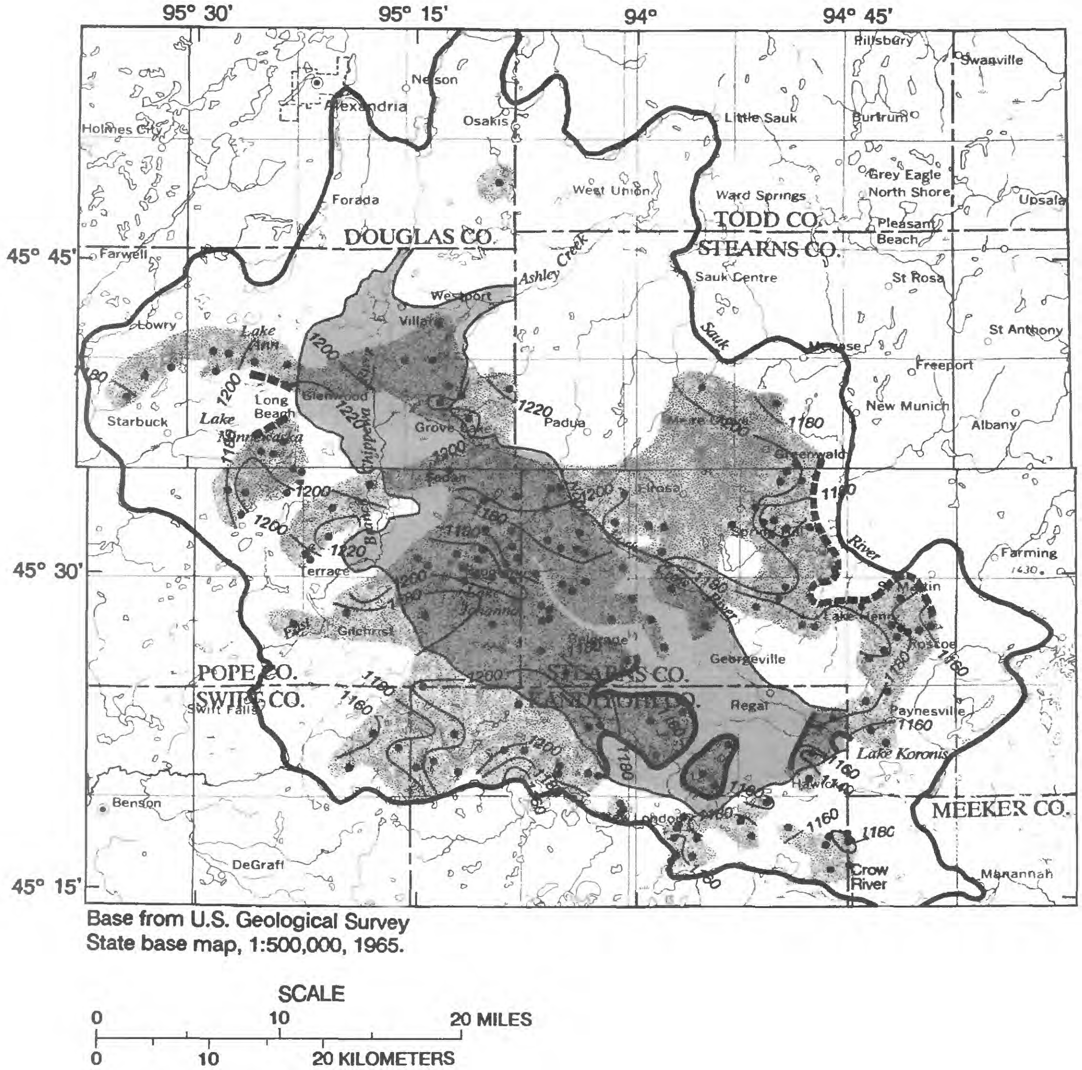
Base from U.S. Geological Survey
State base map, 1:500,000, 1965.

SCALE
0 10 20 MILES
0 10 20 KILOMETERS

EXPLANATION

- Brooten-Belgrade sand plain
- Known areal extent of aquifers in zone C
- Hydrologic boundary of study area
- —10— Line of equal thickness. *Interval 10, 20, and 30 feet.*
- • Well or test-hole location
- × Aquifer not present

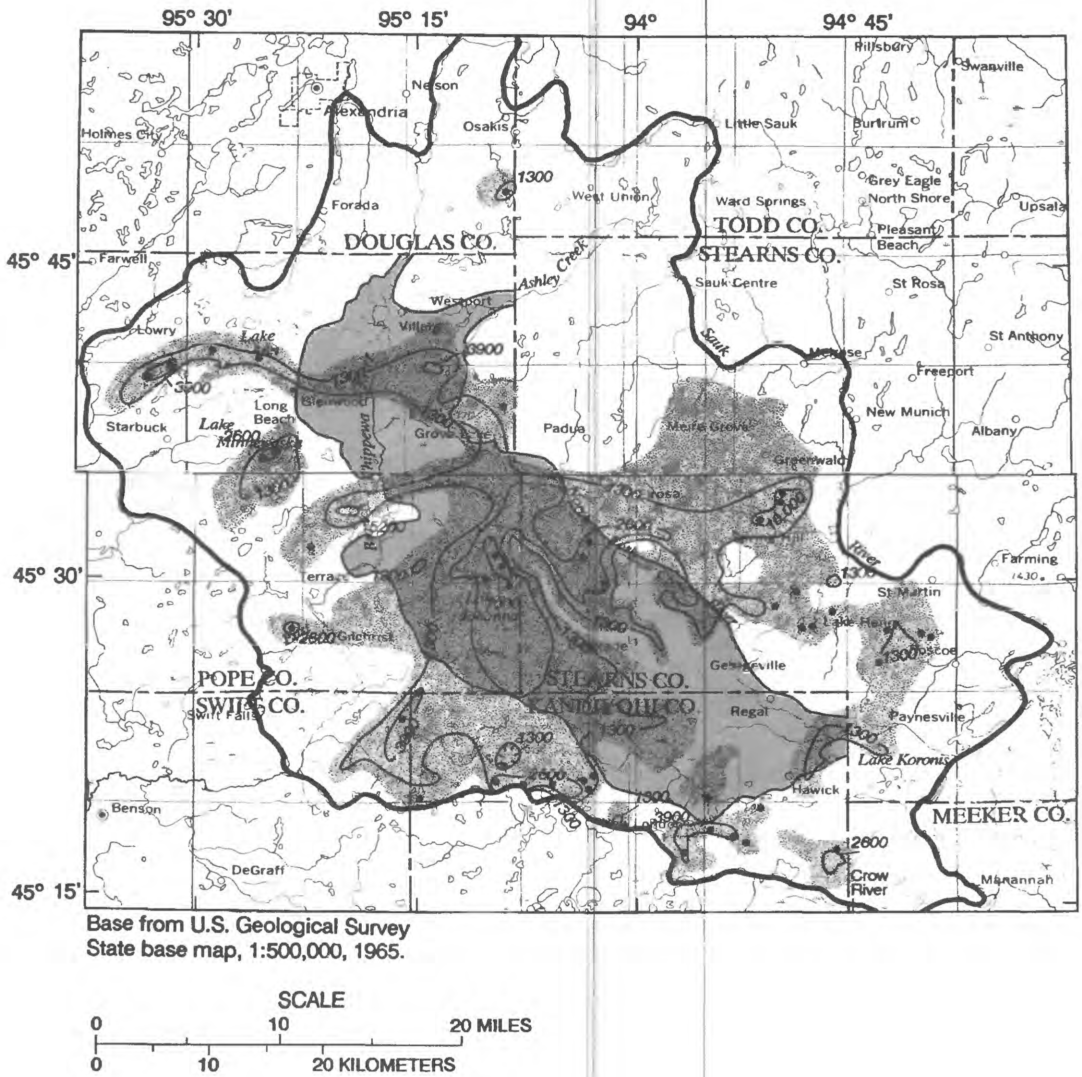
Figure III-11.--Thickness of aquifers in zone C



EXPLANATION

- Brooten-Belgrade sand plain
- Known areal extent of aquifers in zone C
- Hydrologic boundary of study area
- —1200— Structure contour. *Shows altitude of top of aquifer Interval 20 feet. Datum is sea level.*
- Boundary between an unconfined aquifer and confined aquifers in zone C, where they coalesce
- Possible location of springs from aquifers in zone C
- • Well or test-hole location

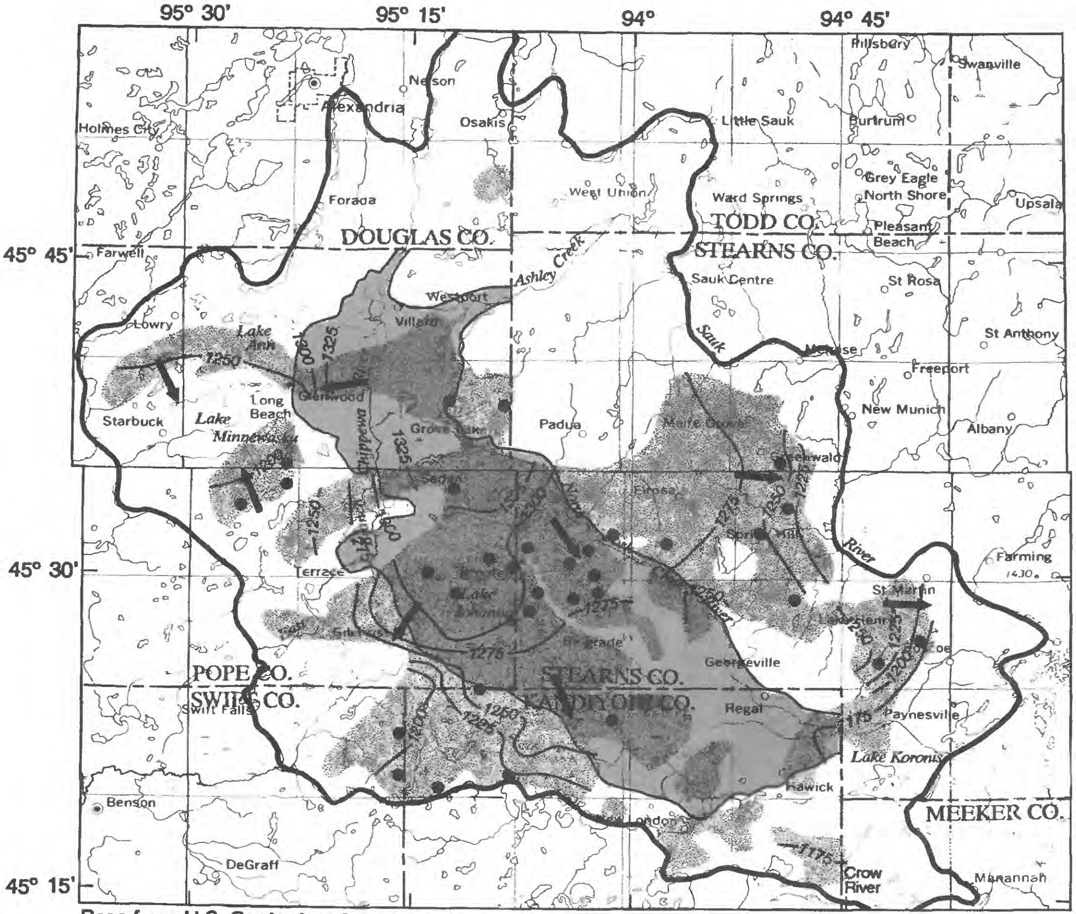
Figure III-12.--Configuration of top of aquifers in zone C



EXPLANATION

- Brooten-Belgrade sand plain
- Known areal extent of aquifers in zone C
- Hydrologic boundary of study area
- —1300— Line of equal transmissivity. *Interval variable, in feet squared per day.*
- • Transmissivity data point derived from specific-capacity or aquifer-test data

Figure III-13.--Transmissivity of aquifers in zone C.



Base from U.S. Geological Survey
State base map, 1:500,000, 1965.

SCALE

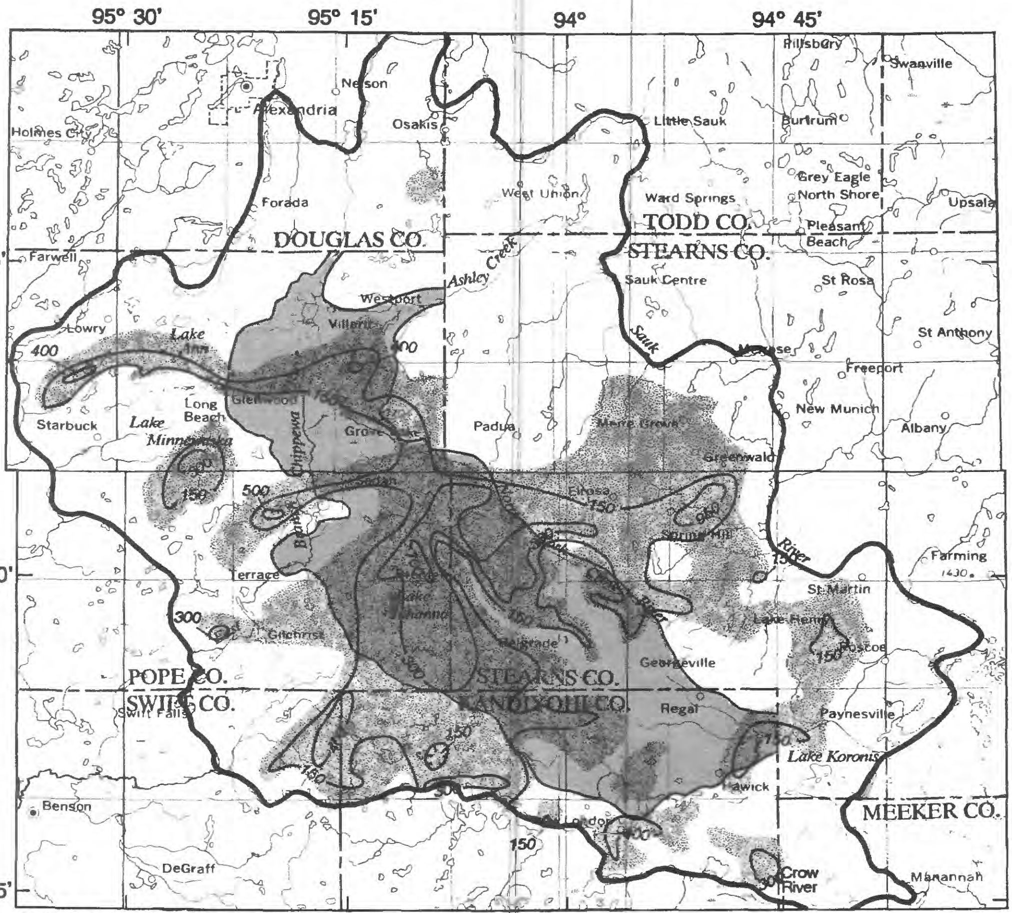
0 10 20 MILES

0 10 20 KILOMETERS

EXPLANATION

- Brooten-Belgrade sand plain
- Known areal extent of aquifers in zone C
- Hydrologic boundary of study area
- —1175— Potentiometric contour. *Interval 25 and 50 feet. Datum is sea level.*
- Direction of ground-water flow
- U.S. Geological Survey measured water level

Figure III-14.--Potentiometric surface of aquifers in zone C, 1985



Base from U.S. Geological Survey
State base map, 1:500,000, 1965.

SCALE

0 10 20 MILES

0 10 20 KILOMETERS

EXPLANATION

Brooten-Belgrade sand plain

Known areal extent of aquifers in zone C

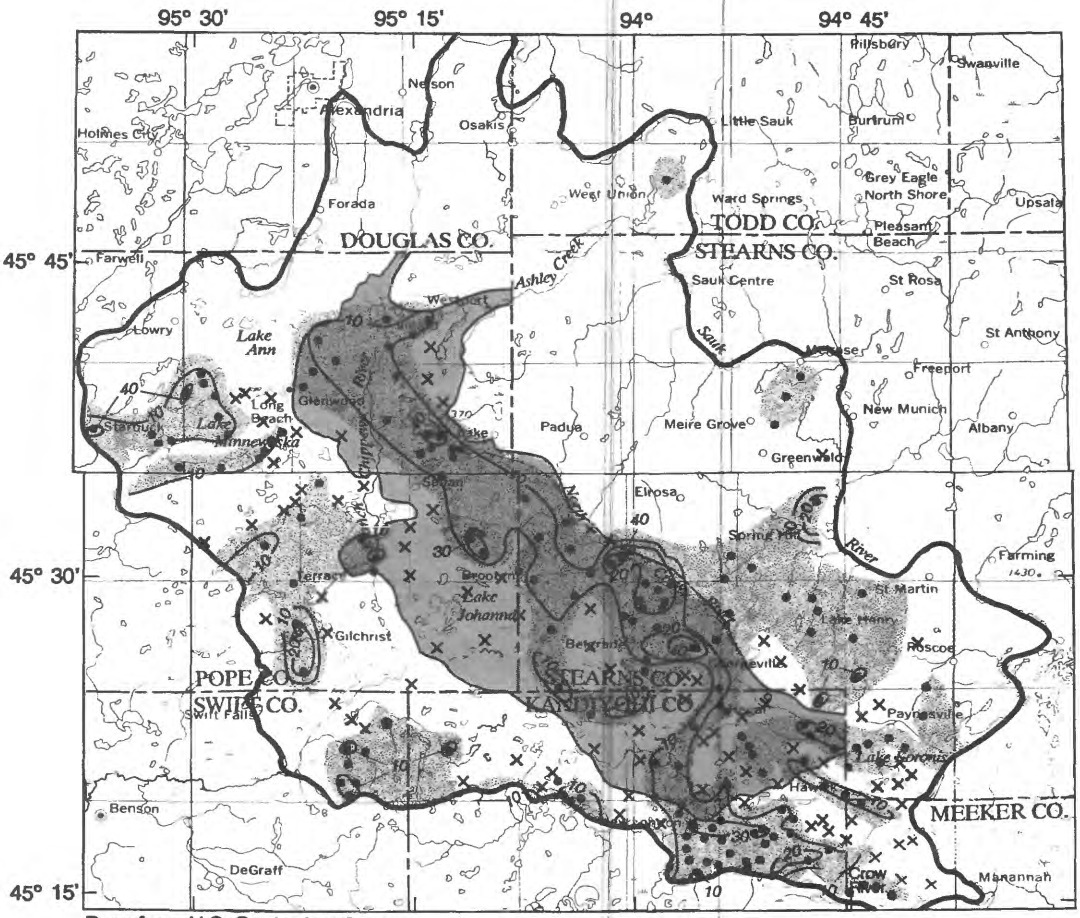
Hydrologic boundary of study area

—150— Line of equal theoretical maximum yield. *Assuming an efficient fully penetrating well with an arbitrary drawdown of 30 feet. Interval variable, in gallons per minute.*

Figure III-15.--Theoretical maximum yield of wells in aquifer zone C

APPENDIX III - ZONE D

THICKNESS OF AQUIFERS,
CONFIGURATION OF TOP OF AQUIFERS,
TRANSMISSIVITY OF AQUIFERS,
POTENTIOMETRIC SURFACE OF CONFINED AQUIFERS,
AND THEORETICAL MAXIMUM YIELD OF WELLS IN AQUIFER

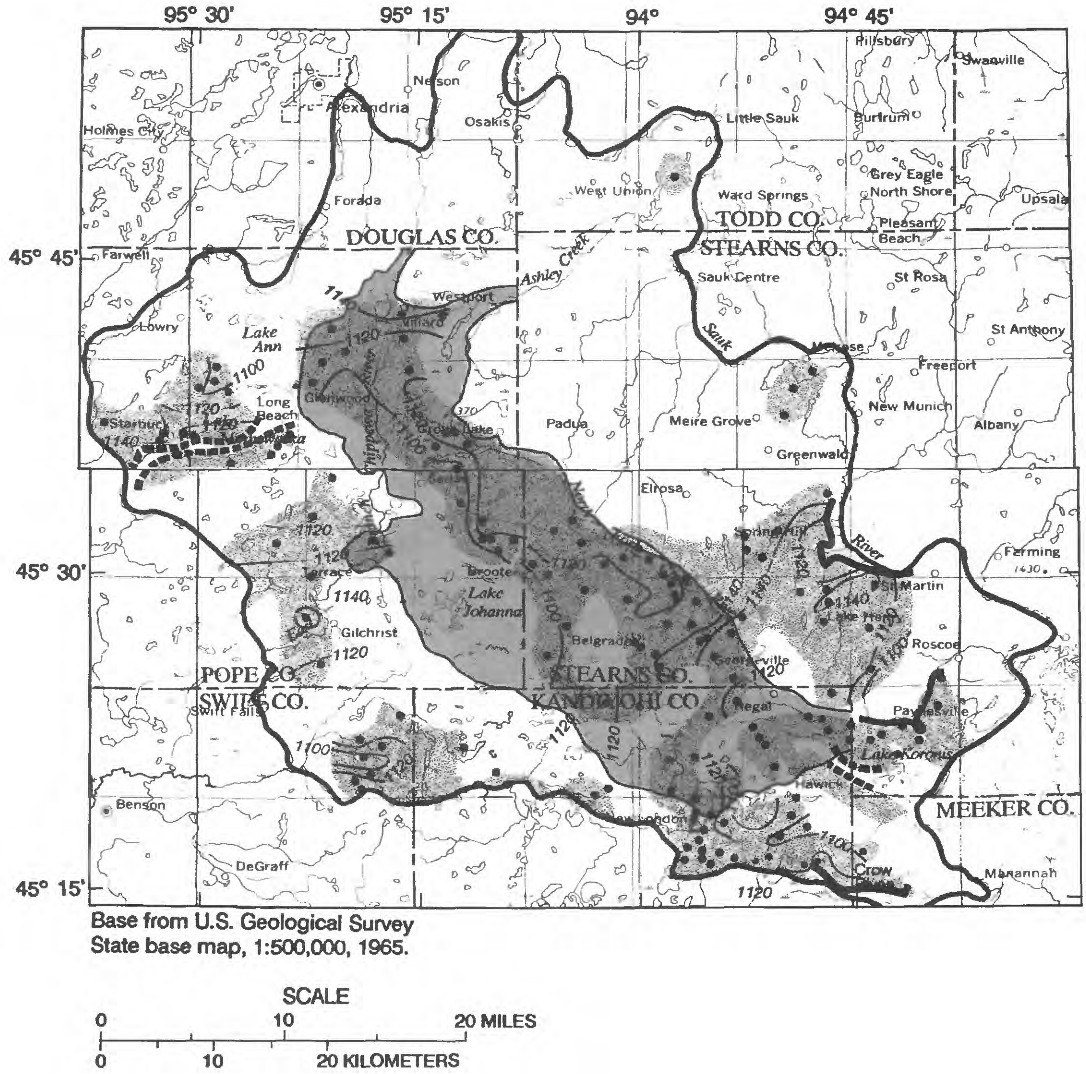


Base from U.S. Geological Survey
State base map, 1:500,000, 1965.

EXPLANATION

- Brooten-Belgrade sand plain
- Known areal extent of aquifers in zone D
- Hydrologic boundary of study area
- —10— Line of equal thickness. *Interval 10, 20, and 30 feet.*
- • Well or test-hole location
- × Aquifer not present

Figure III-16.--Thickness of aquifers in zone D



EXPLANATION

Brooten-Belgrade sand plain

Known areal extent of aquifers in zone D

Hydrologic boundary of study area

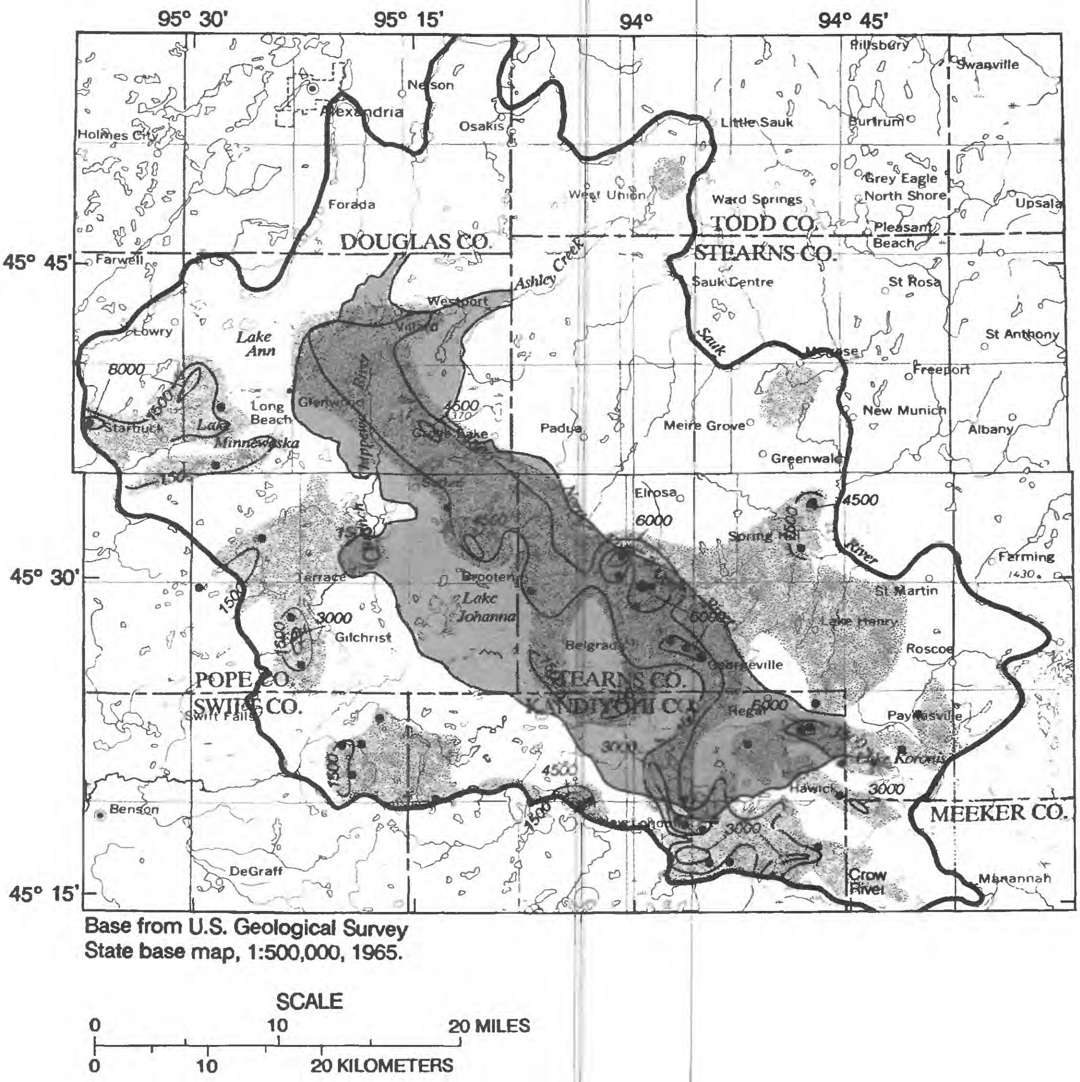
—1100— Structure contour. *Shows altitude of top of aquifer. Interval 20 feet. Datum is sea level.*

Boundary between an unconfined aquifer and confined aquifers in zone D, where they coalesce.

Boundary between aquifers in zone D and lake sediments, where they coalesce.

• Well or test-hole location

Figure III-17.--Configuration of top of aquifers in zone D



EXPLANATION

Brooten-Belgrade sand plain

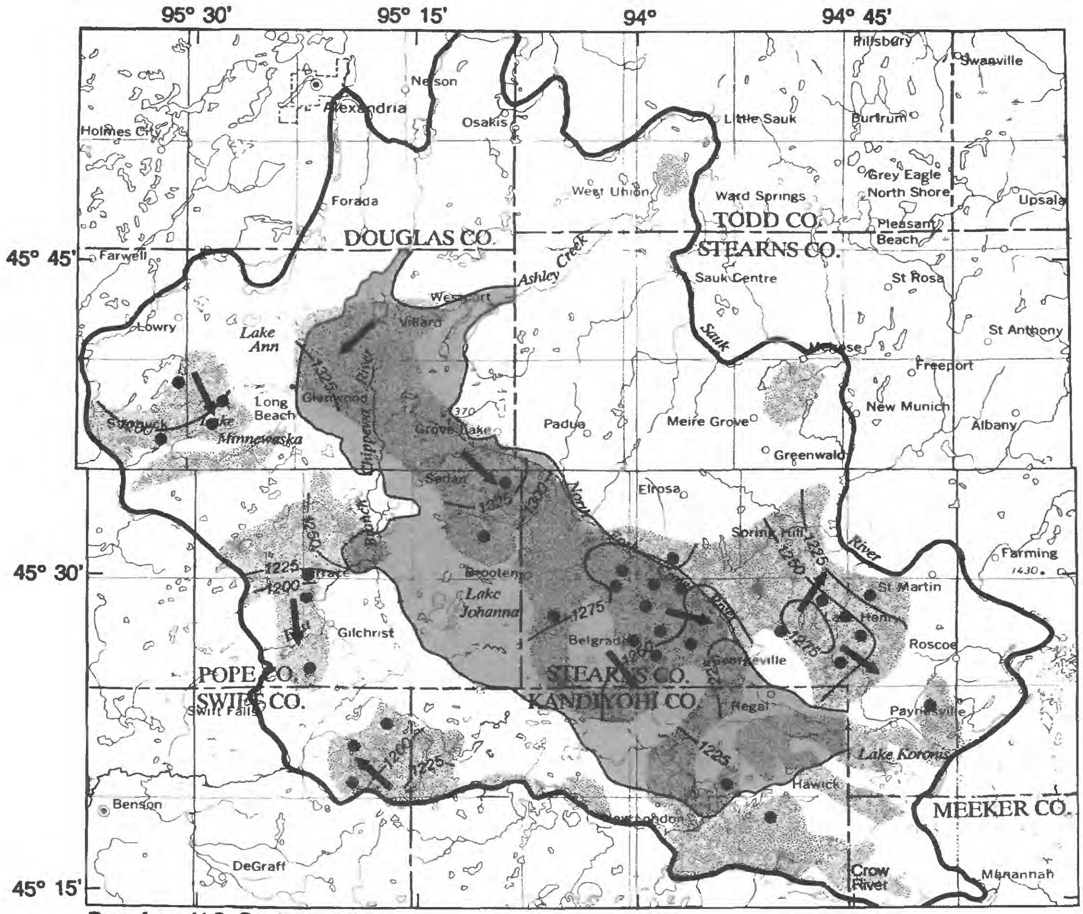
Known areal extent of aquifers in zone D

Hydrologic boundary of study area

—1500— Line of equal transmissivity. *Interval variable, in feet squared per day.*

• Transmissivity data point derived from specific-capacity or aquifer-test data

Figure III-18.--Transmissivity of aquifers in zone D



Base from U.S. Geological Survey
State base map, 1:500,000, 1965.

SCALE

0 10 20 MILES

0 10 20 KILOMETERS

EXPLANATION

Brooten-Belgrade sand plain

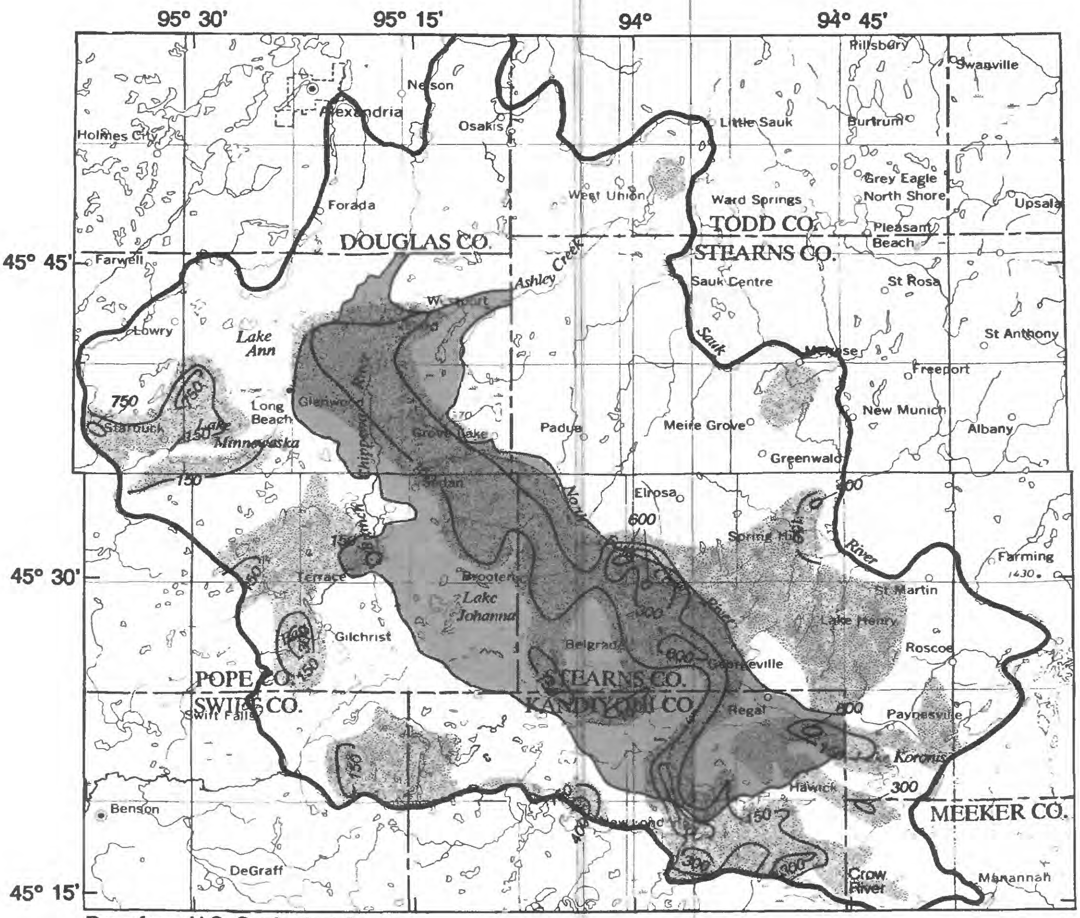
Known areal extent of aquifers in zone D

Hydrologic boundary of study area

—1200— Potentiometric contour. *Interval 25 feet Datum is sea level.*

Direction of ground-water flow

• U.S. Geological Survey measured water level



Base from U.S. Geological Survey
State base map, 1:500,000, 1965.

SCALE

0 10 20 MILES

0 10 20 KILOMETERS

EXPLANATION

Brooten-Belgrade sand plain

Known areal extent of aquifers in zone D

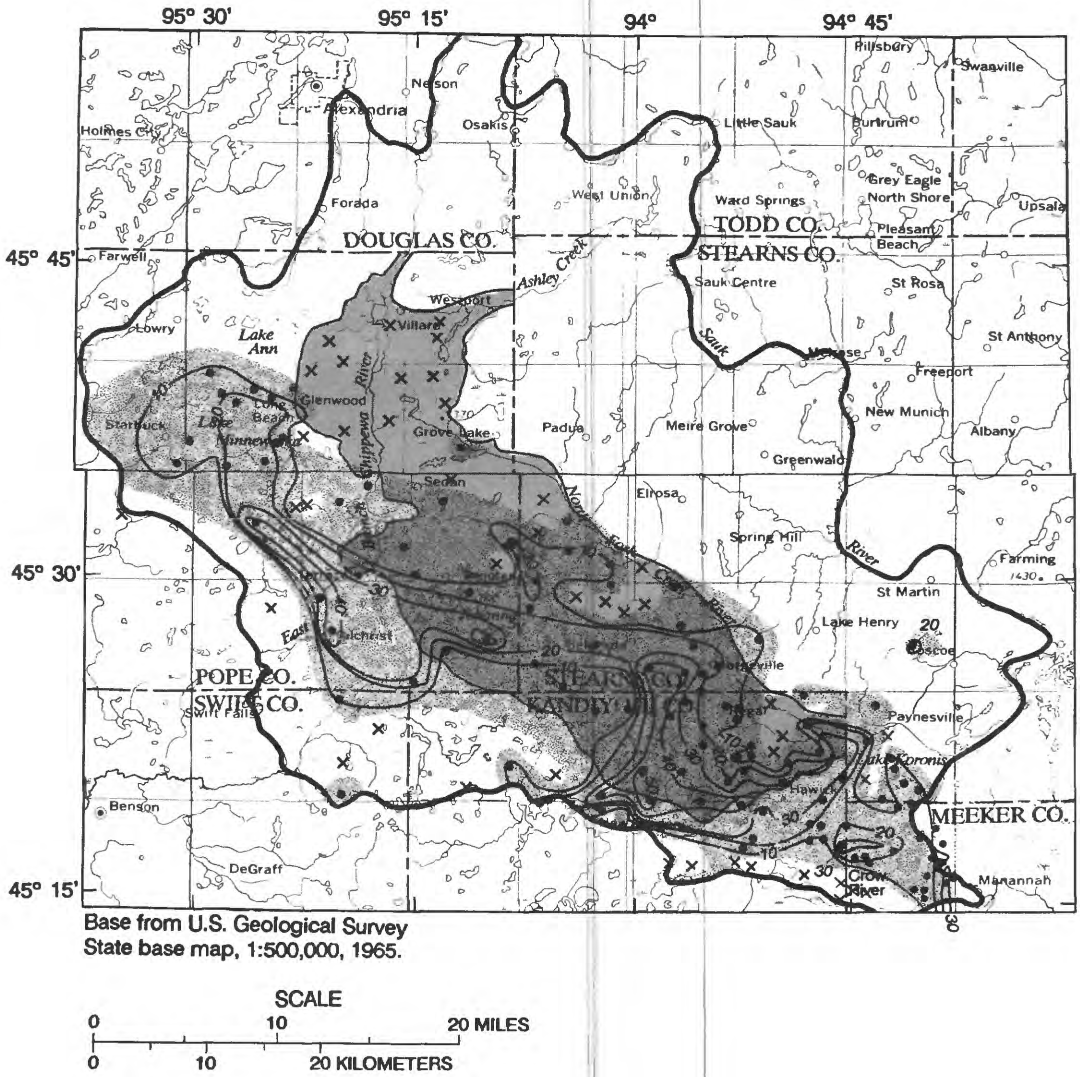
Hydrologic boundary of study area

—150— Line of equal theoretical maximum yield. *Assuming an efficient fully penetrating well with an arbitrary drawdown of 30 feet. Interval variable, in gallons per minute.*

Figure III-20.--Theoretical maximum yield of wells in aquifer zone D

APPENDIX III - ZONE E

THICKNESS OF AQUIFERS,
CONFIGURATION OF TOP OF AQUIFERS,
TRANSMISSIVITY OF AQUIFERS,
POTENTIOMETRIC SURFACE OF CONFINED AQUIFERS,
AND THEORETICAL MAXIMUM YIELD OF WELLS IN AQUIFER



EXPLANATION

Brooten-Belgrade sand plain

Known areal extent of aquifers in zone E

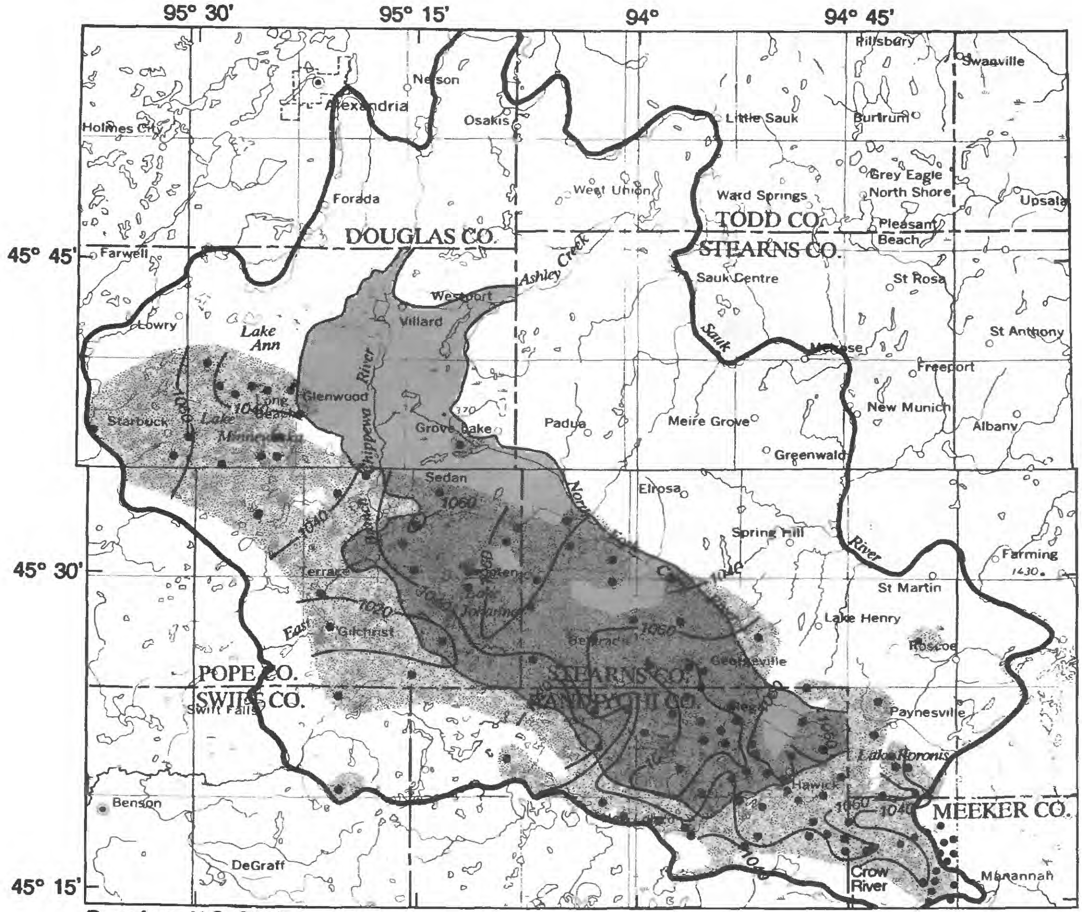
Hydrologic boundary of study area

—10— Line of equal thickness. *Interval 10 and 20 feet.*

• Well or test-hole location

× Aquifer not present

Figure III-21.--Thickness of aquifers in zone E



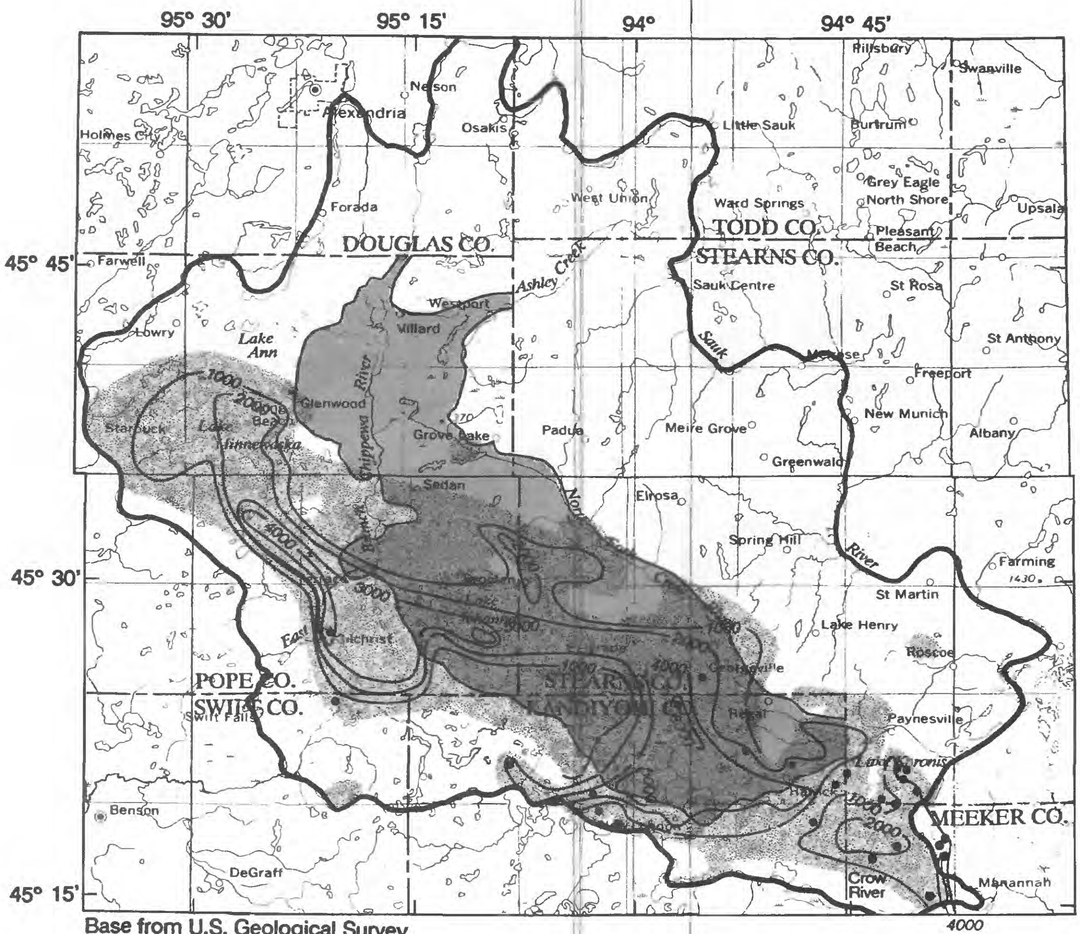
Base from U.S. Geological Survey
State base map, 1:500,000, 1965.

SCALE
0 10 20 MILES
0 10 20 KILOMETERS

EXPLANATION

- Brooten-Belgrade sand plain
- Known areal extent of aquifers in zone E
- Hydrologic boundary of study area
- —1020— Structure contour. *Shows altitude of top of aquifer. Interval 20 feet. Datum is sea level.*
- • Well or test-hole location

Figure III-22.--Configuration of top of aquifers in zone E



Base from U.S. Geological Survey
State base map, 1:500,000, 1965.

SCALE

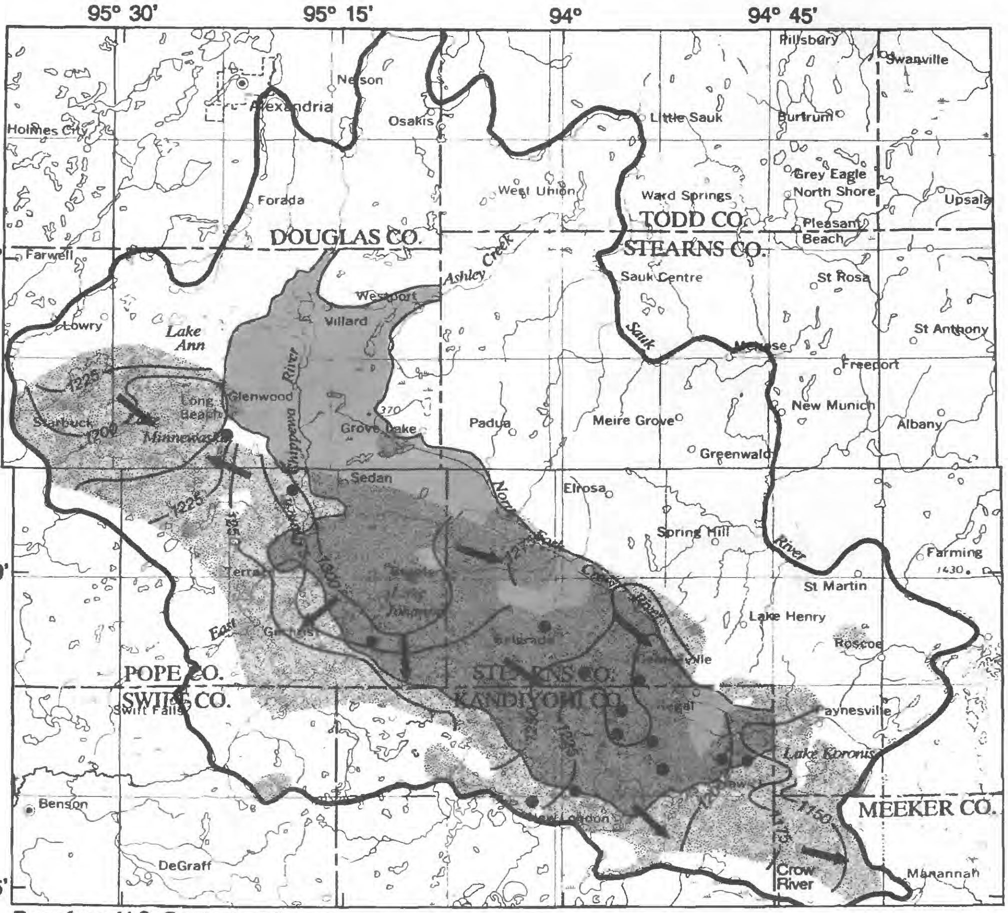
0 10 20 MILES

0 10 20 KILOMETERS

EXPLANATION

- Brooten-Belgrade sand plain
- Known areal extent of aquifers in zone E
- Hydrologic boundary of study area
- —1000— Line of equal transmissivity. *Interval variable, in feet squared per day.*
- • Transmissivity data point derived from specific-capacity or aquifer-test data

Figure III-23.--Transmissivity of aquifers in zone E



Base from U.S. Geological Survey
State base map, 1:500,000, 1965.

SCALE

0 — 10 — 20 MILES

0 — 10 — 20 KILOMETERS

EXPLANATION

Brooten-Belgrade sand plain

Known areal extent of aquifers in zone E

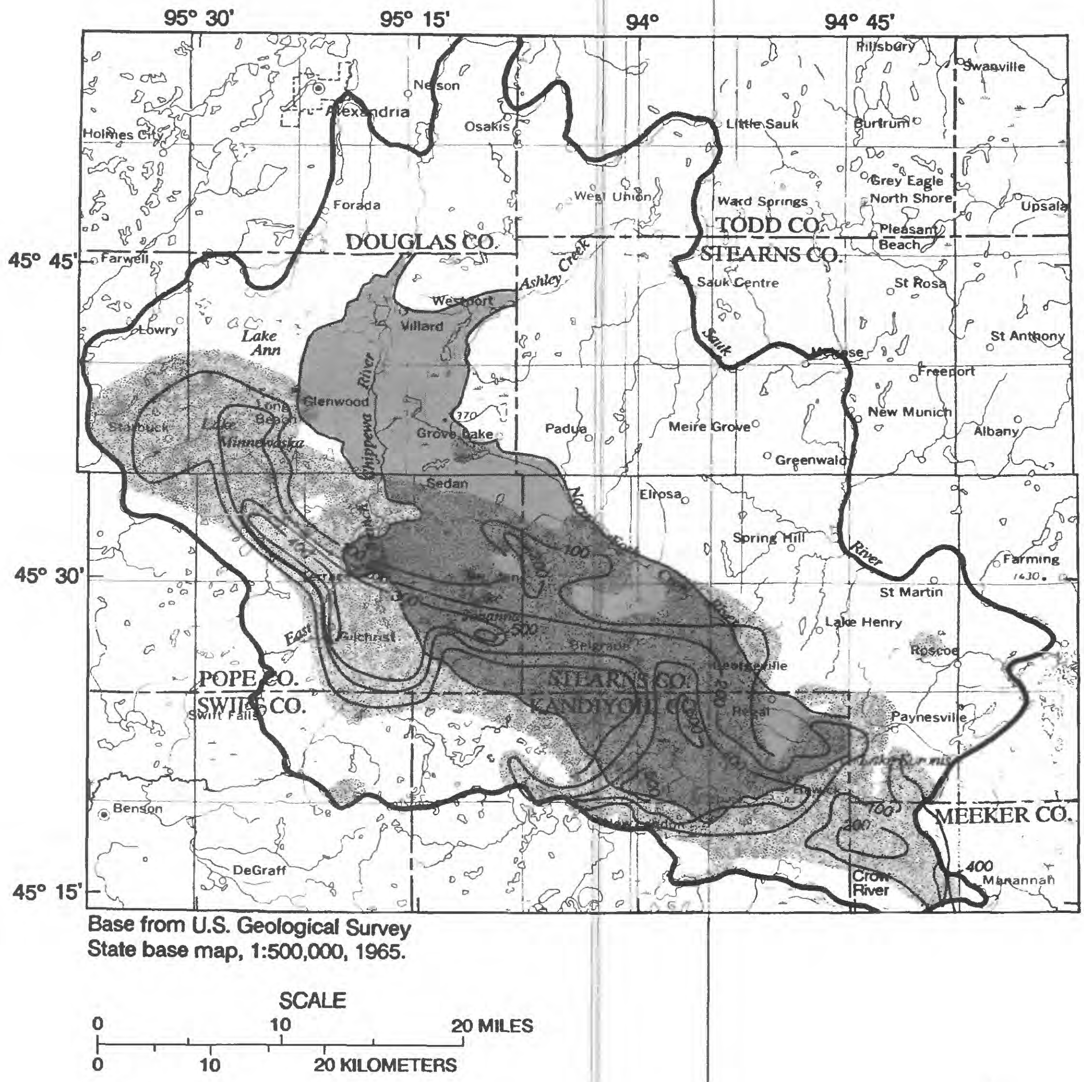
Hydrologic boundary of study area

—1150— Potentiometric contour. *Interval 25 feet Datum is sea level.*

Direction of ground-water flow

U.S. Geological Survey measured water level

Figure III-24.--Potentiometric surface of aquifers in zone E, 1985



EXPLANATION

Brooten-Belgrade sand plain

Known areal extent of aquifers in zone E

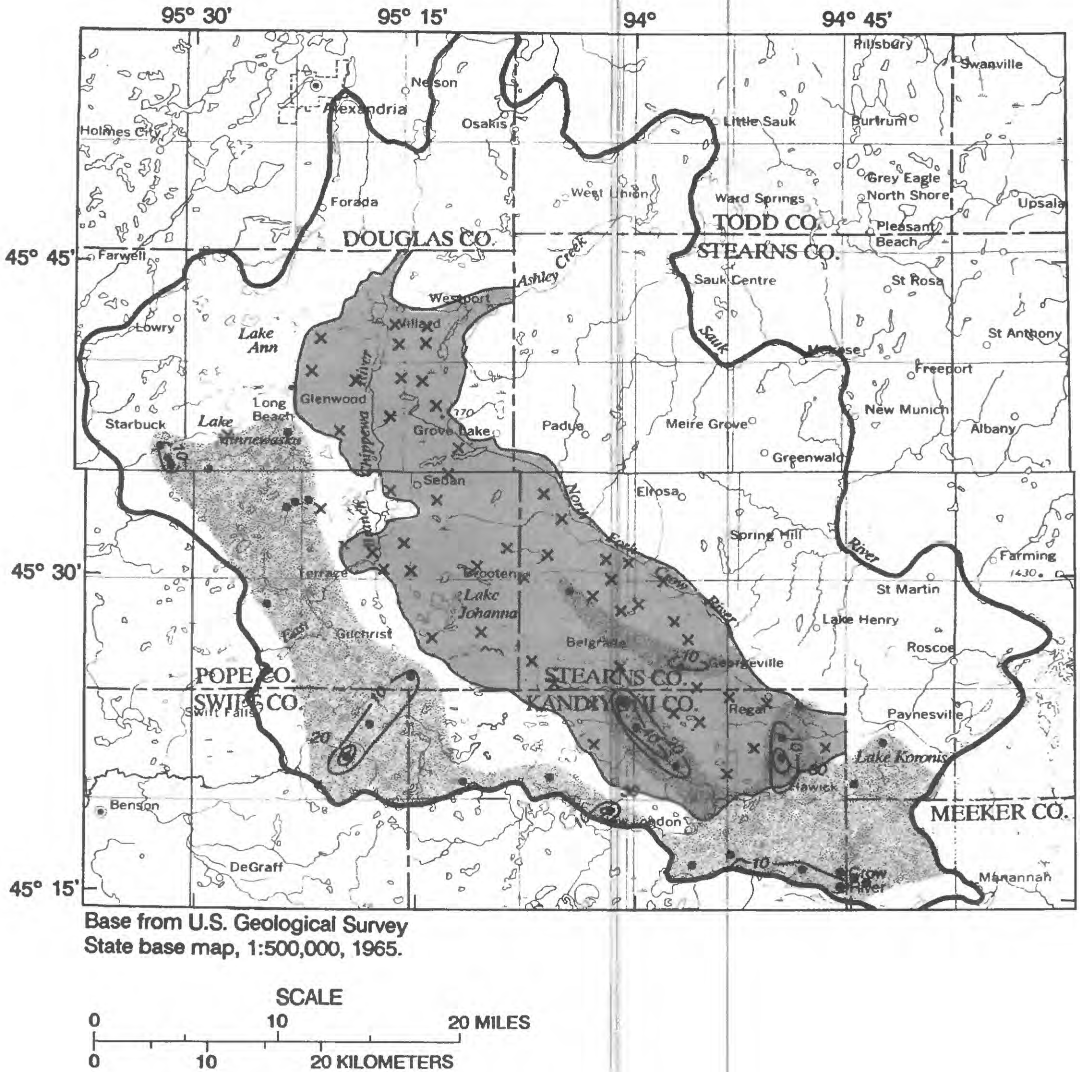
Hydrologic boundary of study area

—100— Line of equal theoretical maximum yield. *Assuming an efficient fully penetrating well with an arbitrary drawdown of 30 feet. Interval variable, in gallons per minute.*

Figure III-25.--Theoretical maximum yield of wells in aquifer zone E

APPENDIX III - ZONE F

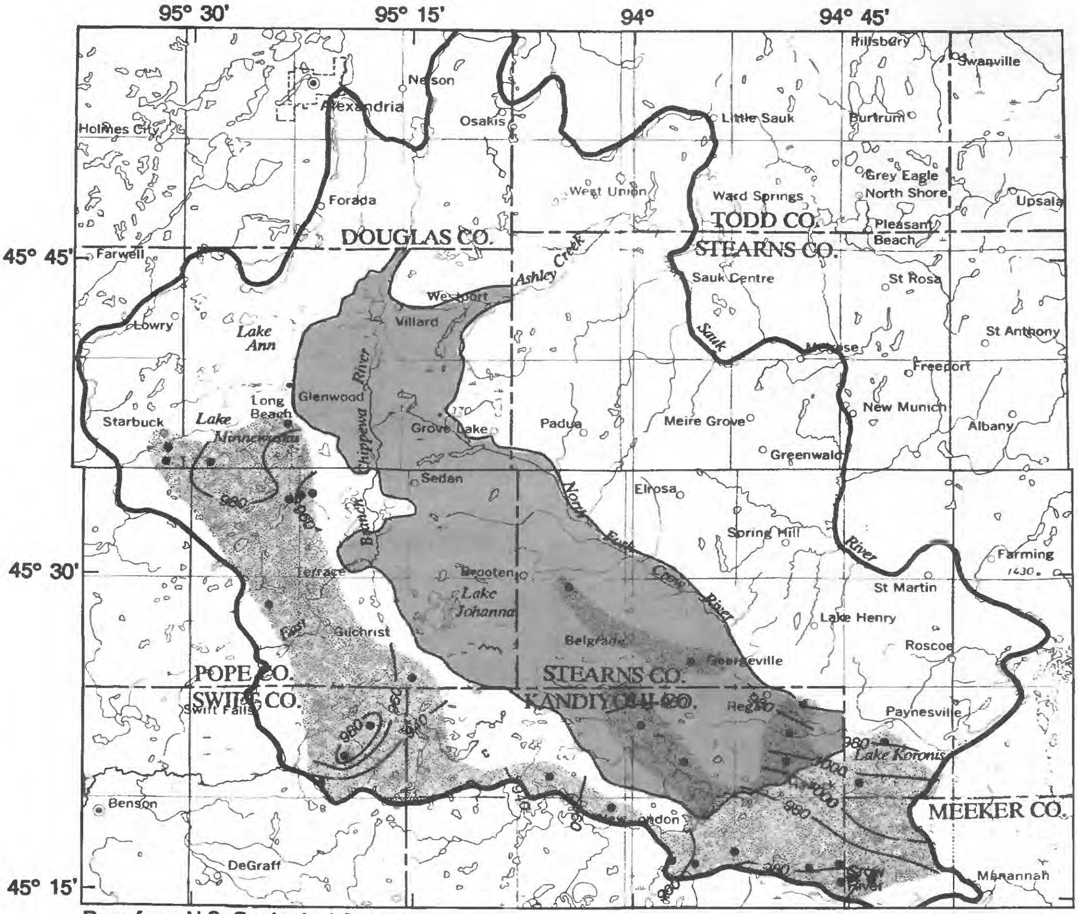
THICKNESS OF AQUIFERS,
CONFIGURATION OF TOP OF AQUIFERS,
TRANSMISSIVITY OF AQUIFERS,
POTENTIOMETRIC SURFACE OF CONFINED AQUIFERS,
AND THEORETICAL MAXIMUM YIELD OF WELLS IN AQUIFER



EXPLANATION

- Brooten-Belgrade sand plain
- Known areal extent of aquifers in zone F
- Hydrologic boundary of study area
- —10— Line of equal thickness. *Interval 10 and 20 feet.*
- • Well or test-hole location
- × Aquifer not present

Figure III-26.--Thickness of aquifers in zone F



Base from U.S. Geological Survey
State base map, 1:500,000, 1965.

SCALE

0 10 20 MILES

0 10 20 KILOMETERS

EXPLANATION

- Brooten-Belgrade sand plain
- Known areal extent of aquifers in zone F
- Hydrologic boundary of study area
- —940— Structure contour. *Shows altitude of top of aquifer. Interval 20 feet. Datum is sea level.*
- • Well or test-hole location

Figure III-27.--Configuration of top of aquifers in zone F

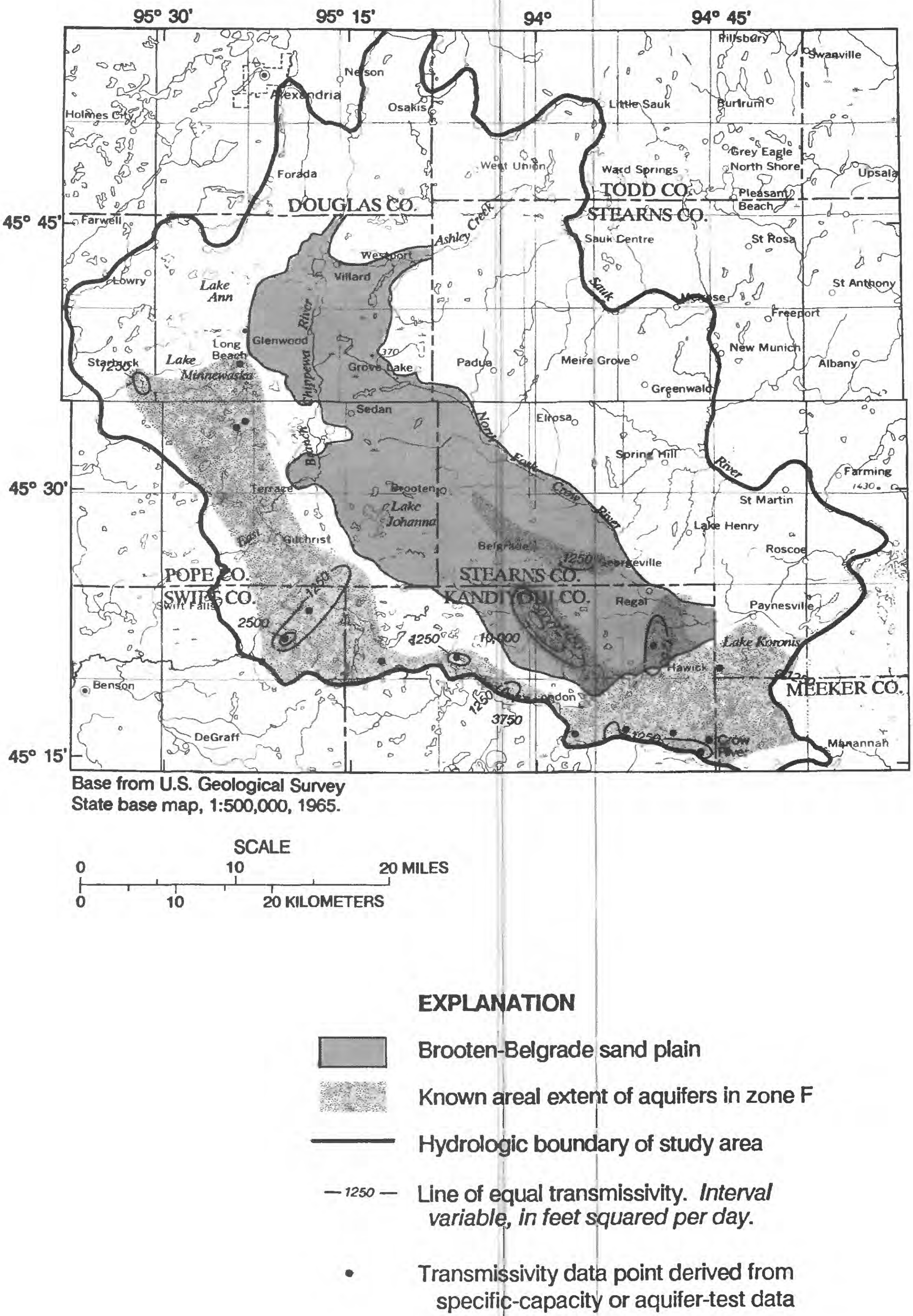
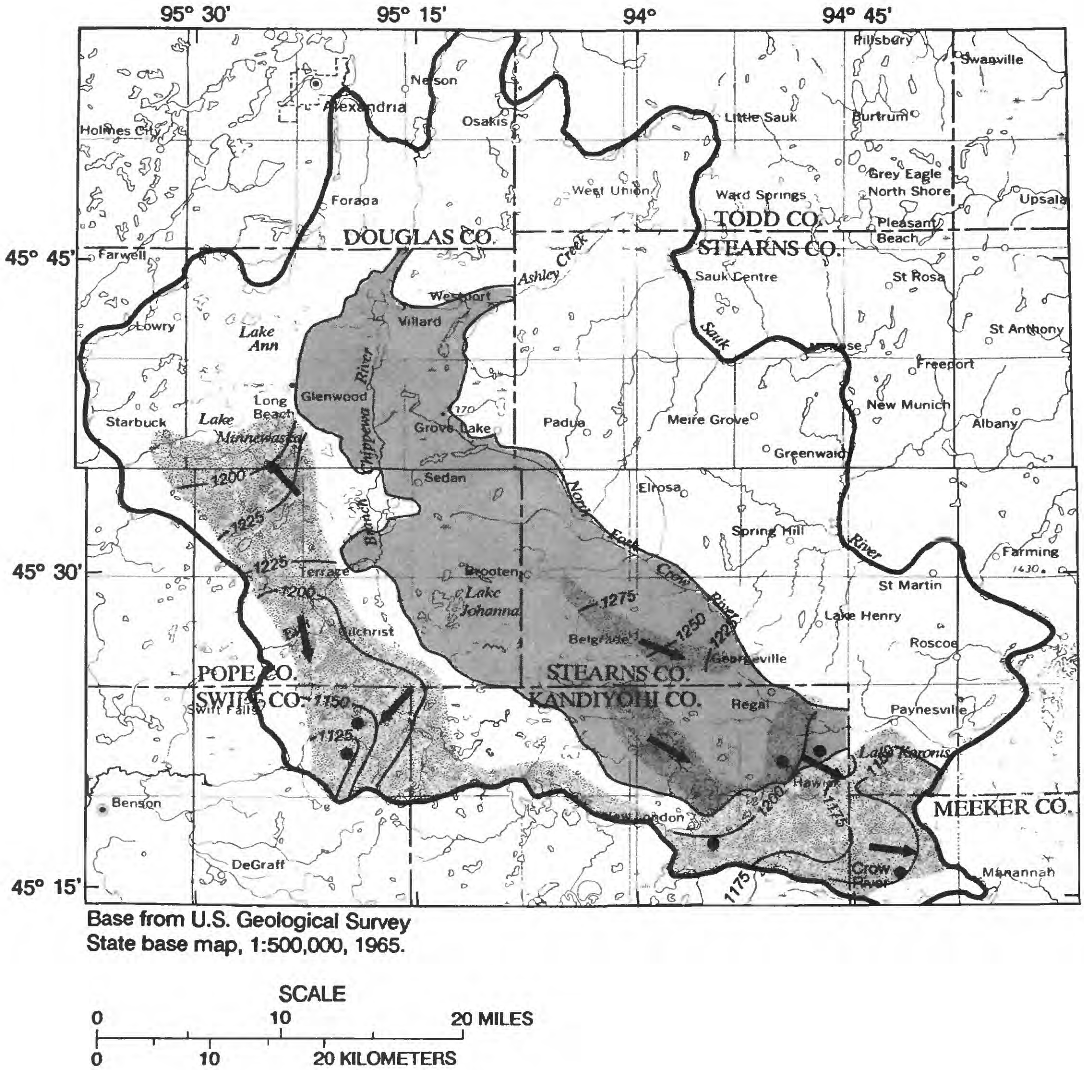


Figure III-28.--Transmissivity of aquifers in zone F



EXPLANATION

Brooten-Belgrade sand plain

Known areal extent of aquifers in zone F

Hydrologic boundary of study area

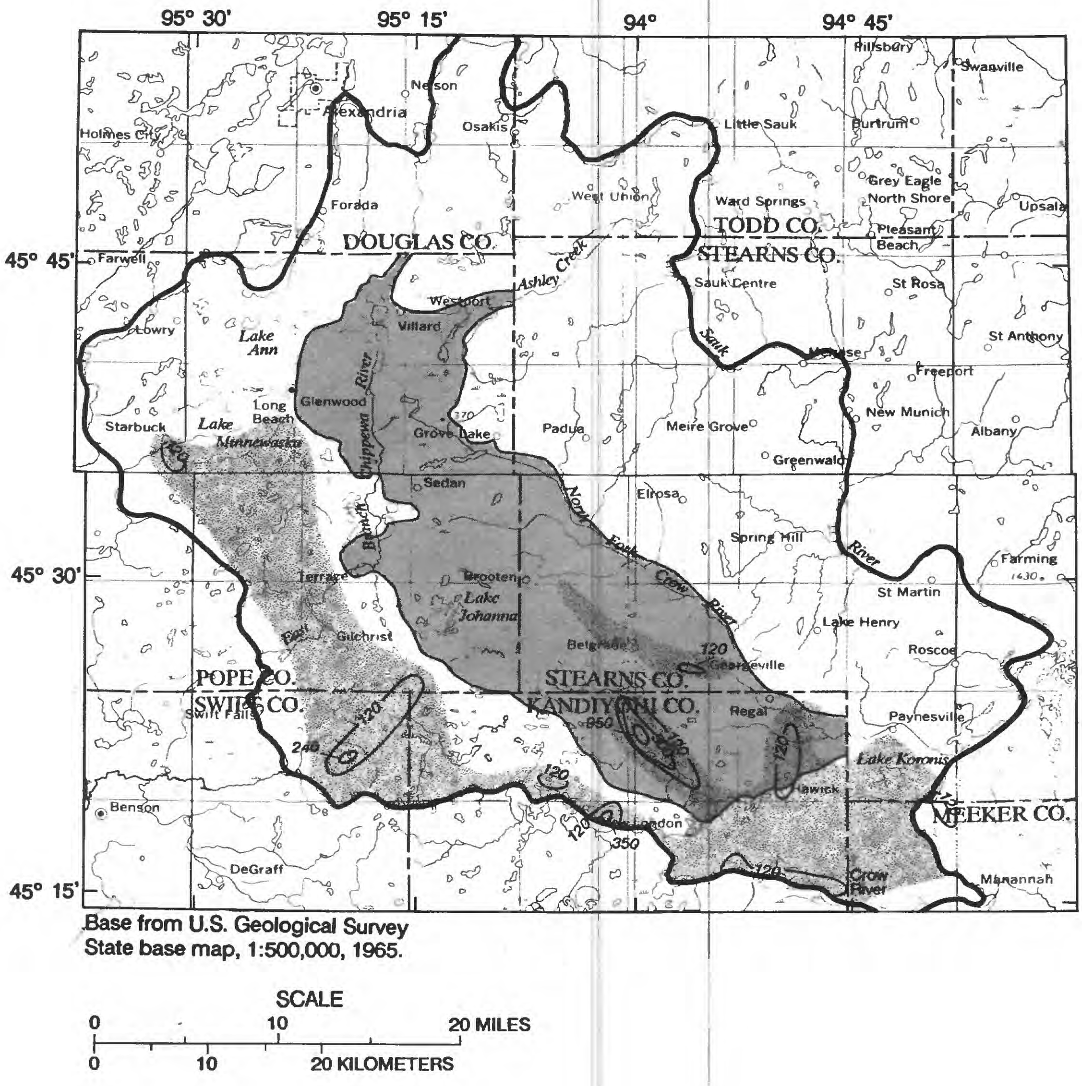
—1200— Potentiometric contour. *Interval 25 and 50 feet. Datum is sea level.*

Direction of ground-water flow

● U.S. Geological Survey measured water level

Figure III-29.--Potentiometric surface of aquifers in zone F, 1985

☆ U.S. Government Printing Office 1990 — 756-250/151



EXPLANATION

Brooten-Belgrade sand plain

Known areal extent of aquifers in zone F

Hydrologic boundary of study area

—120— Line of equal theoretical maximum yield. *Assuming an efficient fully penetrating well with an arbitrary drawdown of 30 feet. Interval variable, in gallons per minute.*

Figure III-30.--Theoretical maximum yield of wells in aquifer zone F