# Hydrogeologic Setting and the Potentiometric Surfaces of Regional Aquifers in the Hollandale Embayment, Southeastern Minnesota, 1970–80

By G. N. DELIN and D. G. WOODWARD

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## GLOSSARY

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

**Alluvium**—sedimentary material deposited by modern rivers, including sediments laid down in river beds, flood plains, and in-stream lakes.

**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.

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

**Drift**—all deposits resulting from glacial activity.

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

**Evapotranspiration**—water withdrawn by evaporation from water surfaces and moist soil and by transpiration from plants.

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

**Ground-water divide**—a ridge in the potentiometric surface from which ground water represented by that surface moves away in both directions.

**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 a rock to transmit water under pressure. It is the rate of flow of water at the prevailing kinematic viscosity passing through a unit section of area, measured at right angles to the direction of flow, under a unit hydraulic gradient.

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

**Karst**—a type of topography that is formed over limestone, dolomite, or gypsum by dissolution and that is characterized by closed depressions or sinkholes, caves, and underground drainage.

**Loess**—a sediment, commonly unstratified and unconsolidated, composed mainly of silt-size particles, ordinarily with accessory clay and sand, deposited primarily by the wind.

**Outwash**—sorted, stratified drift deposited beyond the ice front by melt-water streams.

**Paleozoic**—an era of geologic time that comprises the Cambrian, Ordovician, Silurian, Devonian, Mississippian, Pennsylvanian, and Permian systems; commonly thought to have occurred from 225 to 570 million years ago.

**Potentiometric surface**—a surface that represents the static head of water in an aquifer; defined by the levels to which water will rise in tightly cased wells from a given point in an aquifer.

**Proterozoic**—an eon of geologic time before the beginning of the Paleozoic; commonly thought to have occurred from 570 to 2,500 million years ago.

**Regression**—gradual retreat or contraction of a shallow sea resulting in the emergence of land formerly covered by water.

**Syncline**—a fold, the core of which contains stratigraphically younger rocks; it is concave upward.

**Synclinorium**—a composite synclinal structure of regional extent that is composed of lesser folds.

**Till**—unsorted, unstratified drift deposited directly on or underneath glacial ice.

**Transgression**—gradual advance or expansion of a shallow sea resulting in the progressive submergence of land below water.

**Tunnel valley**—a trench that was cut by a subglacial stream and whose present surface expression is typically an esker with adjacent elongate lakes.

**Valley fill**—drift or alluvium deposited in a valley eroded in the bedrock surface.

**Water table**—the potentiometric surface in an unconfined aquifer at which the pressure is atmospheric. It is defined by the levels at which water stands in tightly cased wells that penetrate the water body just far enough to hold standing water. In wells that penetrate to greater depths, the water level will stand above or below the water table if an upward or downward component of ground-water flow exists.

# HYDROGEOLOGIC SETTING AND THE POTENTIOMETRIC SURFACES OF REGIONAL AQUIFERS IN THE HOLLANDALE EMBAYMENT, SOUTHEASTERN MINNESOTA, 1970–80

By G. N. Delin and D. G. Woodward

## ABSTRACT

Sedimentary Paleozoic rocks in the Hollandale embayment in southeastern Minnesota are as thick as 2,000 ft. This sedimentary sequence, together with the Proterozoic Hinckley Sandstone and the Quaternary drift, is divided into six regional aquifers: undifferentiated drift, Upper Carbonate, St. Peter, Prairie du Chien-Jordan, Ironton-Galesville, and Mount Simon-Hinckley.

Potentiometric-surface maps for each aquifer indicate that movement of ground water is predominantly toward the major rivers. The St. Croix, Minnesota, and Mississippi Rivers constitute regional discharge boundaries for ground-water flow. A major ground-water divide in the St. Peter, Prairie du Chien-Jordan, Ironton-Galesville, and Mount Simon-Hinckley aquifers in the south-central part of the Hollandale embayment separates ground-water flow northward toward the Twin Cities area and southward toward Iowa. The St. Peter and Prairie du Chien-Jordan aquifers in the southeastern part of the embayment contain ground-water mounds as high as 90 ft above the regional potentiometric surface. The mounds occur as a result of increased recharge where the Decorah-Platteville-Glenwood confining bed has been removed by erosion and the aquifers subcrop beneath drift that is about 20 ft thick. This head distribution produces a locally complex pattern of flow in which ground water moves southwesterly toward Iowa instead of directly toward the Mississippi River.

# 1.0 INTRODUCTION

## *1.1 Purpose and Scope*

### Report Prepared as Part of Nationwide Study of Major Aquifer Systems

Hydrogeologic setting and generalized potentiometric surfaces of regional aquifers in southeastern Minnesota are described

This report on southeastern Minnesota was prepared as part of a major investigation by the U.S. Geological Survey of regional aquifer systems in the United States. Each aquifer study is designed to provide quantitative information on ground water for use in developing and managing water supplies. The Northern Midwest Regional Aquifer-System Analysis (RASA) project, of which this is an integral part, consists of investigations of ground water in rocks of Cambrian and Ordovician age in parts of six states: Indiana, Illinois, Iowa, Minnesota, Missouri, and Wisconsin (Steinhilber and Young, 1979).

This report describes the hydrogeologic setting and the generalized potentiometric surface of regional aquifers in southeastern Minnesota. Basic structural and historical geology that relates to these aquifers is presented. Aquifers and confining beds are identified and are delineated on maps that show the relationship between the occurrence of aquifers and confining beds. Maps showing the generalized potentiometric surface of these aquifers for 1970–80 are included, along with sections showing potentiometric profiles. Municipal pumpage constitutes the most significant ground-water use in southeastern Minnesota, and municipalities that derive water supplies from wells in an aquifer are indicated on the appropriate potentiometric maps. The regional movement of ground water in each aquifer is also described.

The area studied for this report contains all or parts of 37 counties in southeastern Minnesota; it covers 17,200 $mi^2$ and includes the Twin Cities (Minneapolis-St. Paul) metropolitan area, hereinafter also called the Twin Cities area (fig. 1.1-1). The area is defined on the north and west by the subcrop of the Hinckley Sandstone of Proterozoic age, on the east by the Mississippi and St. Croix Rivers, and on the south by the Iowa border.

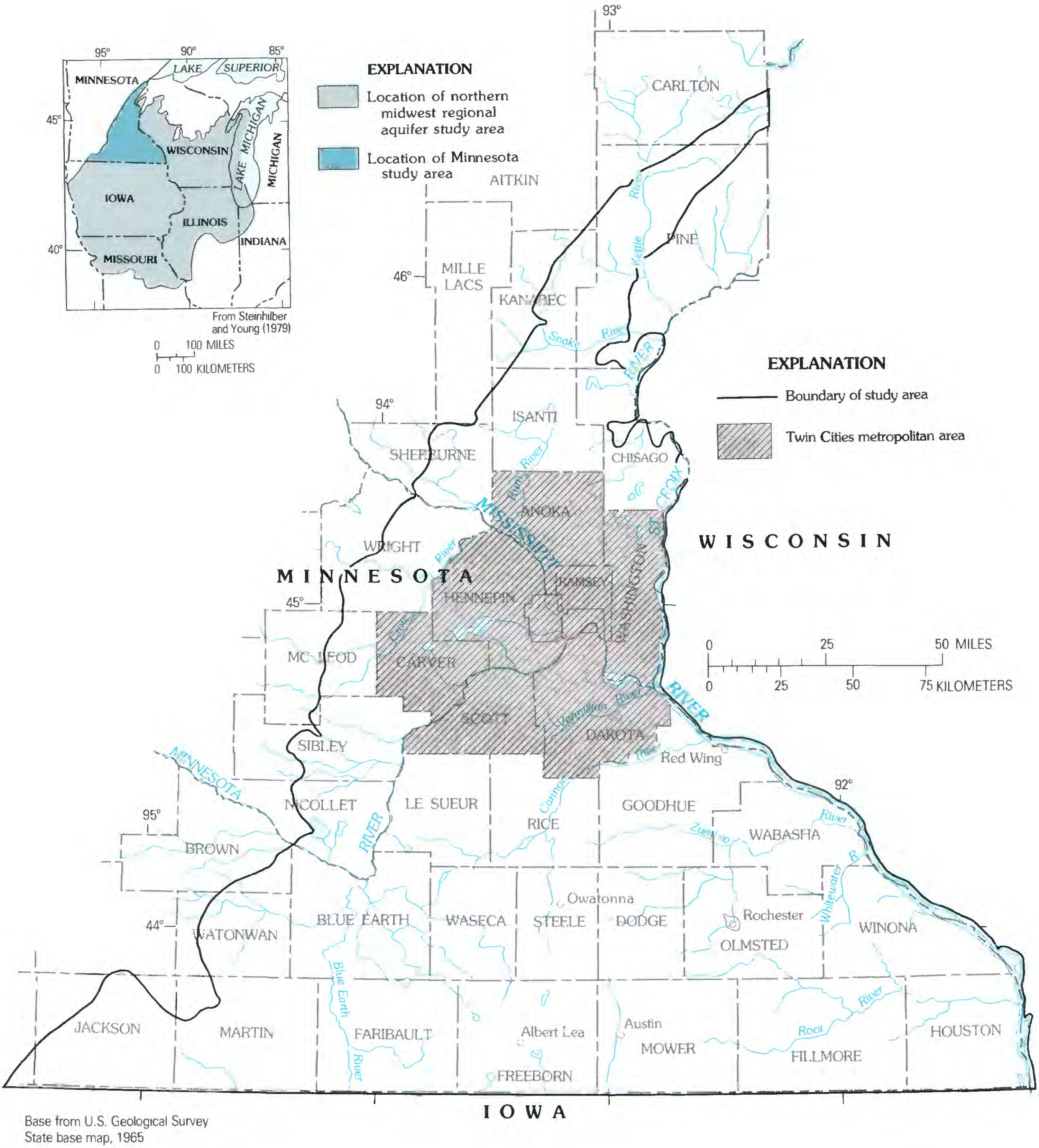



**Figure 1.1-1.** Location of study area

*1.2 Previous Investigations*

# Previous Investigations Have Described the Potentiometric Surfaces of Some Regional Aquifers in Parts of Southeastern Minnesota

The most comprehensive potentiometric mapping was done in the Twin Cities metropolitan area

Potentiometric maps have been constructed previously for some aquifers in parts of the study area. In the Twin Cities area, potentiometric maps have been prepared by the Minnesota Division of Waters (1961) and by Reeder (1966) for the Prairie du Chien-Jordan and Mount Simon-Hinckley aquifers; by Norvitch and others (1973) for the St. Peter, Prairie du Chien-Jordan, and Mount Simon-Hinckley aquifers; and by Larson-Higdem and others (1975) for the undifferentiated drift aquifer. U.S. Geological Survey Hydrologic Investigations Atlases present and describe the potentiometric surfaces of selected aquifers by watershed; atlases relevant to this study are listed with the references.

The potentiometric maps in this report are based, in part, on water levels measured in observation wells located in the study area. The U.S. Geological Survey, in cooperation with the Minnesota Department of Natural Resources, maintains two observation-well networks for monitoring ground-water levels in the State. The first, a network in the Twin Cities area, consists of more than 400 wells. Water-level data from these wells were collected in summer and winter 1965, 1971, 1976–77, and 1980; only the winter 1980 data were used in this report. The other network, which is statewide, has 165 observation wells in the study area (fig. 1.2-1). Frequency of water-level measurements in this network varies from continual (hourly) to four times per year. Most of the water levels are measured bimonthly with a steel tape. Water-level data from 1970 to 1980 for these wells were analyzed for this study.

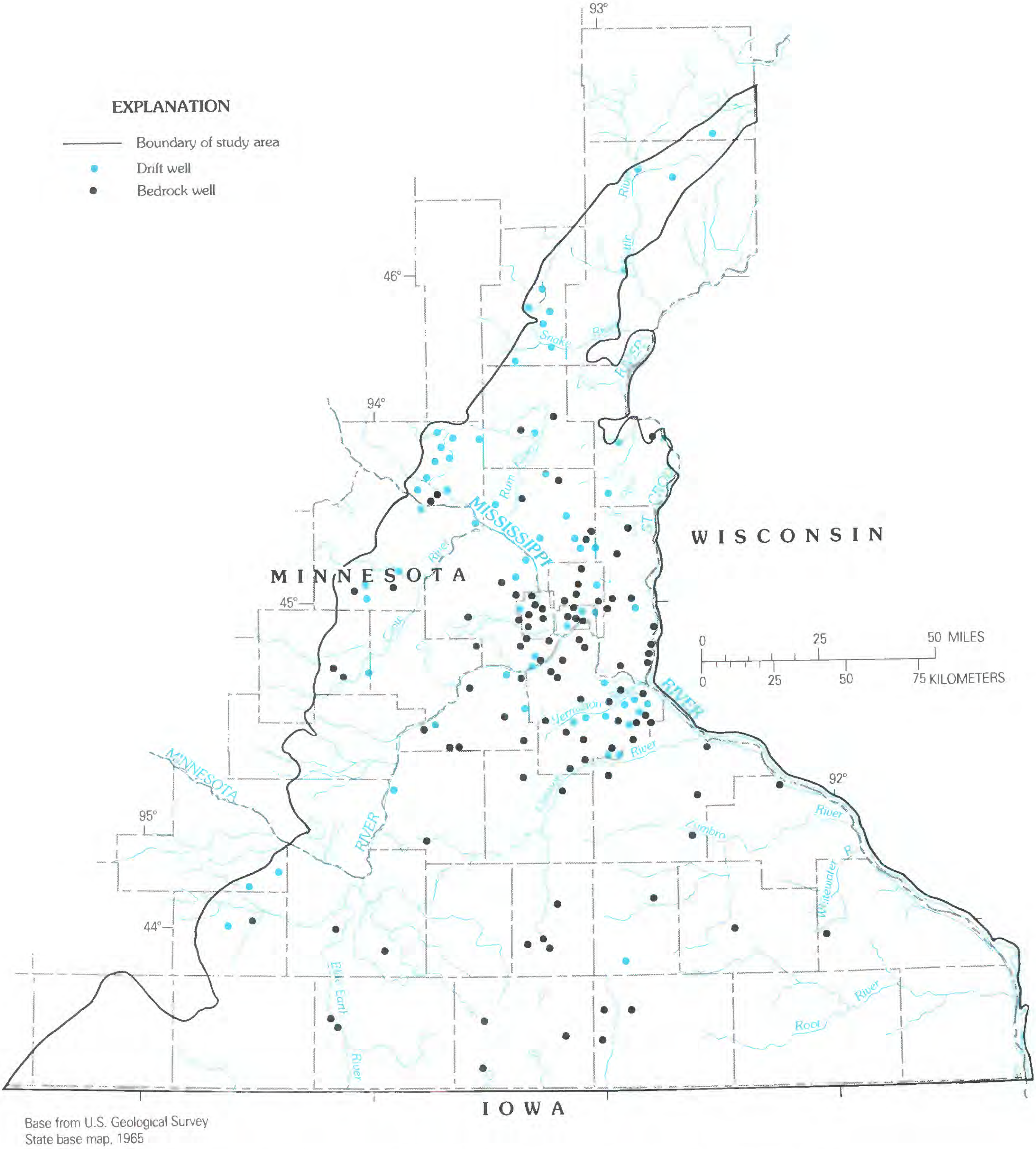



**Figure 1.2-1.** Location of observation wells in statewide monitoring network, 1981.

# Water-Level Data Were Obtained from Measurements in Observation Wells and from Drillers' Logs

Winter water levels used to minimize effects of seasonal pumpage

Water-level data were collected to prepare potentiometric maps for each regional aquifer in southeastern Minnesota. These data were obtained either by the direct measurement of water levels in observation wells or by the compilation of water levels recorded on well logs by drillers. Water levels measured in winter were used as much as possible to characterize the potentiometric surface for 1970–80, which minimizes seasonal effects of summer pumpage.

Ground-water withdrawals from the Prairie du Chien-Jordan and the Mount Simon-Hinckley aquifers in summer produce seasonal water-level declines of as much as 100 ft in the Twin Cities area (fig. 1.3-1). Therefore, water levels used to prepare the potentiometric maps for these aquifers in the Twin Cities area were measured in Twin Cities area network observation wells during February 1980. Accuracy for the altitudes of these water levels is ±5 ft.

Water levels monitored in the statewide observation-well network outside the Twin Cities area generally fluctuated through a range of about 5 to 10 ft during 1970–80 (fig. 1.3-2). Although exceptions to this generality may have occurred near large municipalities such as Rochester, Red Wing, Mankato, and Faribault, water levels measured on any date during 1970–80 were considered to be representative of these localities.

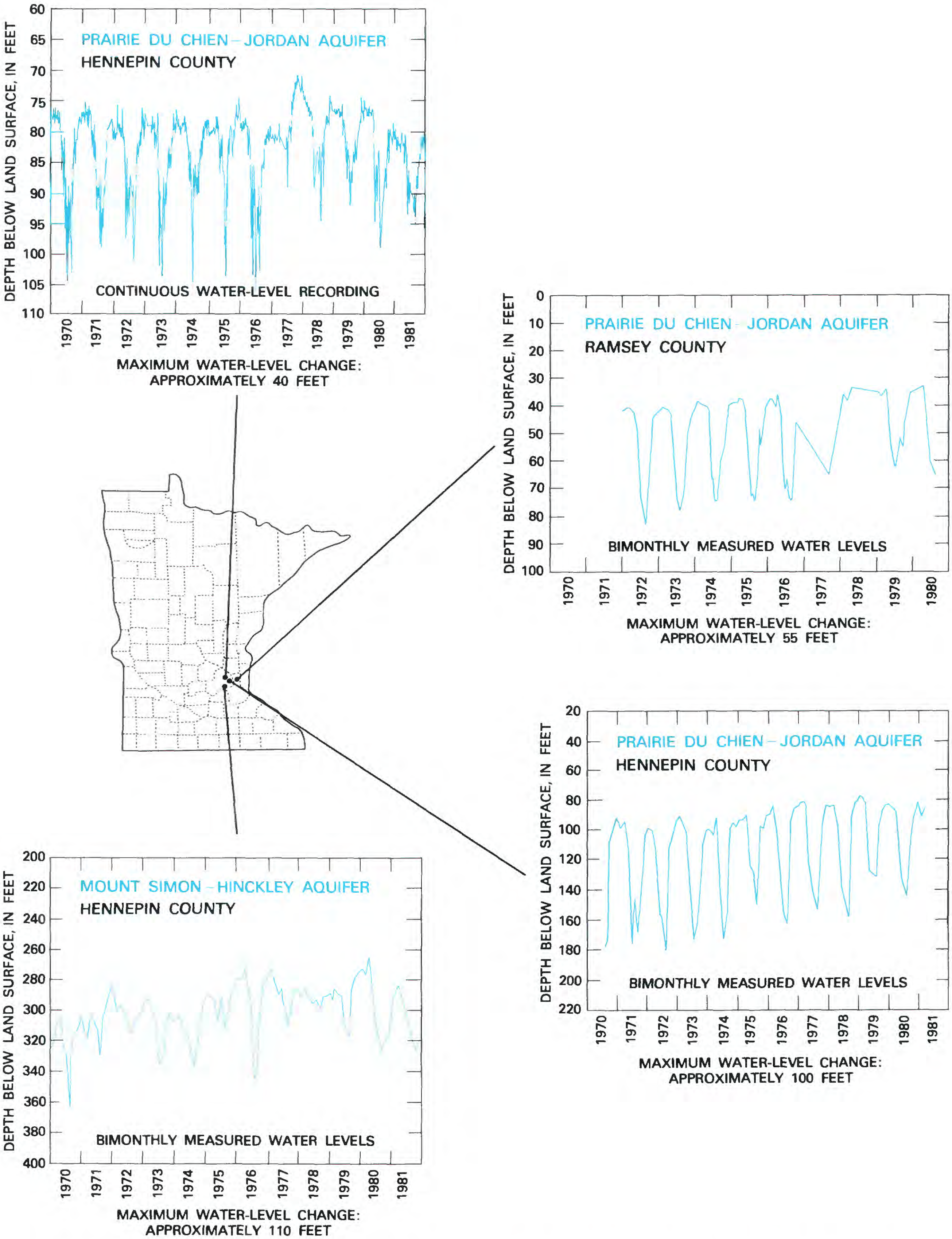



**Figure 1.3-1.** Hydrographs of selected wells in the Twin Cities area for the Prairie du Chien-Jordan and Mount Simon-Hinckley aquifers showing maximum water-level changes during period of record.

Potentiometric maps for the Upper Carbonate, St. Peter, and Ironton-Galesville aquifers, and for the area of the Prairie du Chien-Jordan and Mount Simon-Hinckley aquifers outside the Twin Cities area, were prepared primarily from water levels recorded on drillers' logs. The well logs were found in files of the U.S. Geological Survey, Minnesota Geological Survey, Minnesota Department of Natural Resources, and the Minnesota Department of Health. Only those data meeting the following criteria were used:

1. The well was completed in a single aquifer.
2. The water level and date of measurement were provided.
3. The well location was known.

About 90 percent of the logs analyzed for this study were logs of wells that had been located in the field and plotted on 7½-minute quadrangle maps to the nearest 0.15 acre. The remaining well locations were considered accurate to within 10 acres. The land-surface altitude at each well was obtained from the quadrangle maps, and the altitude of the water level was calculated from this datum. Errors of plus or minus 10 ft are considered to be acceptable in determining the water-level altitude by this method.

The configuration of the water table in the drift aquifer in the Twin Cities area was determined by Larson-Higdem and others (1975) from water-level records in observation wells and from the altitude of the water surface in lakes and streams. Depth to water in the drift generally ranges from 10 to 20 ft below land surface, so the water-table configuration in the drift aquifer was also determined by analysis of topographic contours. The water-table configuration in the bedrock aquifers was determined by analysis of water levels reported on drillers' logs.

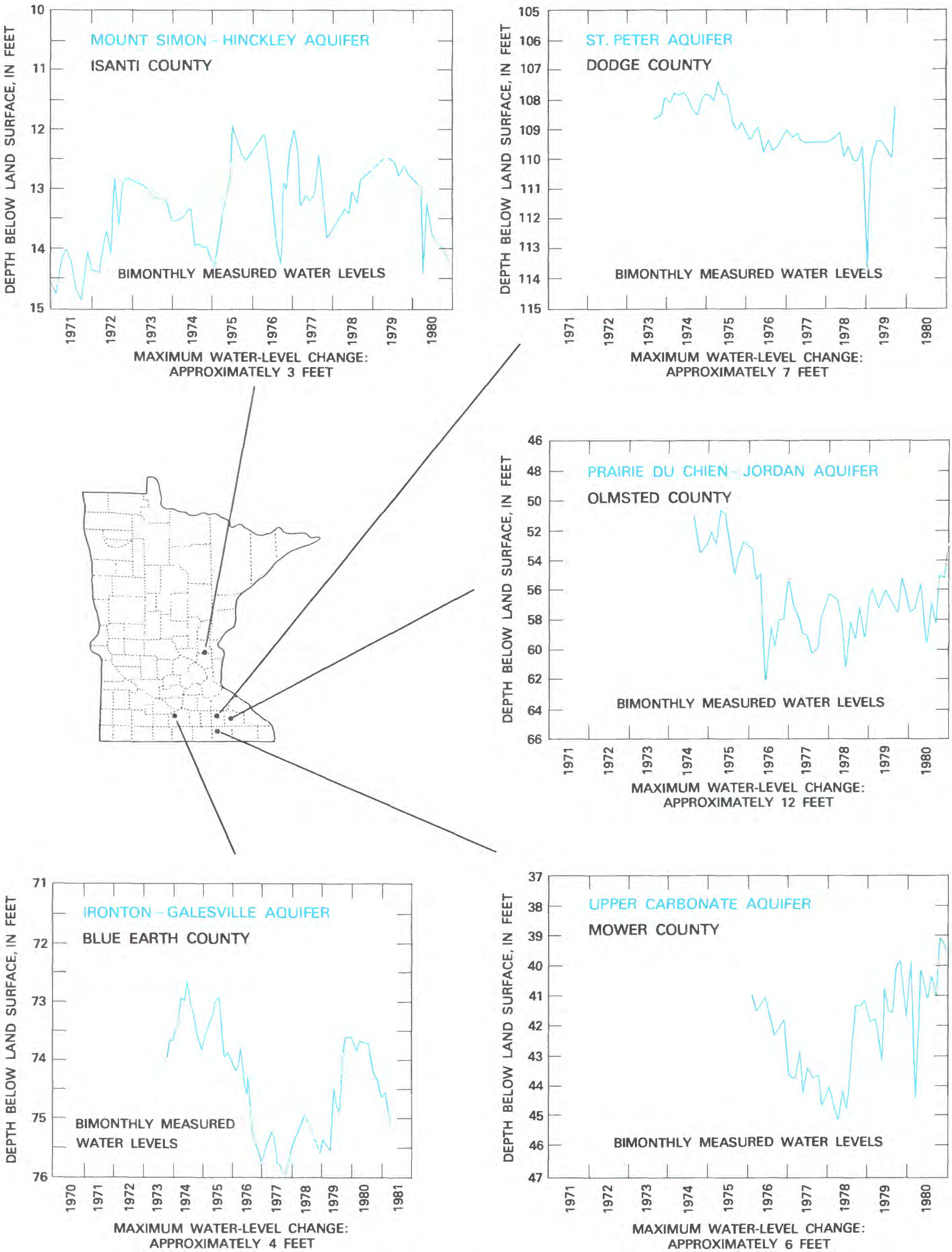



**Figure 1.3-2.** Hydrographs of selected wells outside the Twin Cities area for each bedrock aquifer showing maximum water-level changes during period of record

# Thick Series of Paleozoic Rocks in Southeastern Minnesota Deposited in the Hollandale Embayment

The Hollandale embayment, a southerly-plunging synclinorium, developed over part of an older syncline

As a result of several marine transgressions and regressions during the Paleozoic Era, nearly 2,000 ft of sandstone, carbonate (limestone and dolomite), siltstone, and shale was deposited on older Proterozoic sandstone in southeastern Minnesota. The Paleozoic rocks were deposited in seas that occupied a shallow depression bordered by the Transcontinental arch to the west, and the Wisconsin arch and Wisconsin dome to the east and north (fig. 2.1-1). This shallow depositional basin has been called the Hollandale embayment of the ancestral Forest City basin (Austin, 1970). The maximum extent of the transgressive sea is probably similar to the present boundary of the Paleozoic rocks.

The Hollandale embayment is a southerly-plunging synclinorium (fig. 2.1-2). The embayment developed over the southern part of the older Lake Superior syncline of Proterozoic age, which is dissected by numerous large- and small-scale faults (Sims and Zietz, 1967). Reactivation of some faults in Paleozoic time produced secondary structural features in the embayment, the most notable being the Twin Cities basin (Craddock and others, 1963). Water-level data suggest that most of the faults do not inhibit regional ground-water movement.

The bedrock formations subcrop beneath drift of Quaternary age throughout most of the embayment; bedrock exposures are most commonly seen along river valleys and in road cuts and gravel pits. Structural interpretations in the embayment are based primarily on extrapolation of geologic data between well logs, and on results from numerous surface geophysical surveys.

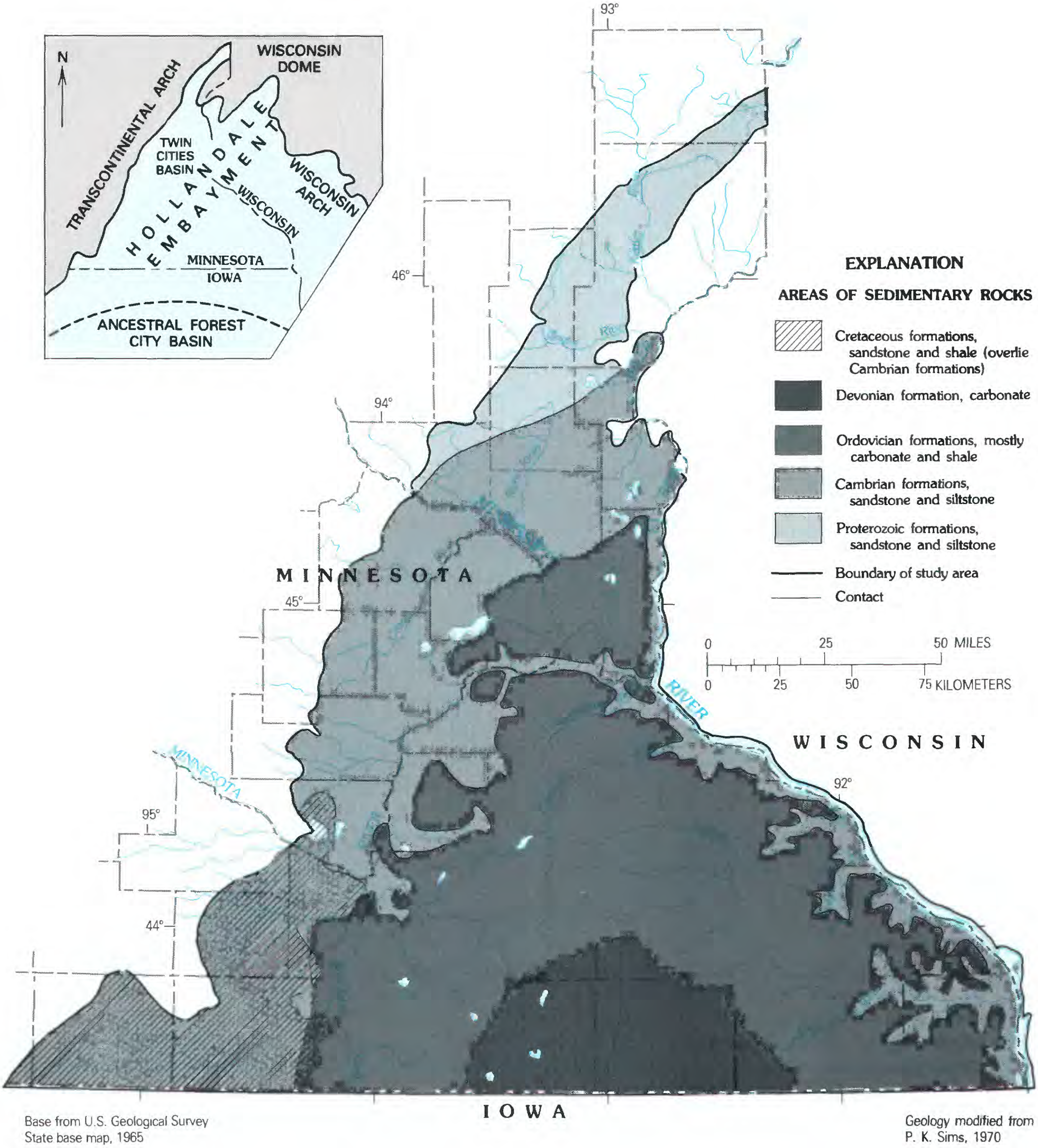



**Figure 2.1-1.** Bedrock geology in the Hollandale embayment, southeastern Minnesota

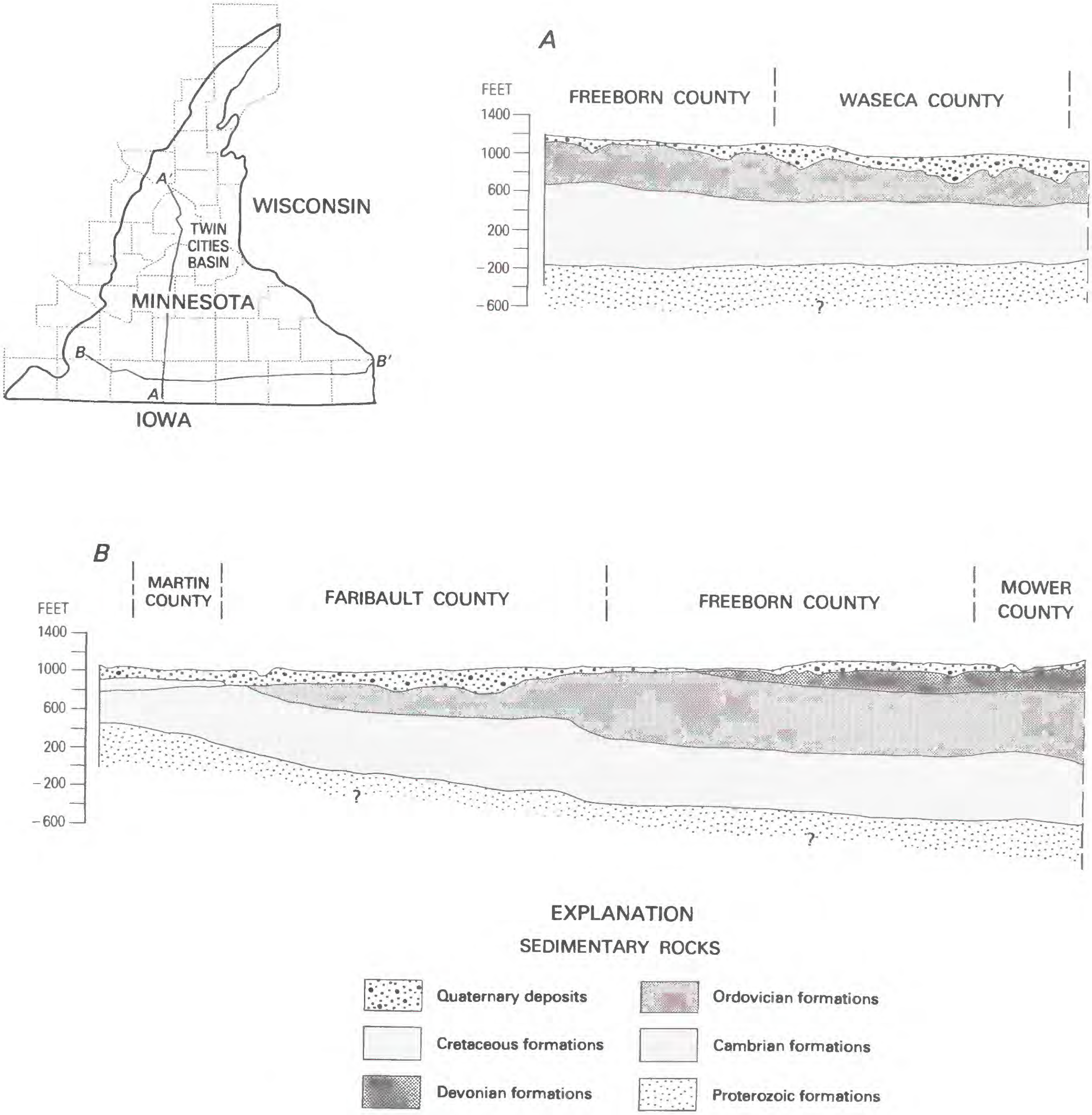
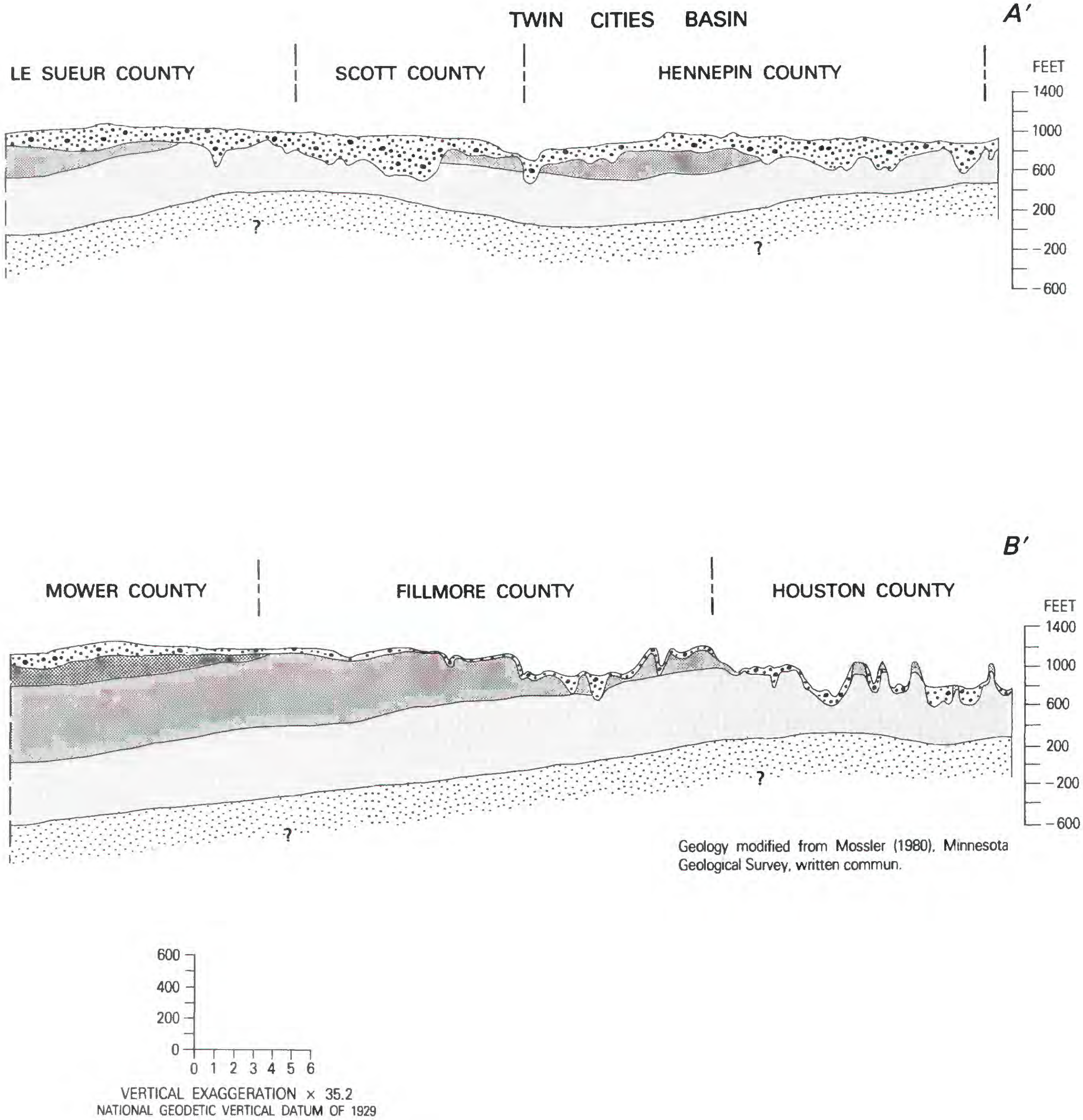



**Figure 2.1-2.** Geologic sections showing structure of sedimentary




formations in Hollandale embayment, southeastern Minnesota

*2.2 Hydrogeologic Relationships*

# Eleven Regional Hydrogeologic Units Identified in Southeastern Minnesota

Regional aquifers in the study area include the undifferentiated drift, Upper Carbonate, St. Peter, Prairie du Chien-Jordan, Ironton-Galesville, and Mount Simon-Hinckley

The sequence of sedimentary rocks in southeastern Minnesota has been divided into 11 hydrogeologic units of aquifers and confining beds (fig. 2.2-1). Regional aquifers identified include the undifferentiated drift, Upper Carbonate, St. Peter, Prairie du Chien-Jordan, Ironton-Galesville, and Mount Simon-Hinckley. Confining beds identified are the Decorah-Platteville-Glenwood, basal St. Peter, St. Lawrence-Franconia, Eau Claire, and sedimentary Proterozoic rocks.

Lindholm and Norvitch (1976), Kanivetsky (1978), and Hult (1979) have identified principal aquifers in Minnesota from a statewide perspective. Minor differences between the designations of regional aquifer and statewide principal aquifers involve treatment of the drift and of the Franconia and Fond du Lac Formations. In this study all drift, whether surficial or buried, is included in the undifferentiated drift aquifer; the Franconia Formation is identified as a confining bed; and the Fond du Lac Formation is not considered to be part of the Mount Simon-Hinckley aquifer. Localized well-completion zones do not constitute regionally significant aquifers. For example, the consolidated Cretaceous aquifer in western Minnesota overlaps most of the older bedrock aquifers in the southwestern part of the study area (fig. 2.1-1). Although this Cretaceous aquifer is utilized locally, it is not considered a regional aquifer.

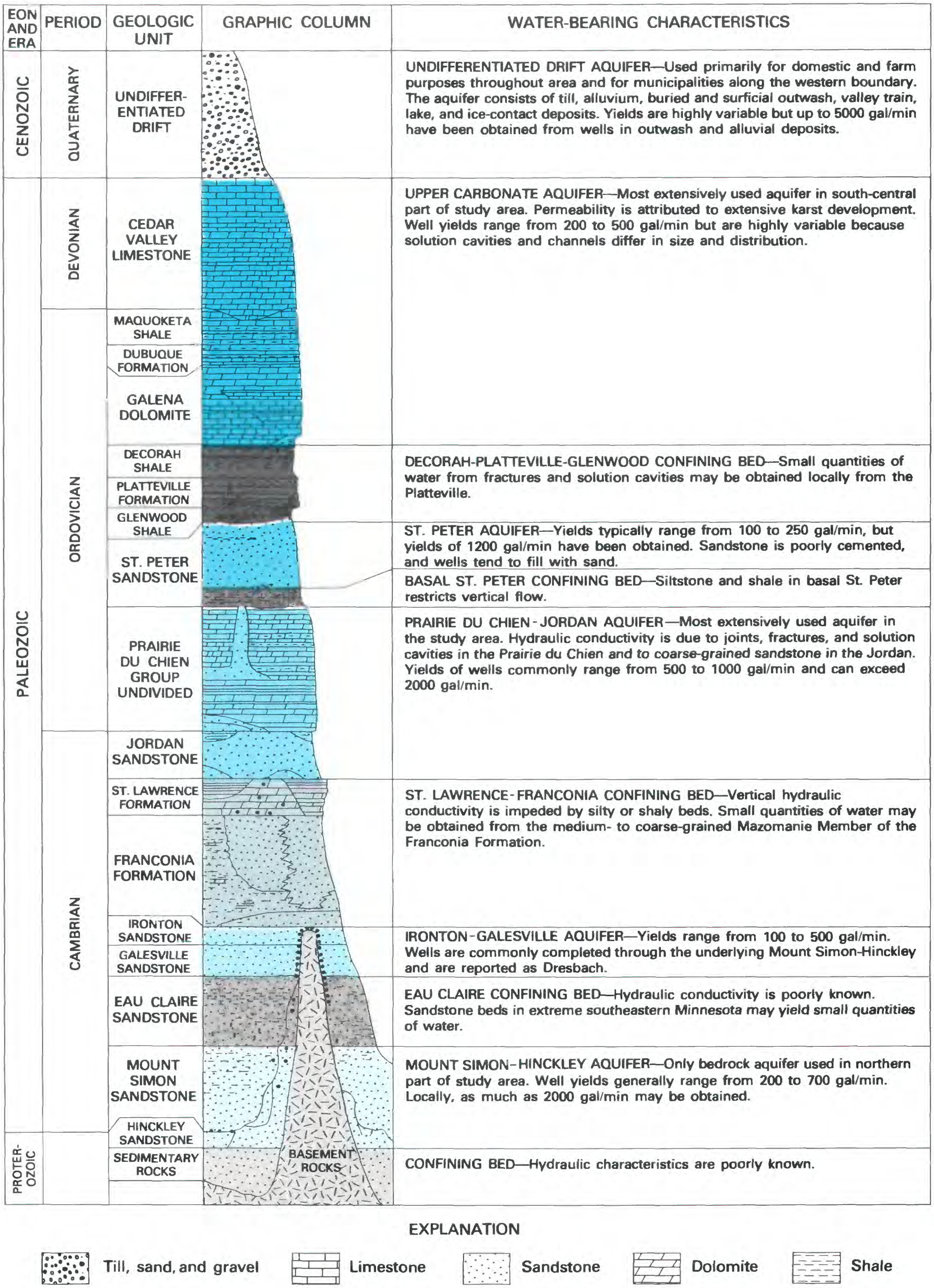



**Figure 2.2-1.** Generalized hydrogeologic column showing regional aquifers and confining beds in southeastern Minnesota (modified from Austin, 1969)

# Drift Covers Nearly All Bedrock in Southeastern Minnesota

Drift thicknesses of less than 50 feet characterize the extreme southeastern part of the area

Wisconsin and pre-Wisconsin drift covers nearly all the bedrock in southeastern Minnesota. The undifferentiated drift aquifer in southeastern Minnesota is composed of till, surficial and buried outwash, ice-contact and tunnel-valley deposits, glacial and modern-day alluvium, and loess. Differentiation between components of the drift is beyond the scope of this study. Thin outliers of unconsolidated Cretaceous deposits occur discontinuously throughout the southern part of the area. Because they have hydraulic characteristics and lithologies similar to drift, these scattered Cretaceous deposits were incorporated into the undifferentiated drift aquifer for this study.

The undifferentiated drift ranges in thickness from 0 to 500 ft (fig. 2.3-1). Drift in the extreme southeastern part of the area is generally less than 50 ft thick. Locally, loess less than 20 ft thick directly overlies the bedrock. Successive glaciations altered the course of some rivers. These former alluvial channels were covered with younger drift resulting in a total drift thickness of more than 500 ft locally to the west and the north. Elsewhere, modern-day rivers have eroded deep channels into the bedrock. These channels subsequently have been filled with alluvium (mostly sand and gravel) with a maximum known thickness of 260 ft.

Hydrologic properties of the undifferentiated drift aquifer are extremely variable, owing in part to the wide range of lithologies represented. Selected hydraulic conductivity values reported in the area are 127 ft/d for Mississippi River alluvium in Dakota County (Mikels, 1955, p. 4),-30 to 650 ft/d for outwash in Sherburne County (Lindholm, 1980), 150 ft/d for surficial outwash in Pine County (Helgesen and others, 1973), and 46 ft/d for buried outwash in Brown County (Johnston and others, 1980, p. 40).

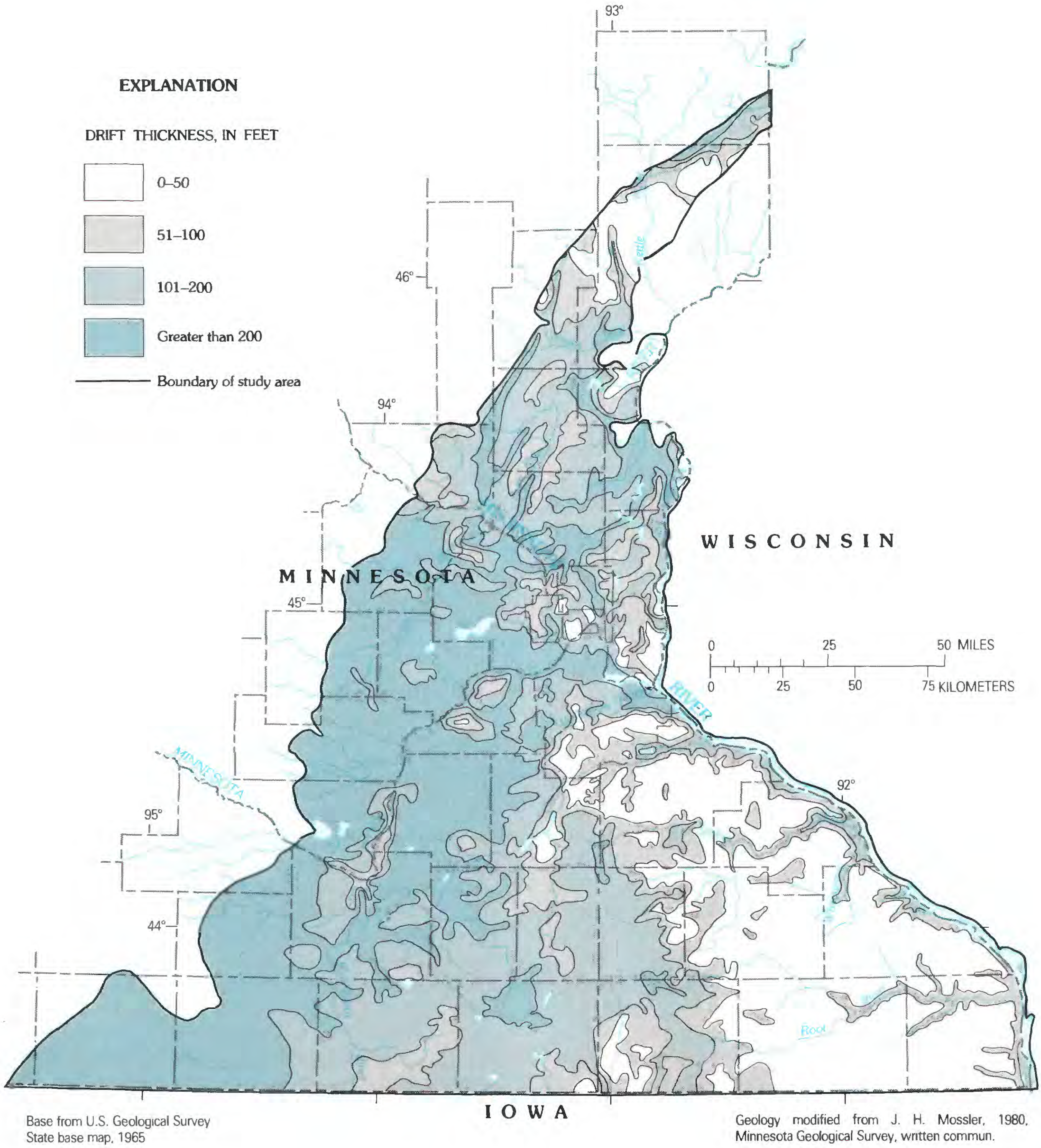



**Figure 2.3-1.** Thickness of undifferentiated drift

# Bedrock Aquifers and Confining Beds Mapped in Southeastern Minnesota

Hydrogeologic properties described for the regional aquifers and confining beds in the area

The location and areal extent of regional bedrock aquifers and confining beds have been mapped for southeastern Minnesota (fig. 2.4-1). The Mount Simon-Hinckley aquifer is the most widespread aquifer in the study area and is the only bedrock aquifer present in the northern part of the area. In the south, five bedrock aquifers are present, separated by confining beds (fig. 2.4-2). Hydrogeologic properties of the bedrock aquifers and confining beds are discussed below.

The Upper Carbonate aquifer is composed of the Cedar Valley Limestone of Devonian age and the Maquoketa Shale, Dubuque Formation, and Galena Dolomite of Ordovician age; it consists of limestone, dolomite, dolomitic limestone, and shale. The aquifer has a maximum known thickness of 640 ft and covers about 3,800 mi$^2$ in the south-central part of the area. The aquifer yields water primarily from fractures, joints, and solution channels in the carbonate rocks. Hydraulic conductivities generally range from 3 to 40 ft/d (Kanivetsky and Walton, 1979).

The Decorah-Platteville-Glenwood confining bed of Ordovician age is composed of shale, shaley dolomite and limestone, and dolomitic limestone. Average thickness of the rocks is 70 ft and they cover nearly 4,800 mi$^2$ in southeast Minnesota.

The St. Peter aquifer of Ordovician age is a fine- to medium-grained, well-sorted, friable, quartzose sandstone. The aquifer covers about 6,300 mi$^2$ and has an average thickness of 100 ft throughout the area. Movement of water in the St. Peter is primarily through intergranular spaces; however, it may be through fractures in some parts of the aquifer. Hydraulic conductivities generally range from 3 to 33 ft/d (Kanivetsky and Walton, 1979).

The basal St. Peter confining bed consists of shale and silty sandstone in the Twin Cities basin where a thickness of nearly 80 ft has been found. The bed is about 40 ft thick in the southwestern part of the embayment, but is known to be thin or locally absent in parts of Dodge, Steele, Olmsted, Rice, Goodhue, Freeborn, and Mower Counties. Because the occurrence of the basal St. Peter confining bed is not fully known, it is not shown in figure 2.4-2.

The Prairie du Chien-Jordan aquifer is composed of the dolomitic Prairie du Chien Group of Ordovician age and the Jordan Sandstone of Cambrian age. The Prairie du Chien Group is predominantly a

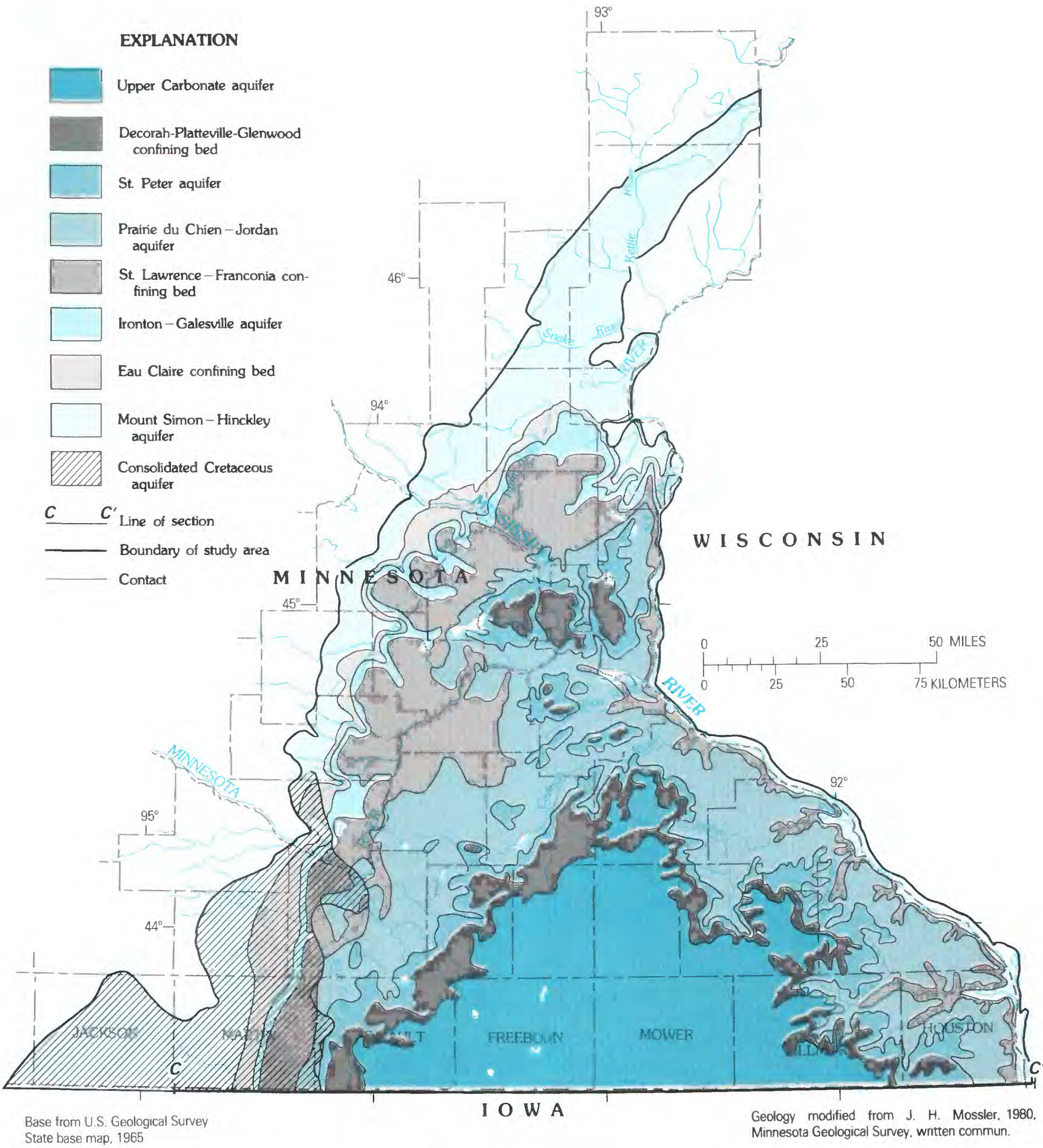



**Figure 2.4-1.** Bedrock hydrogeology in the Hollandale embayment, southeastern Minnesota

sandy, thin- to thick-bedded dolomite. Movement of water in the Prairie du Chien is primarily through fractures, joints, and solution channels. The underlying Jordan Sandstone is a quartzose, friable to well-cemented, fine- to coarse-grained sandstone. Flow in the Jordan is intergranular. The aquifer covers about 10,500 $mi^2$ and generally ranges in thickness from 240 ft in the Twin Cities basin to more than 450 ft in the south. Hydraulic conductivities range from 5 to 67 ft/d (Kanivetsky and Walton, 1979).

The St. Lawrence-Franconia confining bed of Cambrian age consists of shale, fine-grained dolomitic sandstone, and dolomitic siltstone. The confining bed covers about 12,800 $mi^2$ and has an average thickness of 200 ft. Although the Franconia Formation is regionally considered a confining bed, the Mazomanie Member of the formation yields domestic supplies to wells in Scott, Carver, Anoka, and western Hennepin Counties.

The Ironton-Galesville aquifer of Cambrian age consists of fine- to medium-grained, poor- to well-sorted, quartzose sandstone with an average thickness of 70 ft. Areal extent of the aquifer is about 13,000 $mi^2$. Flow in the aquifer is intergranular. Hydraulic conductivities range from 4 to 33 ft/d (Kanivetsky and Walton, 1979).

The Eau Claire confining bed of Cambrian age consists of fine-grained sandstone and shale. The confining bed covers about 14,800 $mi^2$ and has an average thickness of 150 ft.

The Mount Simon-Hinckley aquifer, composed of the Mount Simon Sandstone of Cambrian age and the Hinckley Sandstone of Proterozoic age, is a fine- to coarse-grained sandstone containing interbedded siltstone and shale. The aquifer covers about 17,200 $mi^2$ and has a maximum thickness of about 500 ft. Movement of water in the aquifer is primarily intergranular. Hydraulic conductivities range from 2 to 23 ft/d (Kanivetsky and Walton, 1979).

Interbedded siltstone, mudstone, shale, and fine-grained sandstone of Proterozoic age underlie most of the area. The hydraulic characteristics of these rocks are poorly known. Small quantities of water may be obtained locally from the sandstone, but the rocks are considered to be a confining bed throughout the Northern Midwest RASA region.

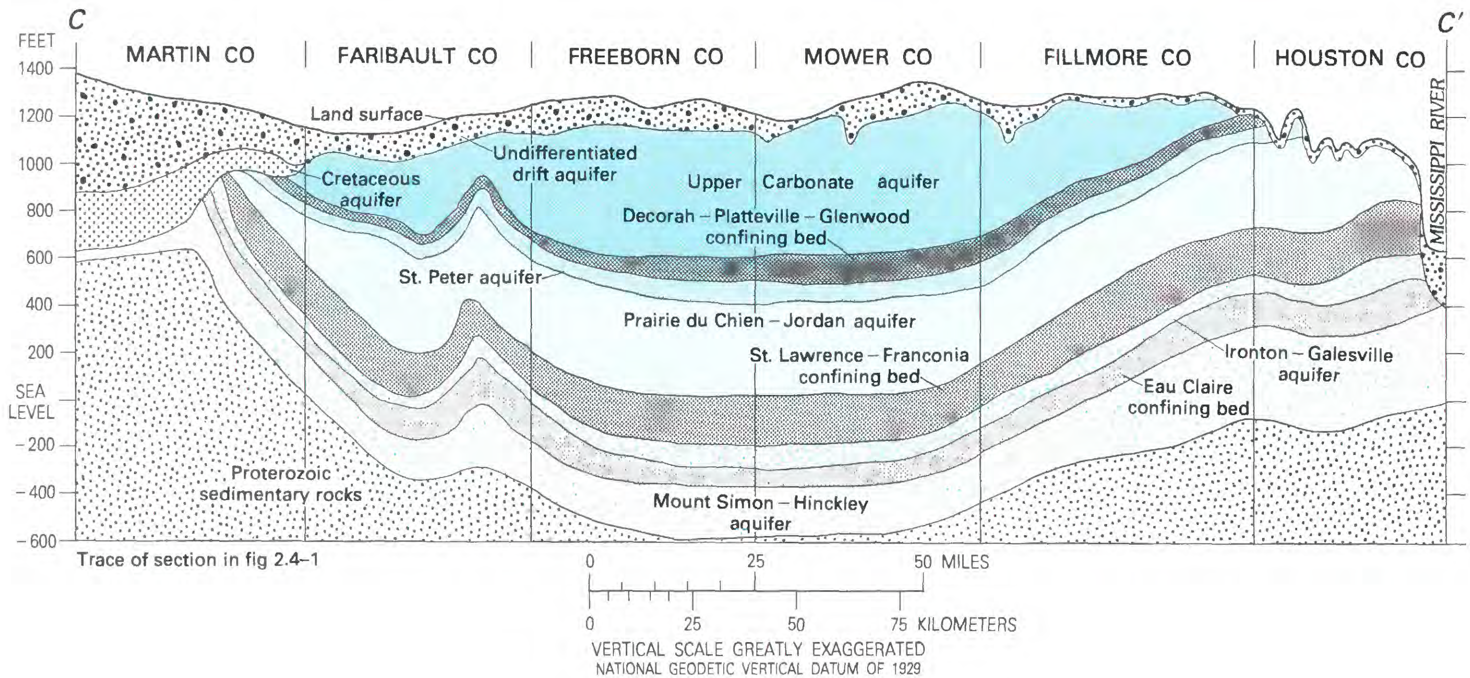



**Figure 2.4-2.** Hydrogeologic section showing relation between aquifers and confining beds along the Minnesota-Iowa border

# Precipitation Is the Principal Source of Recharge to the Ground-Water System

Annual precipitation in southeastern Minnnesota generally ranges from 26 to 31 inches

Precipitation is the principal source of recharge to the ground-water system in southeastern Minnesota. The average annual precipitation ranges from 26 in. in the Twin Cities area to 31 in. along the Iowa border (fig. 2.5-1).

Baker and others (1979) developed a water budget for Minnesota. This budget has been modified slightly to reflect the mean annual precipitation for southeastern Minnesota, and is presented in table 2.5-1. From a regional perspective, only about 0.6 inch, or 2.1 percent of the average precipitation of 28.8 inches, enters the ground-water system annually.

**Table 2.5-1.** Estimated annual water budget for southeastern Minnesota (modified from Baker and others, 1979)

| | Inches | Percent |
|---|---|---|
| Input: | | |
| Mean annual precipitation | 28.8 | 100.0 |
| Output: | | |
| Evapotranspiration | 21.9 | 76.0 |
| Surface runoff | 6.3 | 21.9 |
| Ground water | 0.6 | 2.1 |

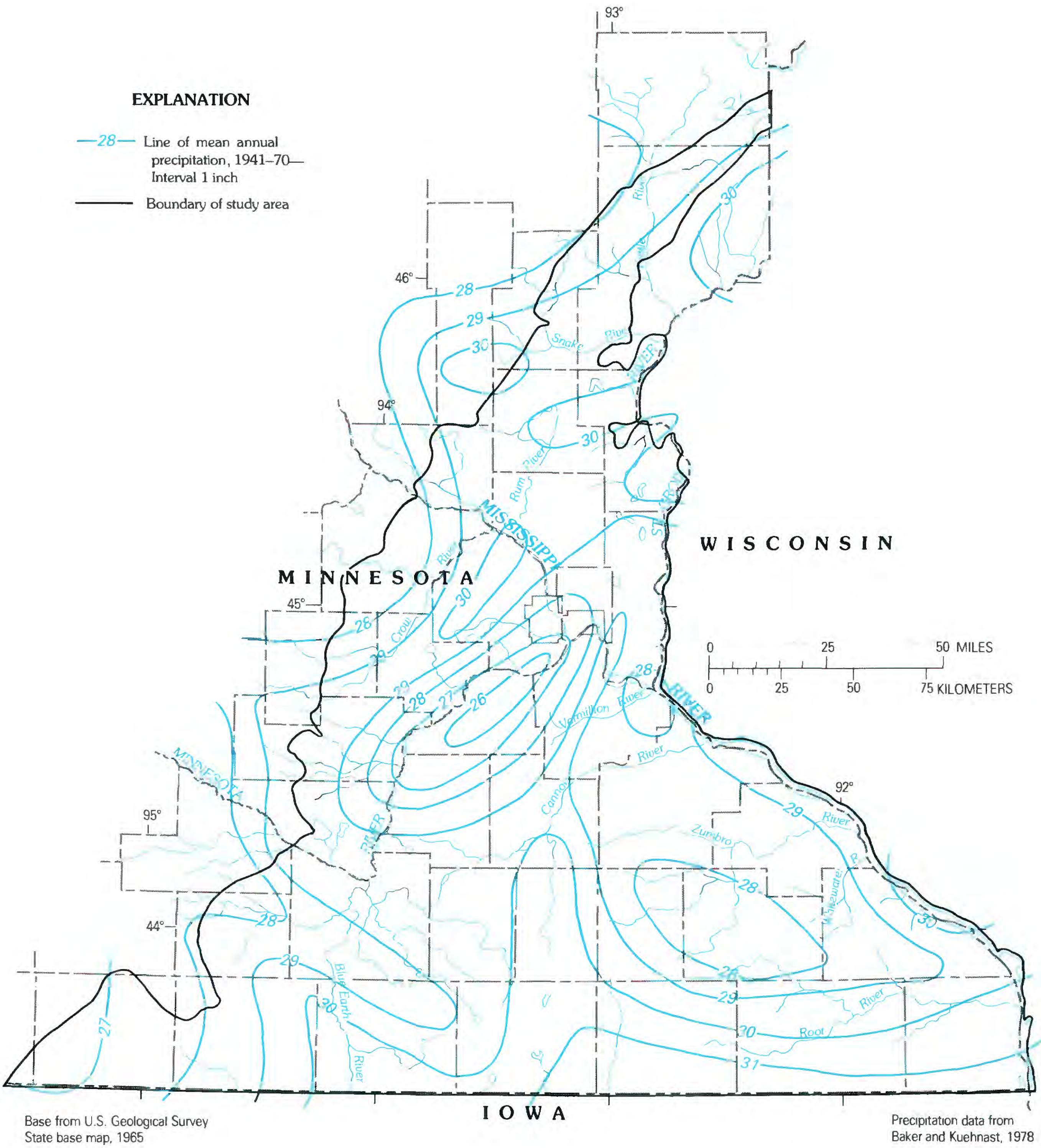



**Figure 2.5-1.** Mean annual precipitation in southeastern Minnesota, 1941–70

# Water in an Aquifer Changes from Being Confined to Unconfined When or Where the Potentiometric Surface Is Below the Top of the Aquifer

Configuration of the potentiometric surface indicates the direction of ground-water flow and the location of recharge and discharge areas

Water in an aquifer is unconfined when or where the potentiometric surface is below the top of the aquifer. Water in an aquifer is confined when or where the potentiometric surface is at or above the top of the aquifer. Water in a particular aquifer may be confined in some places or at some times, and unconfined in other places or at other times. Water in an aquifer changes from being confined to unconfined when or where the potentiometric surface is below the top of the aquifer (fig. 3.1-1).

The configuration of the potentiometric surface is controlled by several factors, including (1) discharge of ground water into streams, (2) recharge to the aquifer from streams, (3) recharge from adjacent deposits, (4) pumpage and recharge by wells, (5) changes in thickness or hydraulic conductivity of saturated materials, and (6) bedrock structure and topography. Several of these factors may influence the configuration of the potentiometric surface in the same area.

Gutentag and Weeks (1980) described how patterns of water-table contours were used to interpret ground-water movement for the High Plains RASA study. A similar analysis was used in this study.

1. Upgradient flexures of potentiometric contours at a stream indicate ground-water flow toward and discharge to the stream. This is a dominant flow pattern in southeastern Minnesota for most of the regional aquifers and is illustrated along the Minnesota River (figs. 3.2-1 and 3.7-1).
2. Downgradient flexures of the potentiometric contours at streams indicate water movement from the stream into the aquifer. Although this pattern is not indicated on any of the accompanying regional potentiometric maps, it may be present locally in the study area.
3. Lack of flexures in potentiometric contours crossing streams generally indicates that the aquifer and stream are not hydraulically connected. This pattern is shown by the Mount Simon-Hinckley potentiometric surface (fig. 3.7-1) near the Blue Earth and upper Cannon Rivers.
4. Upgradient flexures in interstream areas indicate pumpage from the aquifer. This pattern is shown by the Mount Simon-Hinckley potentiometric surface (fig. 3.7-1) in southern Anoka County where several municipal and industrial wells pump from the aquifer.
5. Downgradient flexures, or increased potentiometric-contour spacing in interstream areas, indicate recharge from overlying deposits or a topographic high in the bedrock surface. This pattern is shown by the Prairie du Chien-Jordan potentiometric surface (fig. 3.5-1) in central Wabasha County where the aquifer is overlain by a thin layer of drift.

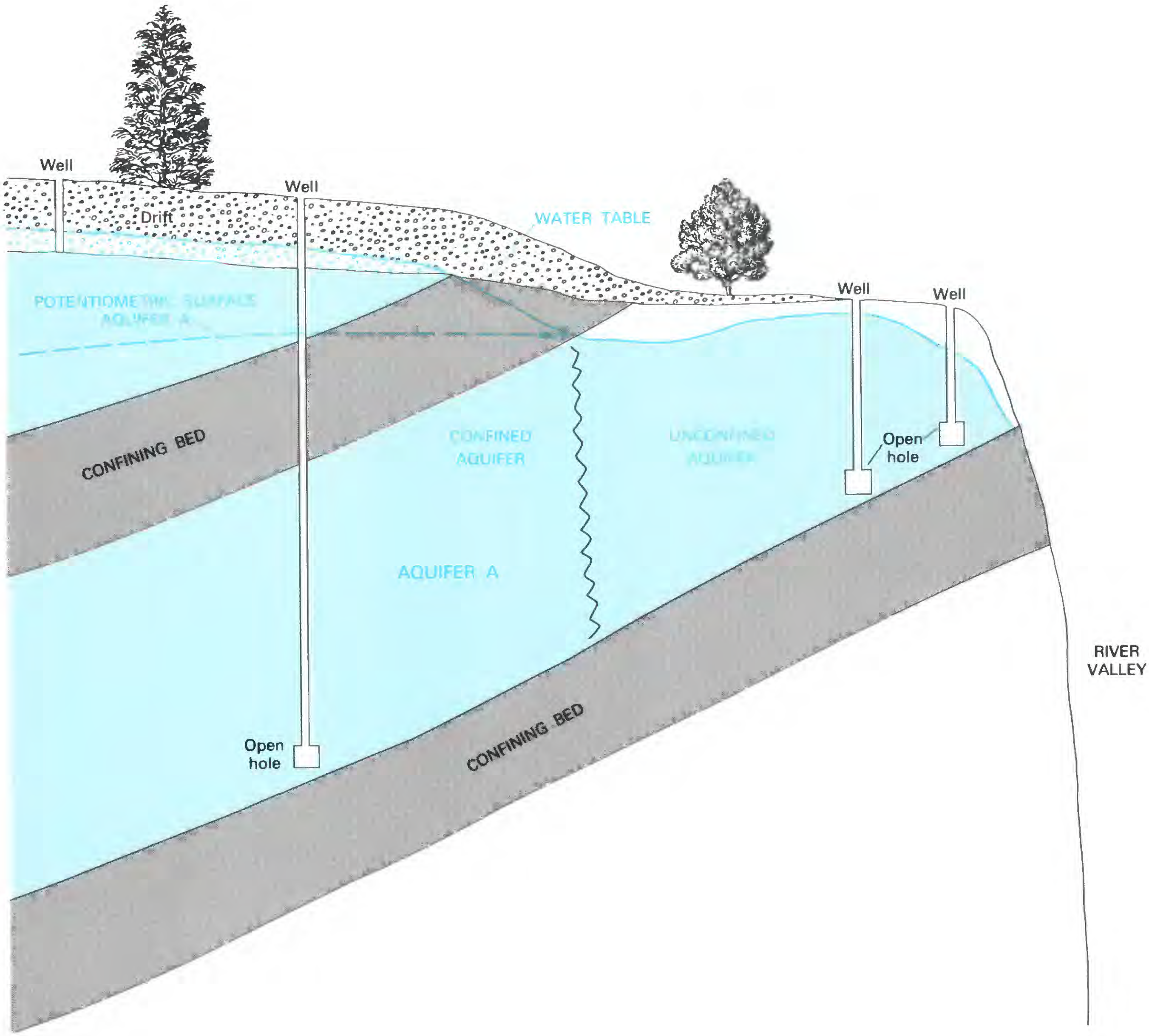



**Figure 3.1-1.** Conceptualized head relationships in bedrock aquifers cut by a river valley, southeastern Minnesota

# Water Table Shows Flow Toward Rivers

The water table is in the drift everywhere except in the eastern part of the area and along major river valleys where it is in the bedrock

Regional flow in the undifferentiated drift aquifer is toward the Minnesota, Mississippi, and St. Croix Rivers (fig. 3.2-1). There are major ground-water divides in eastern Mower and northern Pine Counties. Locally, flow is influenced primarily by the topography and is toward tributary streams with intervening ground-water divides.

In areas where the drift cover is thin, or where adjacent rivers have incised deep channels into bedrock, the water table occurs in bedrock aquifers and confining beds. Extensive areas where the water table is primarily in bedrock are shown in figure

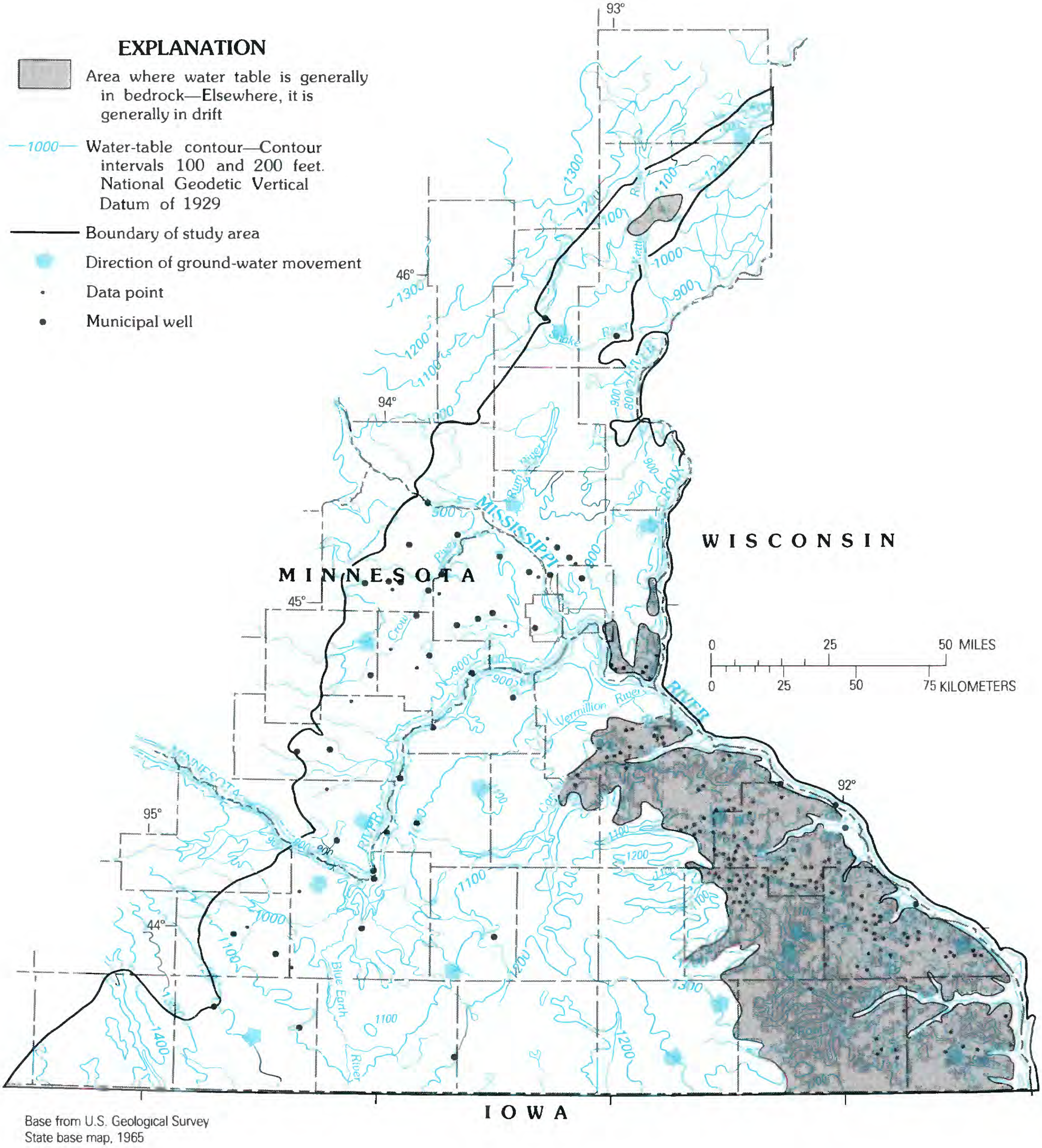



**Figure 3.2-1.** Regional water-table configuration in southeastern Minnesota

3.2-1 and in figure 3.2-2 for the southeastern part of the study area; these areas coincide with drift thicknesses generally less than 20 ft.

Although water in the undifferentiated drift aquifer generally is unconfined, it locally occurs under confined conditions. Wells flow in some areas.

Withdrawal of water from the drift aquifer is predominantly by rural domestic and livestock wells. However, in the western part of the area where the drift is thickest, municipal water supplies are obtained from the aquifer.

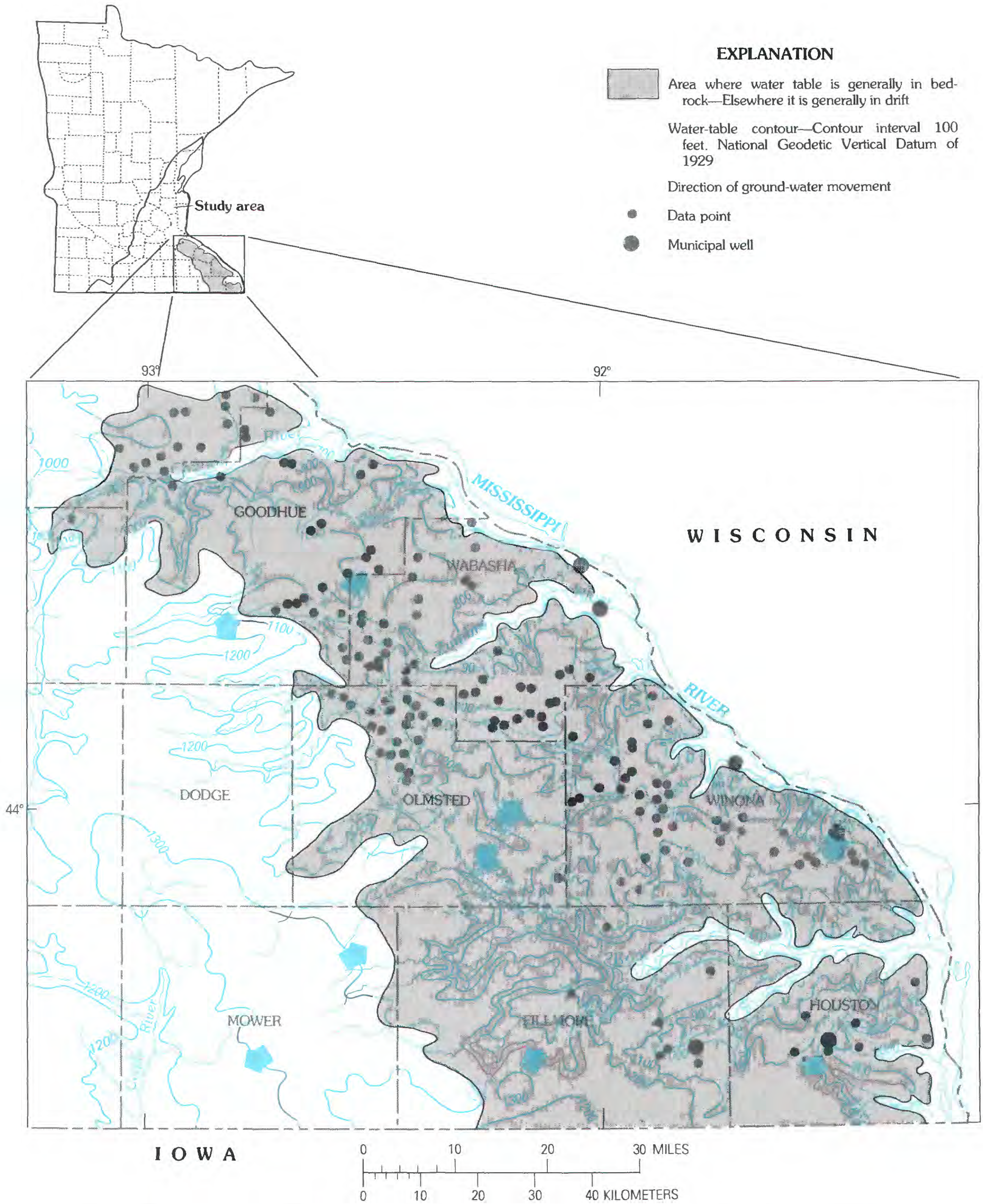



**Figure 3.2-2.** Area in extreme southeastern Minnesota where water table is generally in bedrock

# Upper Carbonate Potentiometric Surface Indicates Flow to Periphery of Aquifer

Karst conditions complicate the flow system in the eastern part of the aquifer

Regional ground-water flow in the Upper Carbonate aquifer is predominantly toward the periphery of the aquifer (fig. 3.3-1). Recharge to the aquifer is by infiltration from the overlying drift. The highest altitude of the potentiometric surface for this aquifer is in eastern Mower County, a location similar to the elevated potentiometric surface in the overlying drift aquifer. Ground water moves toward rivers and bedrock valleys, particularly in the east and south. Stream-discharge measurements indicate that the aquifer discharges water through seeps and springs, sustaining streamflow through dry periods (Farrell and others, 1975). The gradient of the potentiometric surface is generally small but steepens along tributaries of the North, Middle, and South Branches of the Root River (fig. 3.3-2). Drift, composed primarily of till, confines water in the aquifer in most places. In the eastern part of the aquifer, however, water is unconfined.

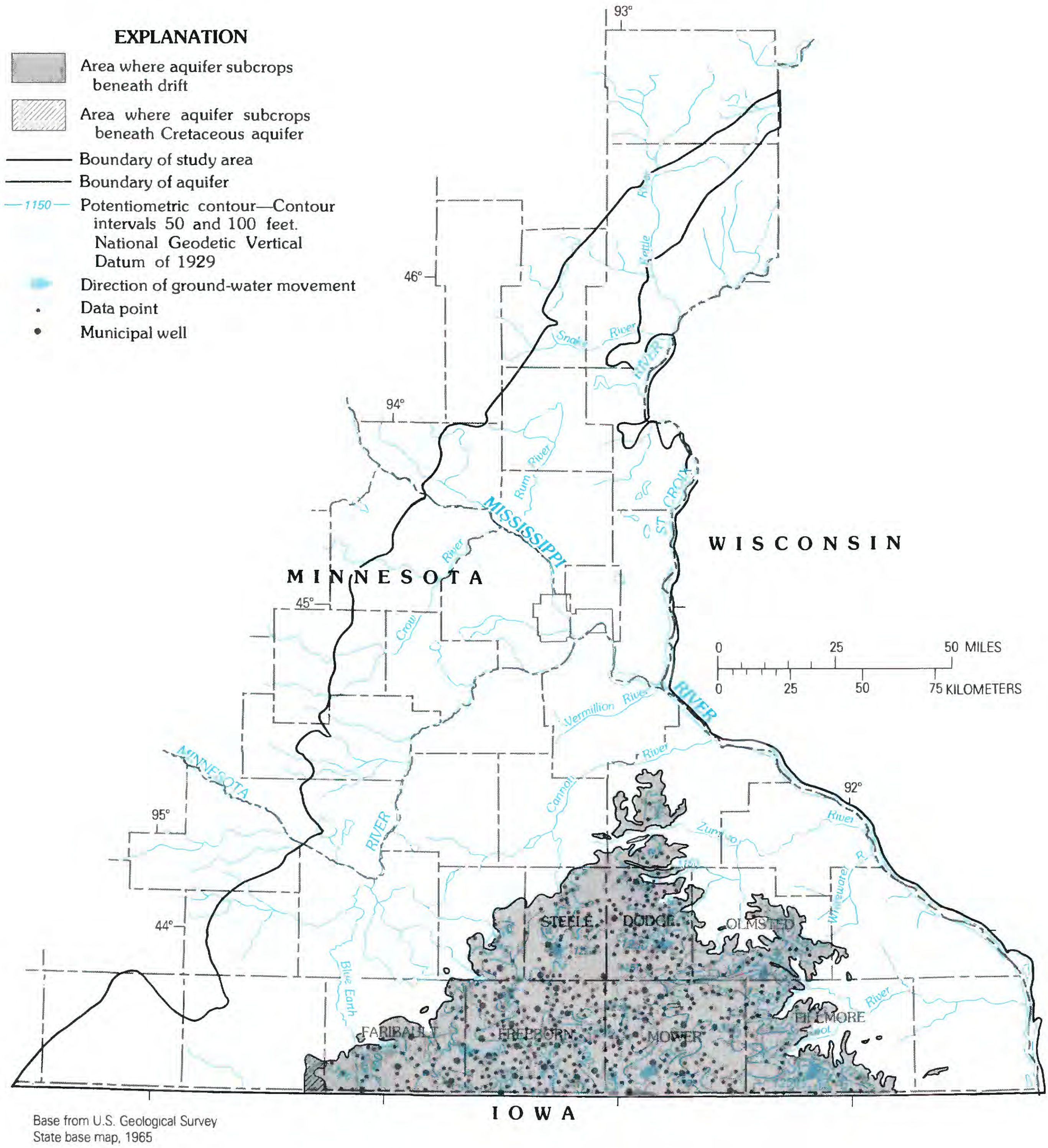



**Figure 3.3-1.** Regional potentiometric surface of the Upper Carbonate aquifer in southeastern Minnesota, 1970–80

Karst features are common in the eastern part of the aquifer, where it is overlain by a thin mantle of drift. Numerous sinkholes, caverns, and disappearing streams are located in Fillmore and Olmsted Counties. Evaluation of the extremely complex flow patterns in the karst area is beyond the scope of this study.

The Upper Carbonate aquifer yields water to many wells throughout Steele, Dodge, Faribault, Freeborn, and Mower Counties for municipal, industrial, and domestic supplies. However, these ground-water withdrawals do not appear to significantly affect the regional flow system. The Minnesota Water Well Construction Code (7MCAR, section 1.220 H.) states that creviced or cavernous limestone or dolomite shall not be used as a source of potable water unless the rocks are overlain by at least 50 ft of drift or a horizontally continuous insoluble unit. Therefore, insufficient drift thickness in Olmsted and Fillmore Counties limits use of the aquifer in that area for municipal and domestic supplies.

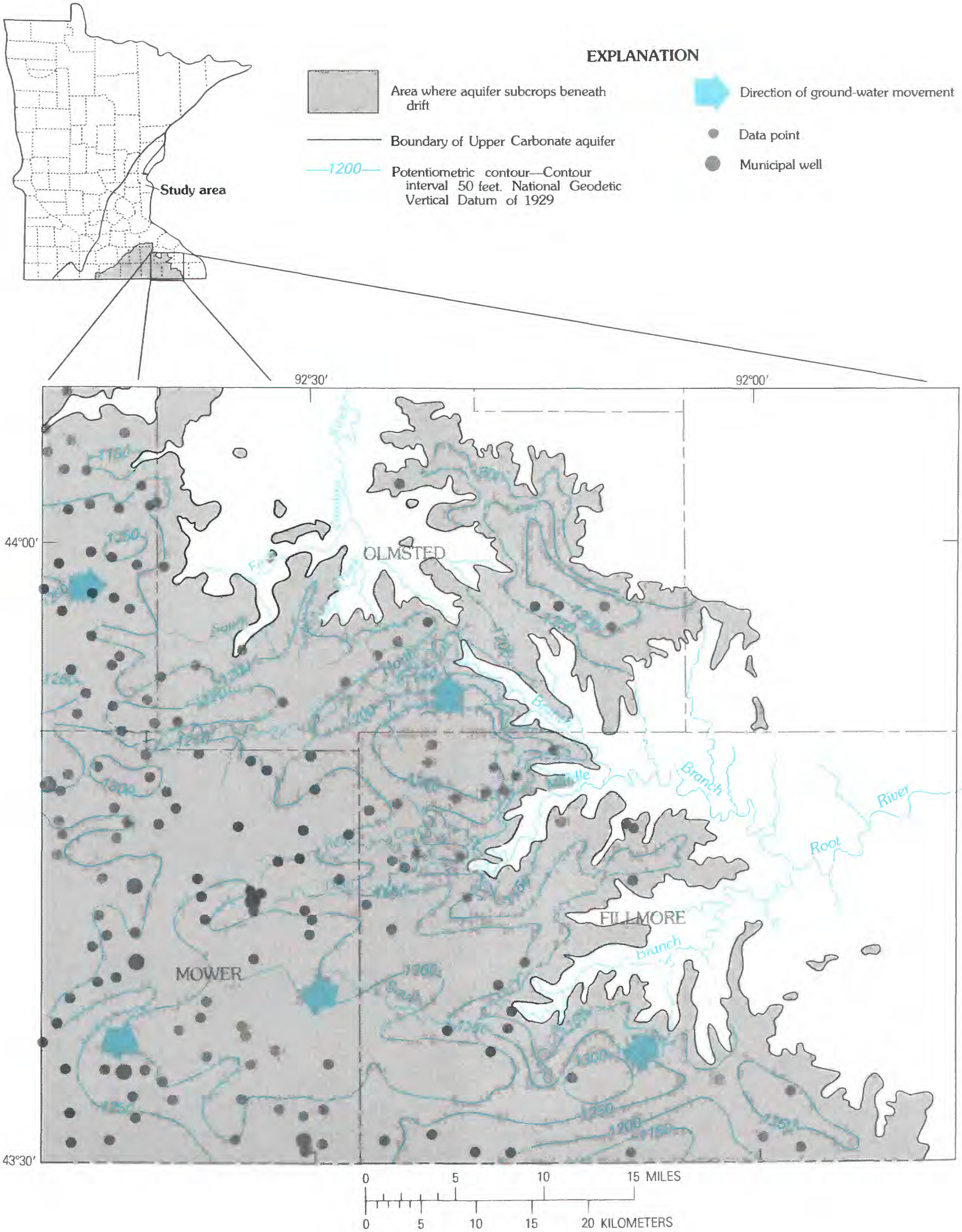



**Figure 3.3-2.** Potentiometric surface of Upper Carbonate aquifer near tributaries of the Root River

# Ground-Water Divide in Northern Steele and Dodge Counties

St. Peter potentiometric surface indicates regional flow southward toward Iowa

The Cannon, Vermillion, Minnesota, and Mississippi Rivers divide the St. Peter aquifer into separate, discontinuous areas. In the largest area, a ground-water divide in northern Steele and Dodge Counties (fig. 3.4-1) separates flow northward toward the Cannon River system and southward toward Iowa (fig. 3.4-2). However, in the east, flow is toward the Whitewater, Zumbro, and Root Rivers and their tributaries. Flow of these rivers is partly sustained by discharge from the St. Peter aquifer (Farrell and others, 1975; Anderson and others, 1975). In the Twin Cities basin, flow in the aquifer is toward the Minnesota and Mississippi Rivers and buried bedrock valleys. Water in about 76 percent of the areal extent of the aquifer is confined by the Decorah-Platteville-Glenwood confining bed.

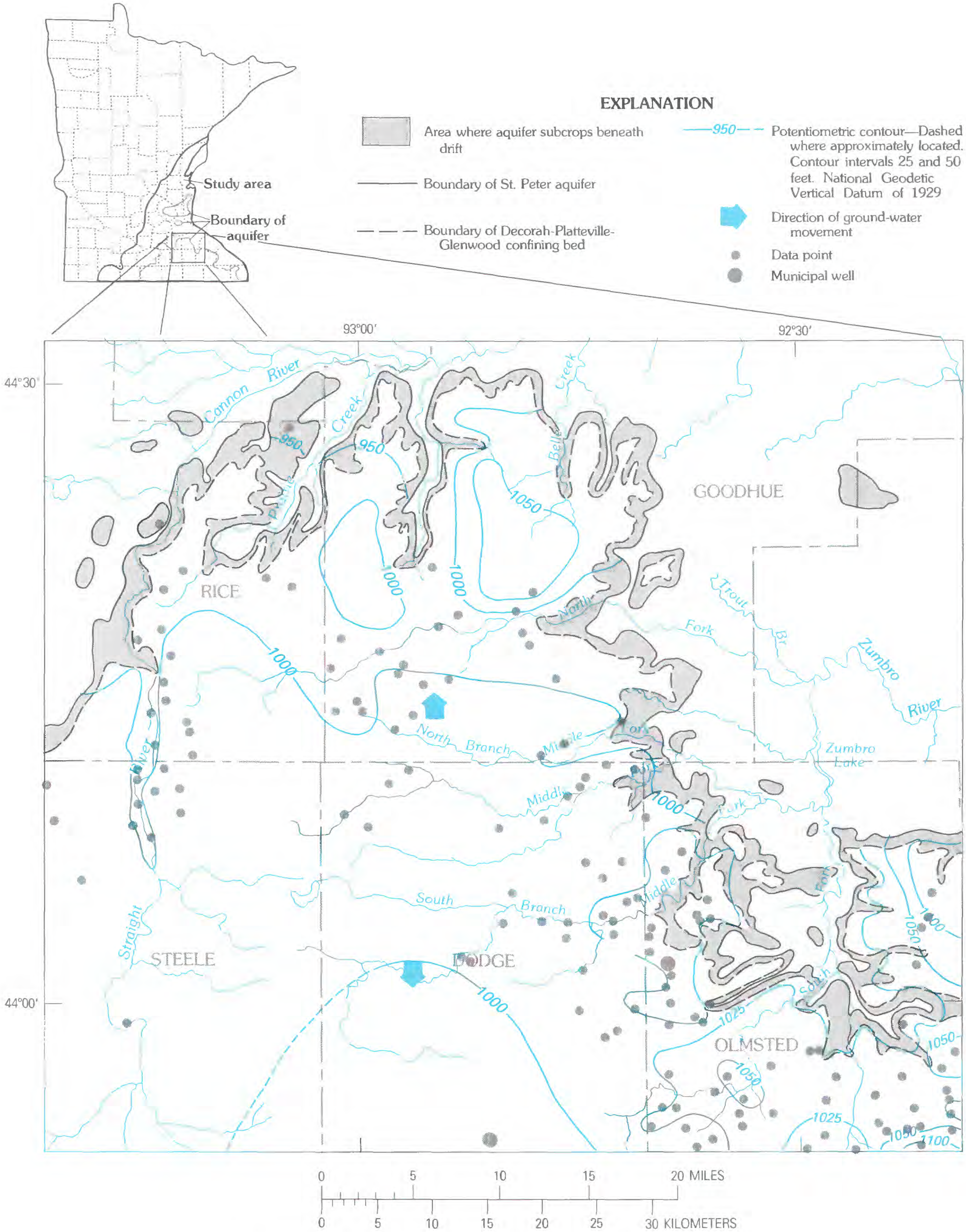



**Figure 3.4-1.** Regional ground-water divide in St. Peter aquifer

The highest potentiometric surfaces are along the eastern margin of the aquifer where recharge is through thin drift deposits. The potentiometric surfaces of the St. Peter in parts of Goodhue, Dodge, and Olmsted Counties is generally about 10 ft higher than the potentiometric surface of the Prairie du Chien-Jordan aquifer, whereas it is about 30 ft higher in the Twin Cities basin.

Although the St. Peter aquifer is tapped primarily by rual domestic and livestock wells, a few wells for municipal supplies have been completed in the aquifer in the southeast. These ground-water withdrawals do not seem to significantly affect the regional flow system.

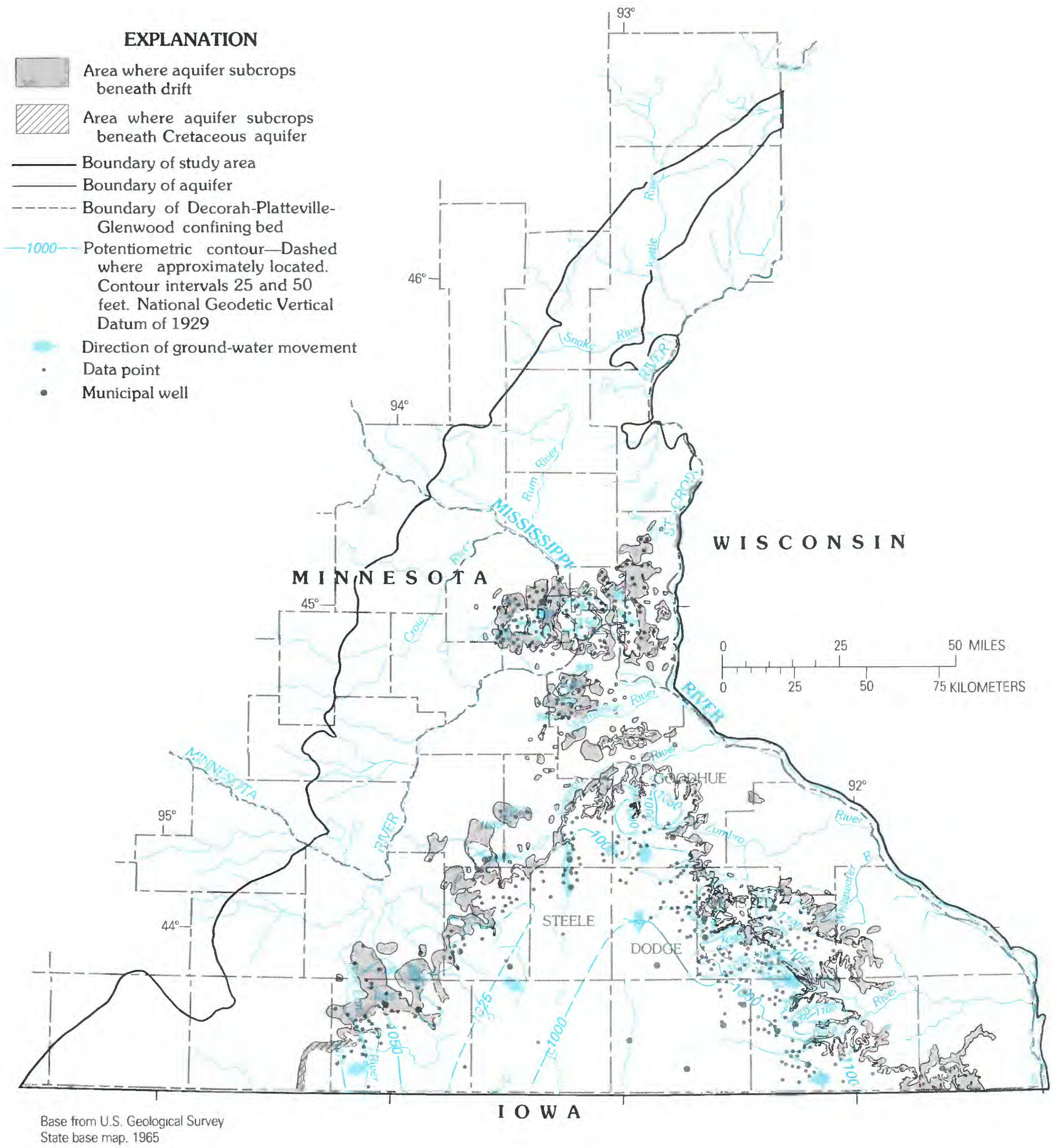



**Figure 3.4-2.** Regional potentiometric surface of the St. Peter aquifer in southeastern Minnesota, 1970–80

*3.5 Prairie du Chien-Jordan Aquifer*

# A Regional Ground-Water Divide Separates Southerly Flow Toward Iowa from Northerly Flow Toward the Twin Cities Basin

Water from the Prairie du Chien-Jordan aquifer discharges to most of the major rivers

A regional ground-water divide occurs in the Prairie du Chien-Jordan aquifer in northern Waseca, Steele, and Dodge Counties and in central Olmsted and Winona Counties (fig. 3.5-1) Ground-water flow south of the divide is affected by recharge along the southwestern boundary from the overlying Cretaceous and drift aquifers and by recharge along the eastern boundary through a thin mantle of drift (fig. 3.5-2). Ground water moves from these recharge areas toward the center of the embayment and southward toward Iowa. The inferred southerly flow into Iowa is confirmed by a potentiometric map of the Jordan Sandstone in Iowa, prepared by Horick and Steinhilber (1978). Water from the aquifer also discharges to the Mississippi and Root Rivers.

Regional flow north of the ground-water divide is toward the major river systems (fig. 3.5-1); the Blue Earth and Minnesota Rivers to the west, the Mississippi, Minnesota, and St. Croix Rivers to the

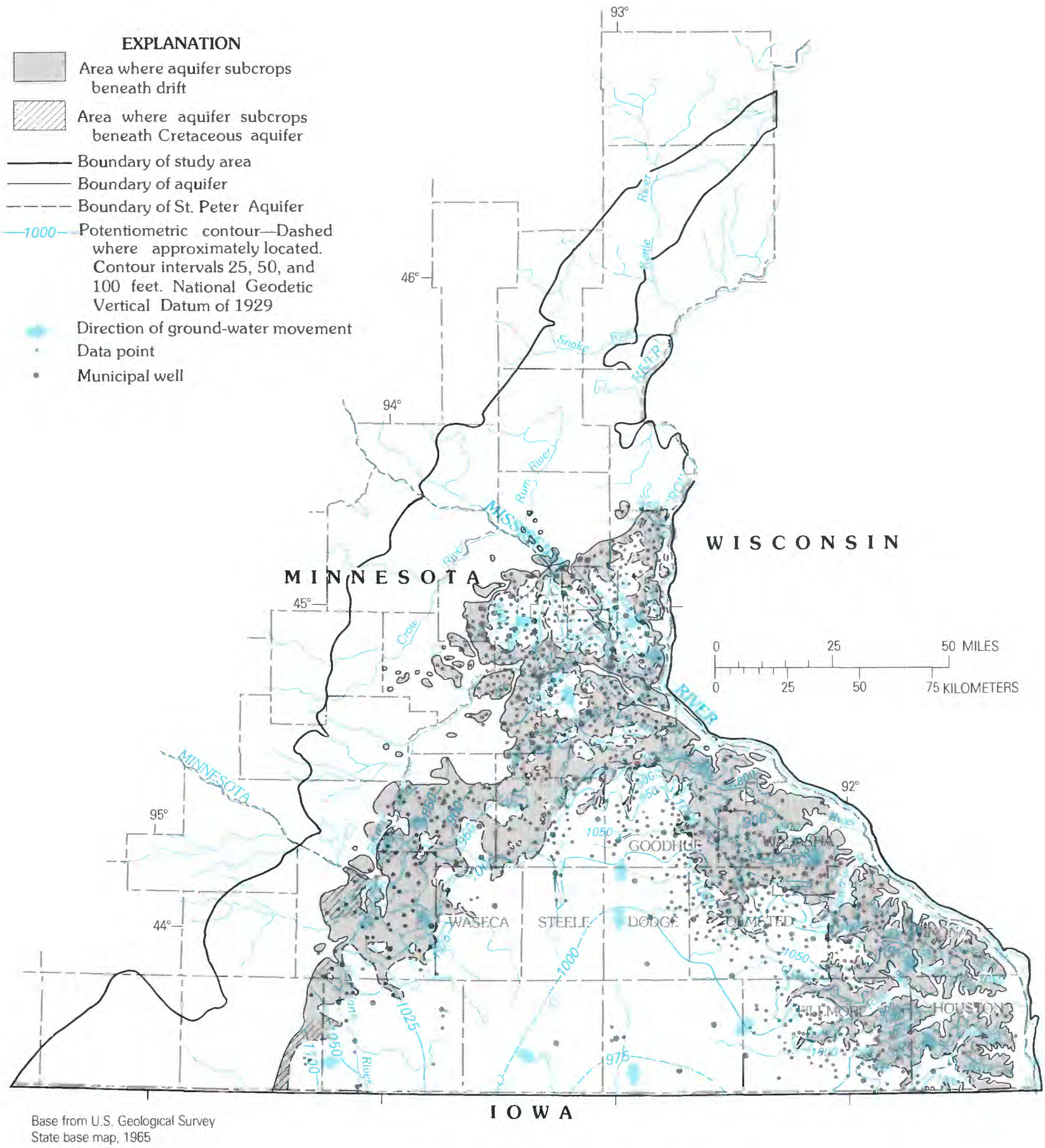



**Figure 3.5-1.** Regional potentiometric surface of the Prairie du Chien-Jordan aquifer in southeastern Minnesota, 1970–80

north, the Mississippi River to the east, and the Cannon, Zumbro, and Whitewater Rivers to the south.

Water in less than 50 percent of the areal extent of the aquifer is confined by the basal St. Peter confining bed. Along the eastern boundary, the drift mantle is thin and there are large areas where water in the aquifer is unconfined (see fig. 3.2-2).

Pumpage in the Minneapolis-St. Paul metropolitan area constitues the largest withdrawal from the ground-water system in the Hollandale embayment. M. A. Horn (written commun., 1980) estimates that 80 percent of this pumpage is from the Prairie du Chien-Jordan, which is the most widely used aquifer throughout the area. Large-volume withdrawals in summer produce seasonal variation in the regional flow pattern for this aquifer in the Twin Cities area. (fig. 1.3-1).

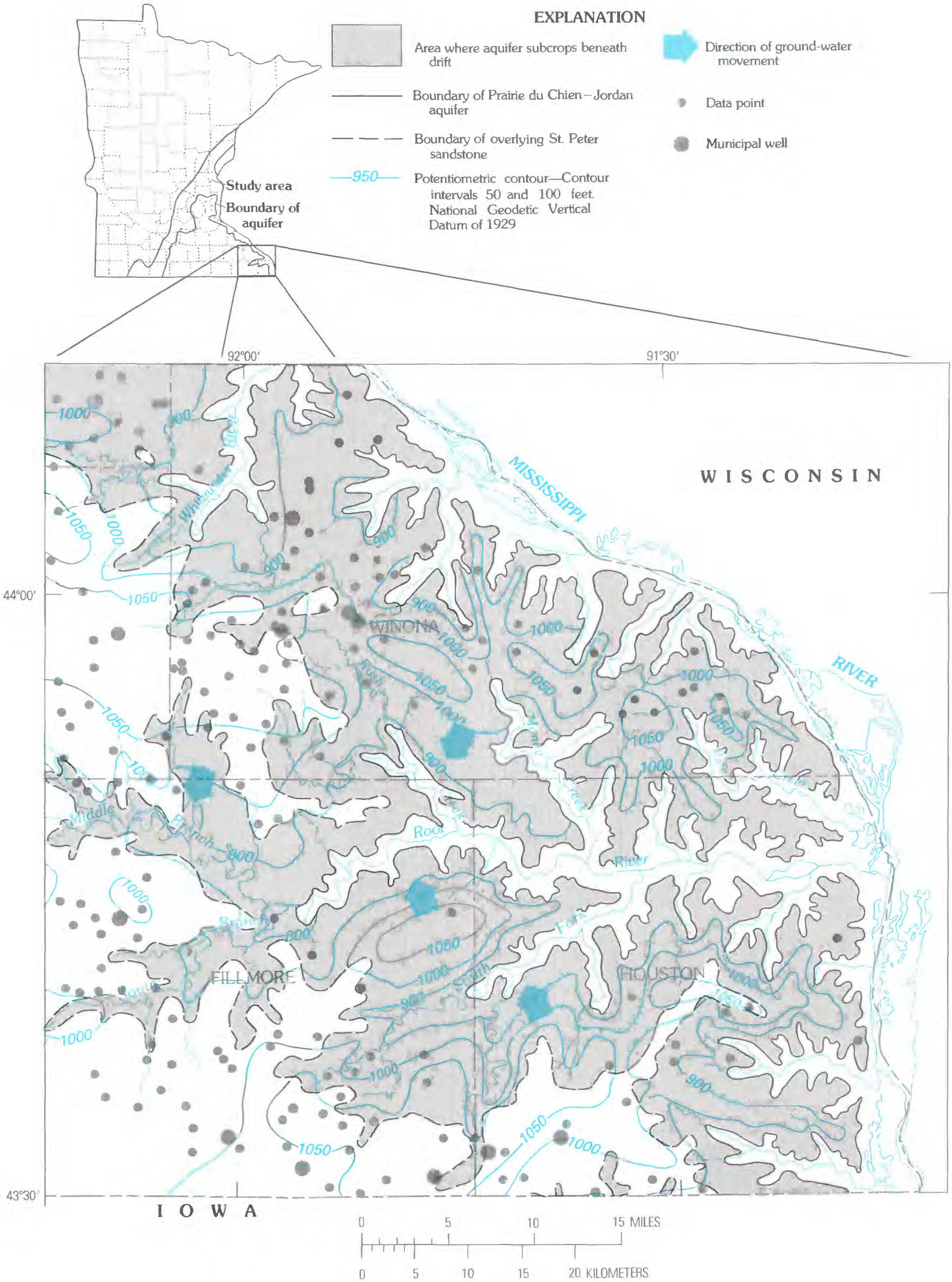
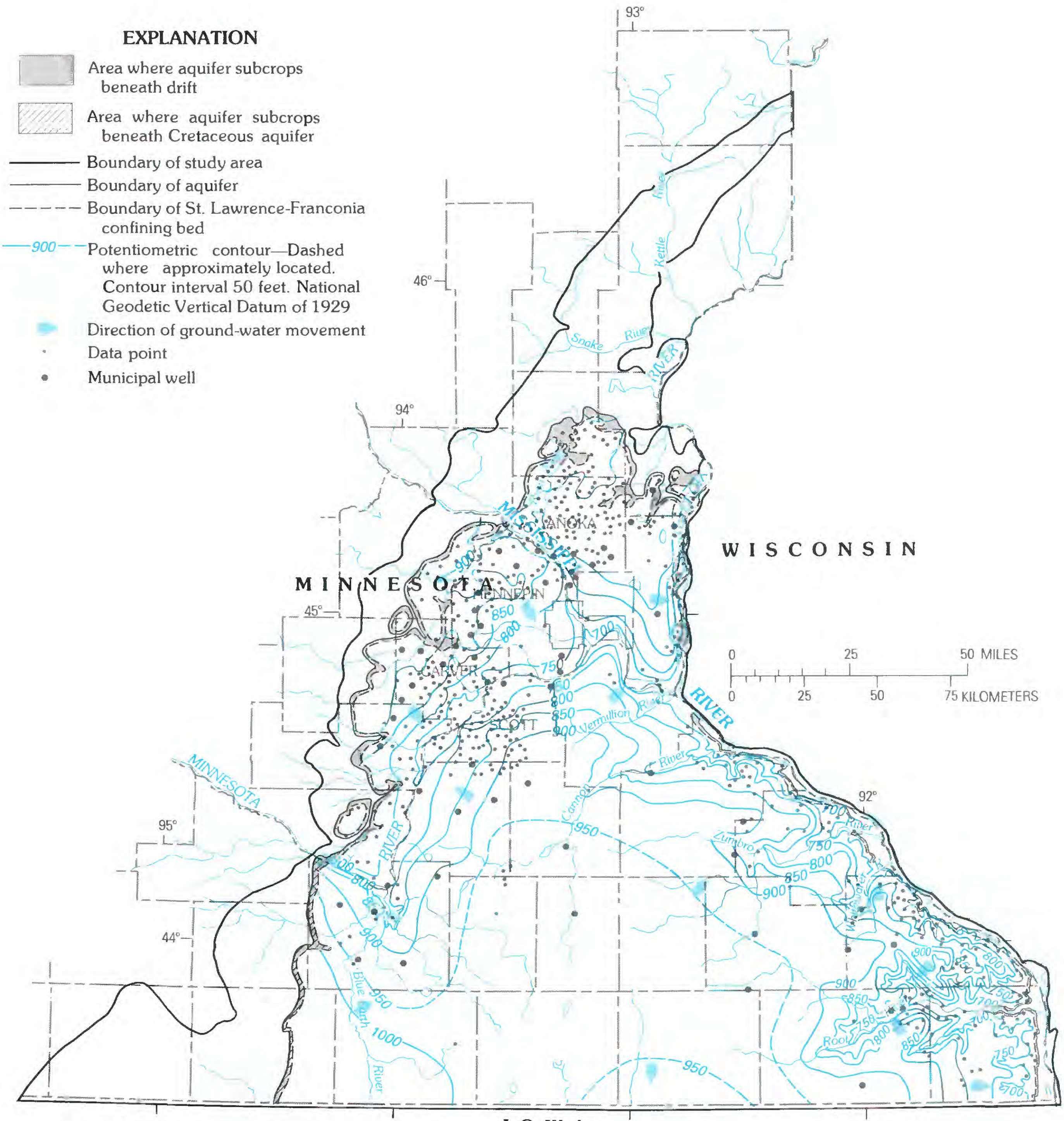



**Figure 3.5-2.** Area where Prairie du Chien-Jordan aquifer receives recharge through thin drift

# Flow to the Minnesota, Mississippi, and St. Croix Rivers Characterizes the Regional Pattern in the Ironton-Galesville Aquifer

Ground water also flows to Iowa

Regional ground-water flow in the Ironton-Galesville aquifer is from the western margin and central interior toward the major streams and toward Iowa (fig. 3.6-1). The rivers constitute major discharge boundaries for the aquifer (fig. 3.6-2). Recharge rates to the aquifer increase along the northwestern margin due to increased vertical permeability of the Mazomanie Member of the overlying Franconia For-




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

**Figure 3.6-1.** Regional potentiometric surface of the Ironton-Galesville aquifer in southeastern Minnesota, 1970–80 mation. Water in 97 percent of the areal extent of the aquifer is confined by the St. Lawrence-Franconia confining bed.

Water supplies from the Ironton-Galesville aquifer are most intensively developed adjacent to the Mississippi and Minnesota Rivers, particularly in Anoka, Hennepin, Scott, and Carver Counties. Many wells completed in the Ironton-Galesville aquifer are also open to the Mount Simon-Hinckley or Prairie du Chien-Jordan aquifers.

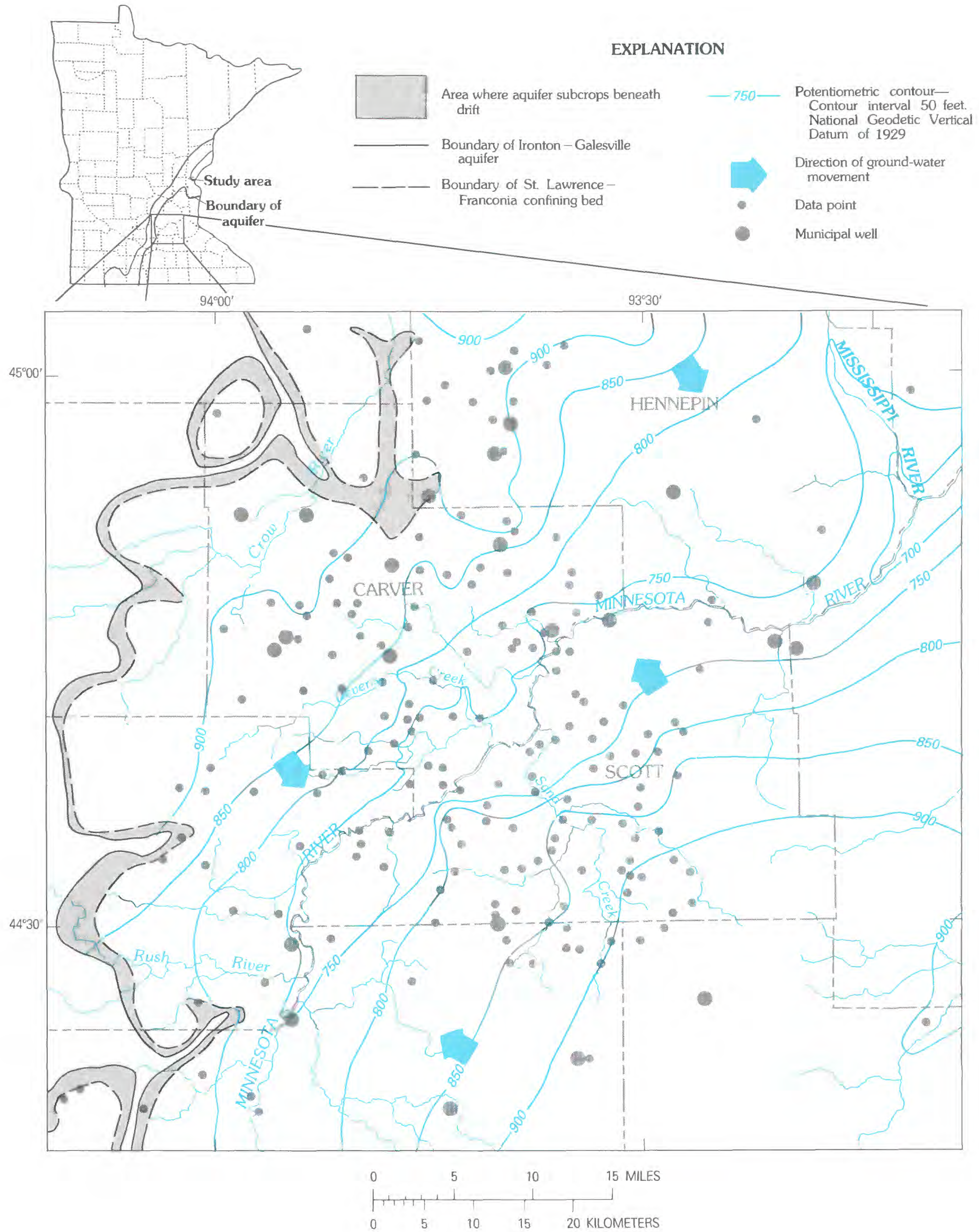



**Figure 3.6-2.** Potentiometric surface of Ironton-Galesville aquifer near the Minnesota River

# Flow in the Mount Simon-Hinckley Aquifer Is Toward Rivers, the Twin Cities Area, and Iowa

Extensive pumping from high-capacity wells in southeastern Hennepin County has created a regional cone of depression in the aquifer

Regional flow in the Mount Simon-Hinckley aquifer is predominantly toward the major rivers (fig. 3.7-1). The configuration of the potentiometric surface in the center of the Hollandale embayment is poorly known, but the data suggest a ground-water divide in this area similar to that in overlying aquifers. Flow from this broad potentiometric high is north toward the Minnesota and Mississippi Rivers and south toward Iowa and the Root River. North of the Twin Cities basin, flow is locally toward the Rum, Snake, Kettle, and St. Croix Rivers. A ground-water divide beneath a topographic high in northern Pine County separates flow into northeast and southwest directions.

Recharge to the aquifer is by leakage through the Eau Clarie confining bed and drift. However, in the southwest, leakage is through the overlying Cretaceous aquifer (fig. 2.1-1), which results in numerous

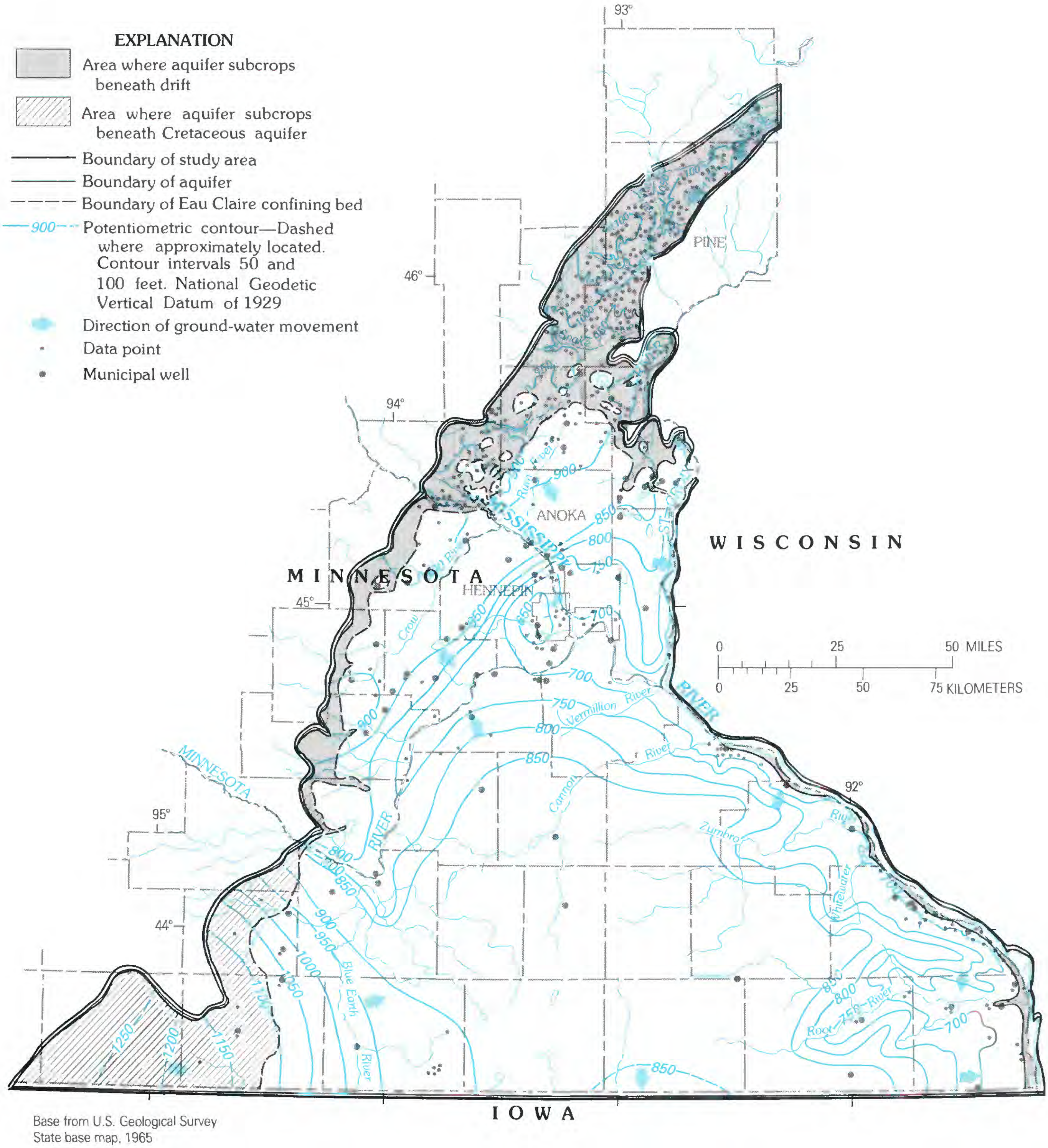



**Figure 3.7-1.** Regional potentiometric surface of the Mount Simon-Hinckley aquifer in southeastern Minnesota, 1970–80

water-quality changes in the Mount Simon-Hinckley aquifer (R. J. Wolf, written commun., 1981). Water in most of the Mount Simon-Hinckley aquifer is confined by the Eau Claire confining bed or by drift. In Pine County, however, the water is unconfined in a small area (fig. 3.2-1).

Within the Hollandale embayment, the Mount Simon-Hinckly aquifer ranks second in development of water supplies. Most of the pumpage is along the western and northern parts of the aquifer and in the Mississippi River valley. In the Twin Cities area, extensive pumpage from municipal, commercial, and industrial wells in southeastern Hennepin County has created a regional cone of depression in the aquifer (fig. 3.7-2) that affects local flow patterns.

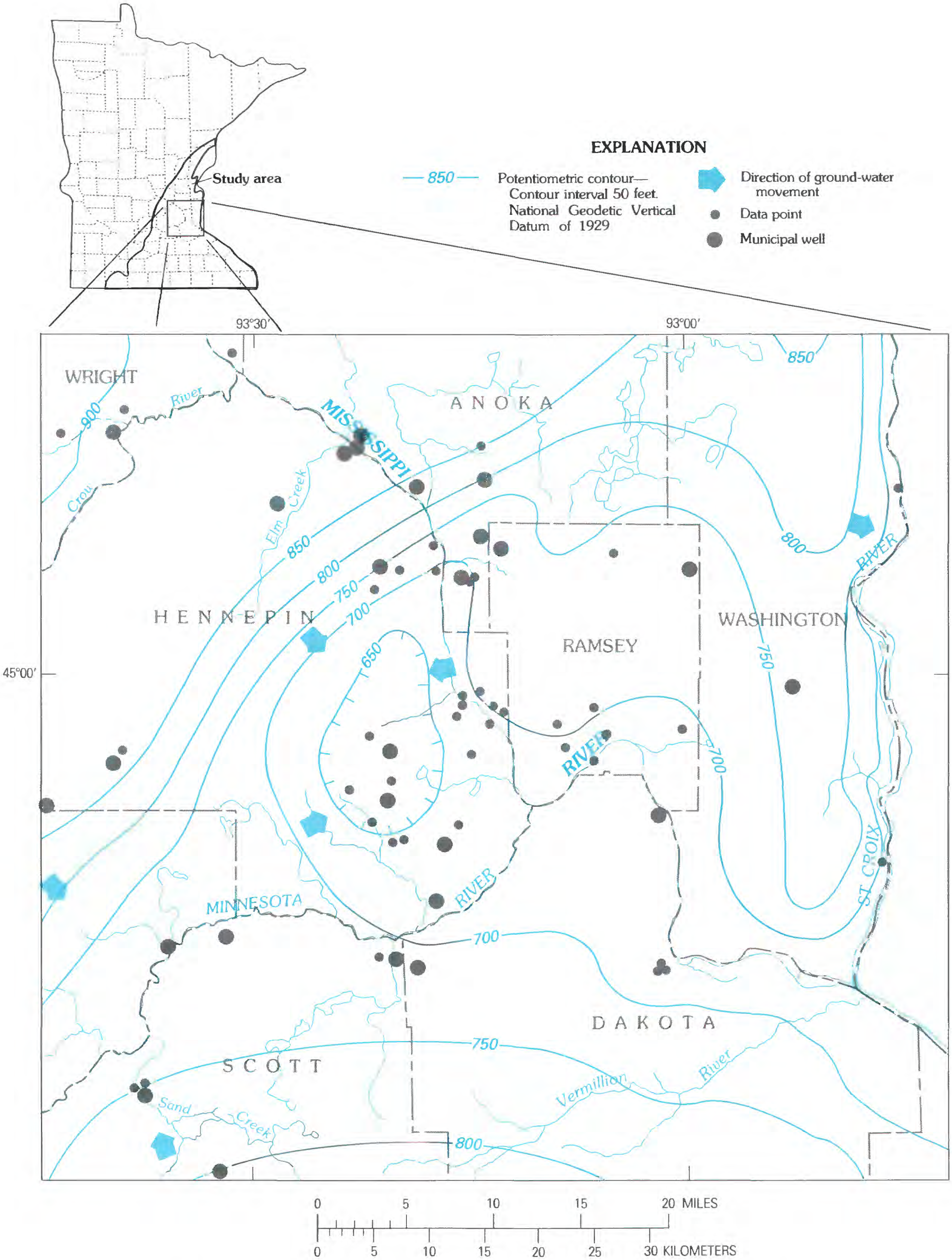



**Figure 3.7-2.** Regional cone of depression in the Mount Simon-Hinckley aquifer

## Head Decreases with Depth in Most of the Area

Head differences between aquifers decrease near mutual discharge and recharge areas

The head in each aquifer is generally higher than in the underlying aquifer(s), indicating downward flow. However, near major ground-water pumping centers and along parts of the Mississippi, Minnesota, St. Croix, and Root River valleys, the head increases with depth and flow is upward. Flowing wells are common in these river valleys. The accompanying hydrogeologic sections (fig. 4.0-1) depict these head relationships and illustrate aquifer discharge to the Minnesota River (section A-A′) and the Mississippi River (section B-B′).

Head differences between aquifers vary regionally, primarily because of changes in the hydraulic characteristics of the rock units, in the location of hydrologic boundaries, and in the rates of discharge and recharge. Regional head differences between the bedrock aquifers are as follows:

1. Between the Upper Carbonate and St. Peter aquifers, head differences range from about 30 ft in the west to 150 ft in the north and 250 ft in the east.
2. Between the St. Peter and Prairie du Chien-Jordan aquifers, head differences range from 10 to 15 ft in the western and eastern parts of the embayment to about 30 ft in the Twin Cities basin.
3. Between the Prairie du Chien-Jordan and Ironton-Galesville aquifers, head differences generally range from 15 ft in the west to 200 ft in the southeast. Head differences of 20 to 50 ft are common in the Twin Cities basin.
4. Between the Ironton-Galesville and Mount Simon-Hinckley aquifers, head differences are about 40 ft in the east and west, 25 ft in the north, and 20 to 75 ft in the Twin Cities basin.

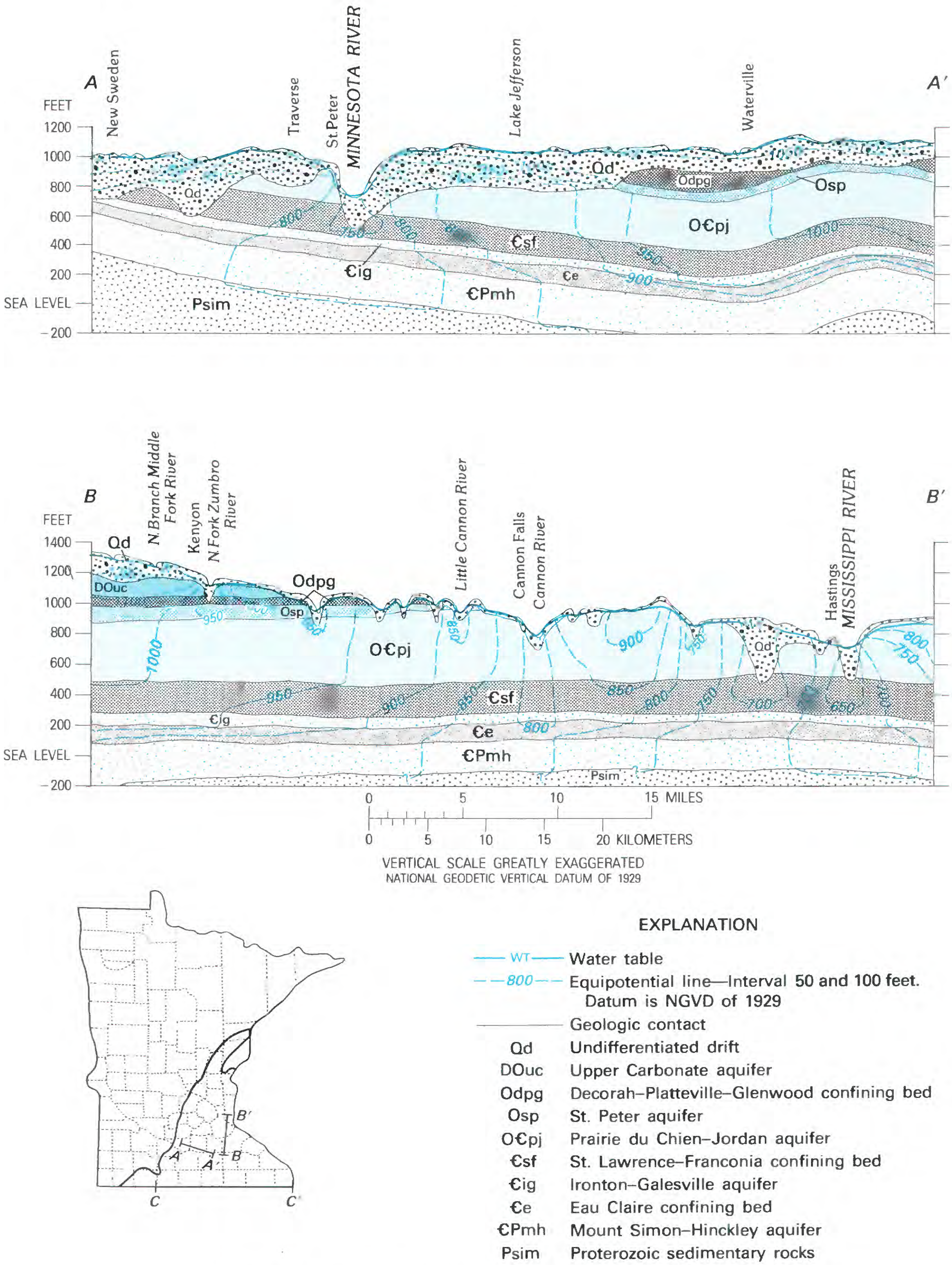



**Figure 4.0-1.** Hydrogeologic sections of southeastern Minnesota

Head differences between aquifers decrease near mutual discharge and recharge areas. Conversely, head differences between aquifers are greatest in areas where the recharge/discharge rates to an aquifer are most different from recharge/discharge rates to an underlying aquifer. Hydrogeologic section C-C′ (fig 4.0-2) illustrates the potentiometric-surface profiles of the regional bedrock aquifers along the Minnesota-Iowa border. Head differences between aquifers tend to decrease toward the mutual recharge areas beneath the Cretaceous and the drift aquifers in the west and toward the mutual discharge boundary of the Mississippi River in the east.

The Prairie du Chien-Jordan aquifer in Fillmore, Winona, and Houston Counties has ground-water mounds as high as 90 ft above the regional potentiometric surface (fig. 3.5-2). Similar mounds are present in the St. Peter aquifer (fig. 4.0-2). These mounds occur where the Decorah-Platteville-Glenwood confining bed has been removed by erosion (fig. 2.4-1) and the aquifers subcrop beneath drift that is generally less than 20 ft thick. Mounds also exist in Olmsted, Wabasha, and Goodhue Counties (figs. 3.4-2 and 3.5-1). The mounds represent ground-water divides that locally divert easterly flow in the St. Peter and Prairie du Chien-Jordan to other directions. The mounds are probably the result of increased recharge through the drift. Flow in the underlying Ironton-Galesville and Mount Simon-Hinckley aquifers is not affected by this increased recharge.

Vertical recharge (leakage) is directly proportional to the vertical hydraulic conductivity of the deposits overlying an aquifer and to the head difference between aquifers and is indirectly proportional to the saturated thickness of the overlying deposits. The vertical hydraulic conductivity of the deposits overlying the St. Peter and Prairie du Chien-Jordan aquifers is greater in the mound areas where the drift is thin and the Decorah-Platteville-Glenwood confining bed is absent than in areas to the west where the confining bed is present. Head differences between the aquifers are also greater locally in the mound areas.

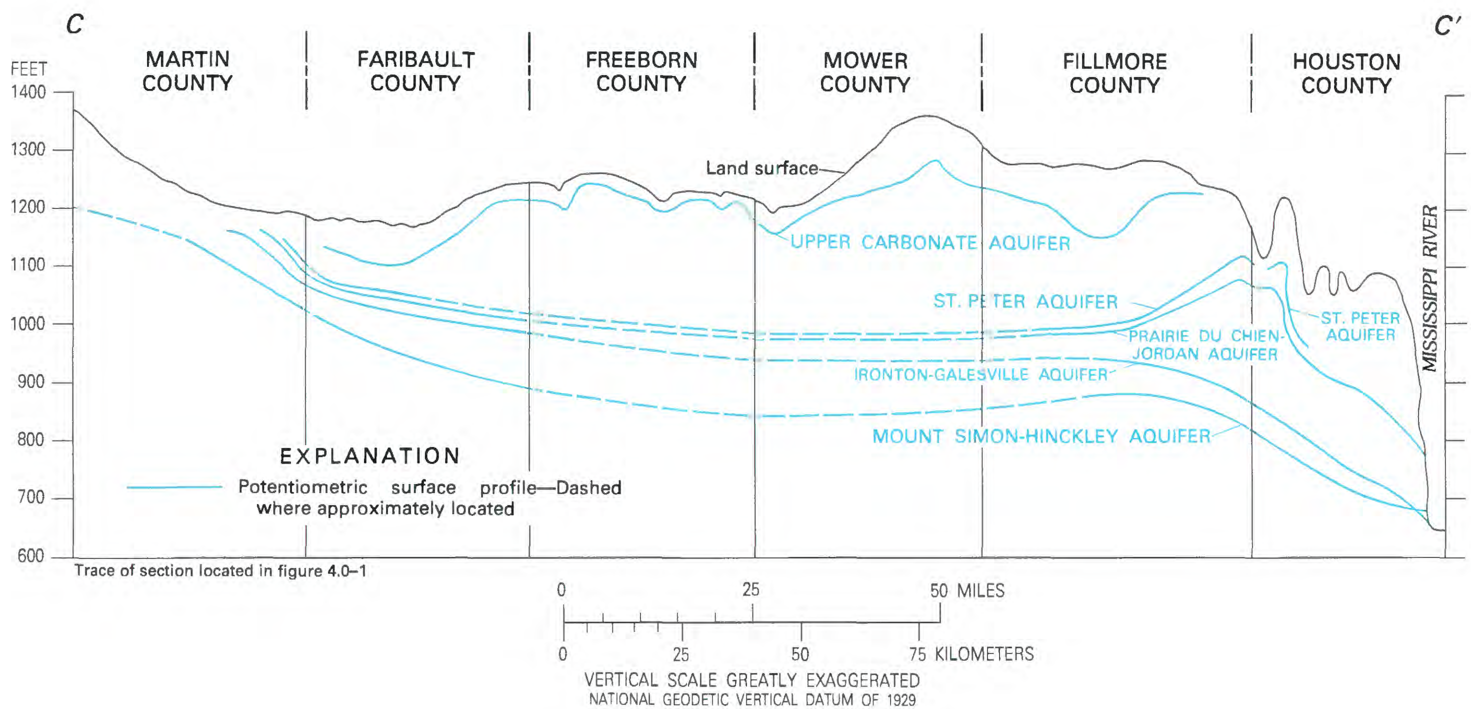



**Figure 4.0-2.** Potentiometric surface profiles of regional aquifers along the Minnesota-Iowa border.

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## Conversion Factors

| *Multiply inch-pound unit* | *By* | *To obtain SI (metric) unit* |
|---|---|---|
| in (inch) | 25.40 | mm (millimeter) |
| ft (foot) | 0.3048 | m (meter) |
| mi (mile) | 1.609 | km (kilometer) |
| gal (gallon) | 3.785 | L (liter) |
| acre | 0.4047 | ha (hectare) |
| acre-ft (acre-foot) | 1233 | $m^3$ (cubic meter) |
| ft/d (foot per day) | 0.3048 | m/day (meter per day) |
| $ft^2$/d (foot squared per day) | 0.0929 | $m^2$/day (meter squared per day) |
| gal/min (gallons per minute) | 0.06309 | L/s (liter per second) |
| $ft^3$/s (cubic foot per second) | 0.02832 | $m^3$/s (cubic meter per second) |

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