Characterization of Ground-Water Discharge from Bedrock Aquifers to the Mississippi and Minnesota Rivers at Three Areas, Minneapolis-St. Paul Area, Minnesota

By M.E. Schoenberg

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Conversion Factors and Vertical Datum

Multiply Inch-Pound Unit	By	To Obtain Metric Unit
inch (in.)	25.4	millimeter
foot (ft)	.3048	meter
mile (mi)	1.609	kilometer
foot per day (ft/d)	.3048	meter per day
square foot per day (ft^2/d)	.09290	square meter per day
square foot per day (ft^2/d)	.0003528	centimeter per second
cubic foot per second (ft^3/s)	.02832	cubic meter per second
cubic foot per day (ft^3/d)	.02832	cubic meter per day
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter

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

Characterization of Ground-Water Discharge from Bedrock Aquifers to the Mississippi and Minnesota Rivers at Three Areas, Minneapolis-St. Paul Area, Minnesota

Abstract

The hydrogeology at three areas along the Mississippi and Minnesota Rivers in the Minneapolis-St. Paul area, Minnesota, were studied in cooperation with the Legislative Commission on Minnesota Resources and the Minnesota Department of Natural Resources. This report characterizes ground-water discharge from bedrock aquifers to the Mississippi and Minnesota Rivers. Along the Mississippi River between Fridley and Brooklyn Center, a buried valley underlying the Mississippi River cuts through the overlying terrace deposits and glacial-drift deposits into two underlying bedrock hydrogeologic units: the St. Peter aquifer, and a rubble zone between the St. Peter and Prairie du Chien-Jordan aquifers. Shallow ground-water flow in the near-surface gray and upper red tills and sand and gravel outwash aquifer discharges to springs along the edge of the river. Ground water flowing through the rubble zone and upper part of the Prairie du Chien-Jordan aquifer probably discharges through alluvial deposits to the river. Along the Minnesota River between Eagan and Bloomington, almost 200 feet of post-glacial alluvium, glaciofluvial sand and gravel, Pleistocene lake deposits, and peat fill a bedrock valley under the present-day Minnesota River. As much as 40 feet of post-glacial peat, silty clay, clay, and muck lie near the river-valley walls. Confining units beneath the river channel impede the discharge of ground water from the underlying Prairie du Chien-Jordan aquifer to the river. Ground water discharges to wetlands, lakes, and springs along both the north and south side of the river. Along the Mississippi River at Minneapolis about 5 miles upstream of the confluence of the Minnesota and Mississippi Rivers, the Mississippi River lies in a post-glacial valley cut through thin glacial drift into the St. Peter aquifer. Beneath the river, ground water flows from the St. Peter aquifer through the overlying post-glacial alluvium to the Mississippi River. No confining unit separates the St. Peter aquifer and the river.

Introduction

Ground water flowing through aquifers near the Mississippi and Minnesota Rivers in the Minneapolis-St. Paul area, Minnesota, discharges to the rivers or is withdrawn for municipal use. Ground water is withdrawn from about 1,300 high-capacity wells (Horn, 1983; Woodward, 1986), most of which are completed in bedrock aquifers. Ground-water discharge to the rivers in the study area accounts for as much as 27 percent of the total streamflow leaving the area (Schoenberg, 1990). Peak ground-water withdrawals, moreover, coincide with times of minimum streamflow during summer months (Norvitch and others, 1974). Withdrawal of ground water by pumping can capture water that would naturally discharge to streams. Continued and increased pumpage can, therefore, reduce streamflow, particularly during the summer months. This could subsequently reduce the availability of surface water for public supply, for dilution of sewage effluent, and for navigation when surface-water flow is naturally small.

Geologic and hydrologic data were collected and analyzed at three areas (fig. 1) along the Mississippi and Minnesota Rivers in the Minneapolis-St. Paul area because of the potential effect of ground-water withdrawals on flow in the rivers (Schoenberg, 1990). The study was done to characterize ground-water discharge from bedrock aquifers to the Mississippi and Minnesota Rivers. This study was conducted between 1987 and 1992 by the U.S. Geological Survey in cooperation with the Legislative Commission on Minnesota Resources and the Minnesota Department of Natural Resources (MDNR).

Each study area is located in a different hydrogeologic setting. Data for each area were interpreted to describe ground-water flow along a single line, or transect, perpendicular to the rivers between upland areas adjacent to the rivers and the rivers themselves.

Purpose and Scope

This report characterizes ground-water discharge from bedrock aquifers to the Mississippi and Minnesota Rivers at three areas in the Minneapolis-St. Paul area, Minnesota. Existing water-level and geologic data, water level and geologic data from 39 new test holes and wells, and data from land and marine geophysical surveys are used to make hydrogeologic sections that describe the

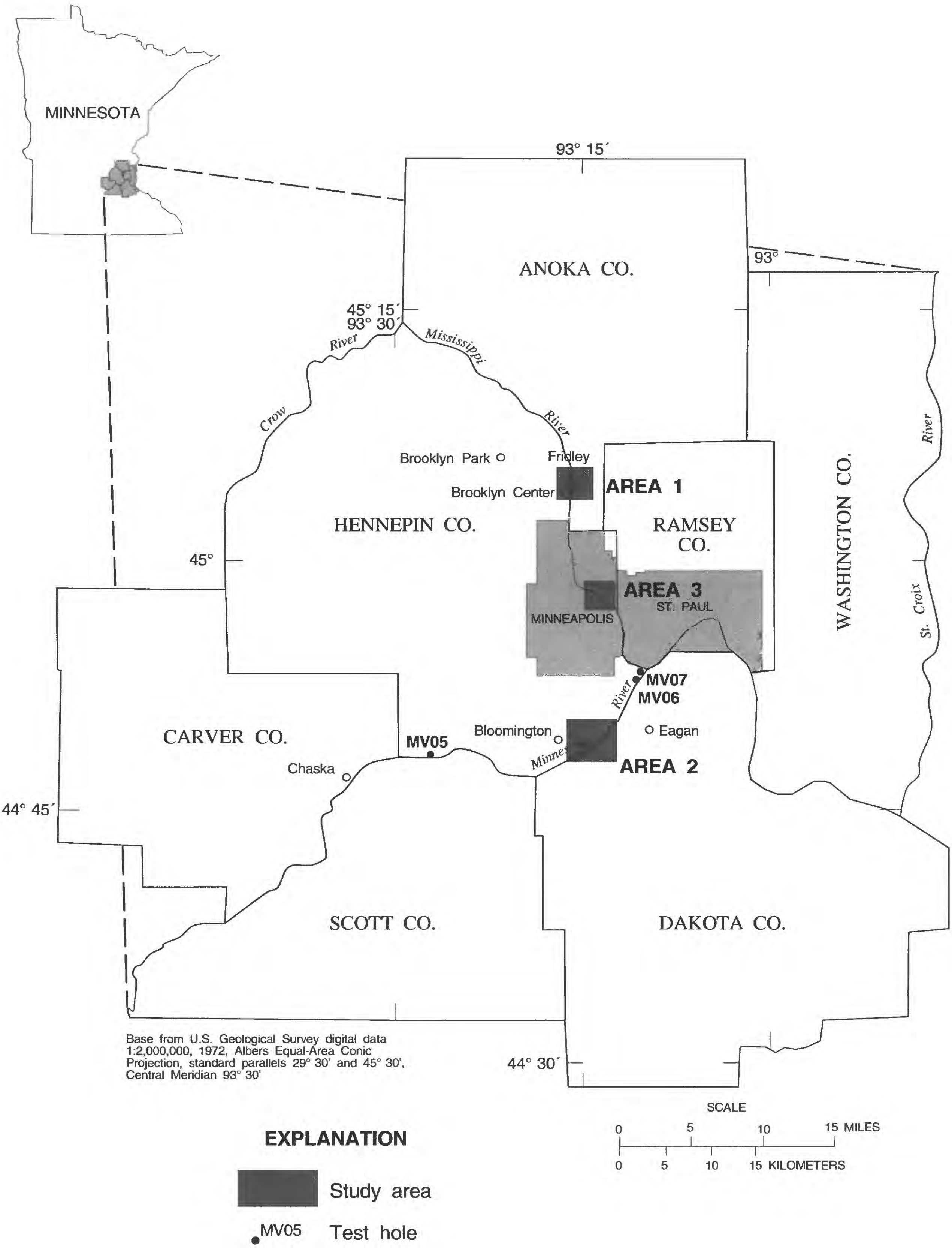


Figure 1. Location of study areas.

hydrogeology of each study area. Results of a numerical model of ground-water flow at one study area also are presented.

Previous Studies

Previous investigations have described hydrogeology and geology related to this study. McBride and Pfannkuch (1975), Pfannkuch and Winter (1984), and Winter and Pfannkuch (1984) discuss seepage between surface and ground water in the Minneapolis-St.Paul area. Schneider and Rodis (1961), Thompson (1965), and Winter and Pfannkuch (1976) describe the hydrology of materials and structures found in buried glacial meltwater deposits in Minnesota. Matsch (1983), and Kehew and Lord (1986) discuss deposits in the Minnesota River valley related to drainage of glacial Lake Agassiz. Schoenberg (1989, 1990) reviewed the geology and hydrogeology of the Twin Cities aquifer system in the Minneapolis-St. Paul area.

Methods of Study

Available data were compiled from logs of test holes for bridge and highway construction of the Minnesota Department of Transportation, from logs of water wells from the files of the Minnesota Geological Survey (MGS), from published reports and geologic maps of the U.S. Geological Survey (USGS), and from consultant's reports. Where data were not available along a transect, additional data from within the study areas and from test holes MV05, MV06, and MV07 (fig. 1) were used.

Hollow-stem auger and mud-rotary drilling methods were used to bore test holes. Samples collected with split-spoon samplers were used to describe the geology. Shuter and Teasdale (1989) describe hollow-stem auger and mud rotary drilling methods. Individual test holes or wells were identified by a number assigned by the State of Minnesota, the Minnesota Unique Number.

Hydraulic properties of selected hydrogeologic units were estimated from analysis of split-spoon cores, analysis of slug tests, or both. Cores were collected in plastic liners inside split-spoon samplers. Constant-head permeability in straight wall cylinders for selected samples of core was determined by Twin Cities Testing Corporation[1] according to methods described in American Society for Testing Materials (ASTM) standard D2434-68 (American Society for Testing Materials, reapproved 1974). Falling-head permeability for selected samples of core was determined by Twin Cities Testing Corporation using a triaxial-like chamber with the flexible-wall method. Hydraulic properties were estimated using grain-size analyses of disaggregated cores. Grain-size analyses of selected samples were determined by Twin Cities Testing Corporation according to ASTM standard D422-63 (American Society for Testing Materials, reapproved 1990) and the University of Minnesota according to the methods of Folk (1974). Hydraulic properties were estimated from grain-size distributions for alluvium and outwash, using the method of Summers and Weber (1984). Slug tests were done by pouring water down a well bore to raise the head in a well. Water-level measurements were made as the water returned to equilibrium in the well bore. Hydraulic conductivity was determined from results of these tests using the methods of Bouwer and Rice (1976) and Bouwer (1989).

Geophysical surveys were used to determine the altitude of the top of the Prairie du Chien-Jordan aquifer. Continuous marine-seismic-reflection profiling was conducted using methods described by Hansen (1986). Seismic-refraction profiling (Haeni, 1986a, 1986b, 1988) was conducted by the MDNR along four lines near the Fridley/Brooklyn Center transect in Area 1.

Continuous water-level measurements were made at selected wells in Area 1 using transducers and data loggers. Calibration check measurements were made monthly. All other water-level measurements were made with steel tape and chalk.

Potentiometric maps of the Prairie du Chien-Jordan and St. Peter aquifers (Norvitch and others, 1974; Norvitch and Walton, 1979; Schoenberg, 1984) were used to select one transect in each area. The transects lay along lines of ground-water flow, perpendicular to potentiometric contours.

Ground-water flow in cross section was simulated under steady-state conditions for the Fridley/Brooklyn Center transect using a finite-difference, ground-water-flow model (McDonald and Harbaugh, 1988).

Acknowledgments

The author thanks officials and employees of the Anoka County Parks System, City of Brooklyn Park, City of Eagan, Fridley Public Schools, Metropolitan Waste Control Commission, and U.S. Fish and Wildlife Service for their cooperation in allowing the installation of observation wells. The author also thanks Sever Peterson and Fort Snelling State Park for access to their property for drilling exploratory test holes. Thanks also goes to Andrew Strietz, Minnesota Department of Natural

[1] Use of the firm name in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

Resources, who conducted refraction geophysical surveys at selected sites and to Howard Hobbs, Minnesota Geological Survey, who constructed detailed lithologic logs of selected boreholes.

Characterization of Ground-Water Discharge from Bedrock Aquifers

Ground-water discharge from bedrock aquifers to rivers was characterized at two areas along the Mississippi River and one area along the Minnesota River. The hydrogeologic framework, hydraulic properties, and ground-water flow system are discussed for each area.

Discharge to the Mississippi River at Fridley/Brooklyn Center

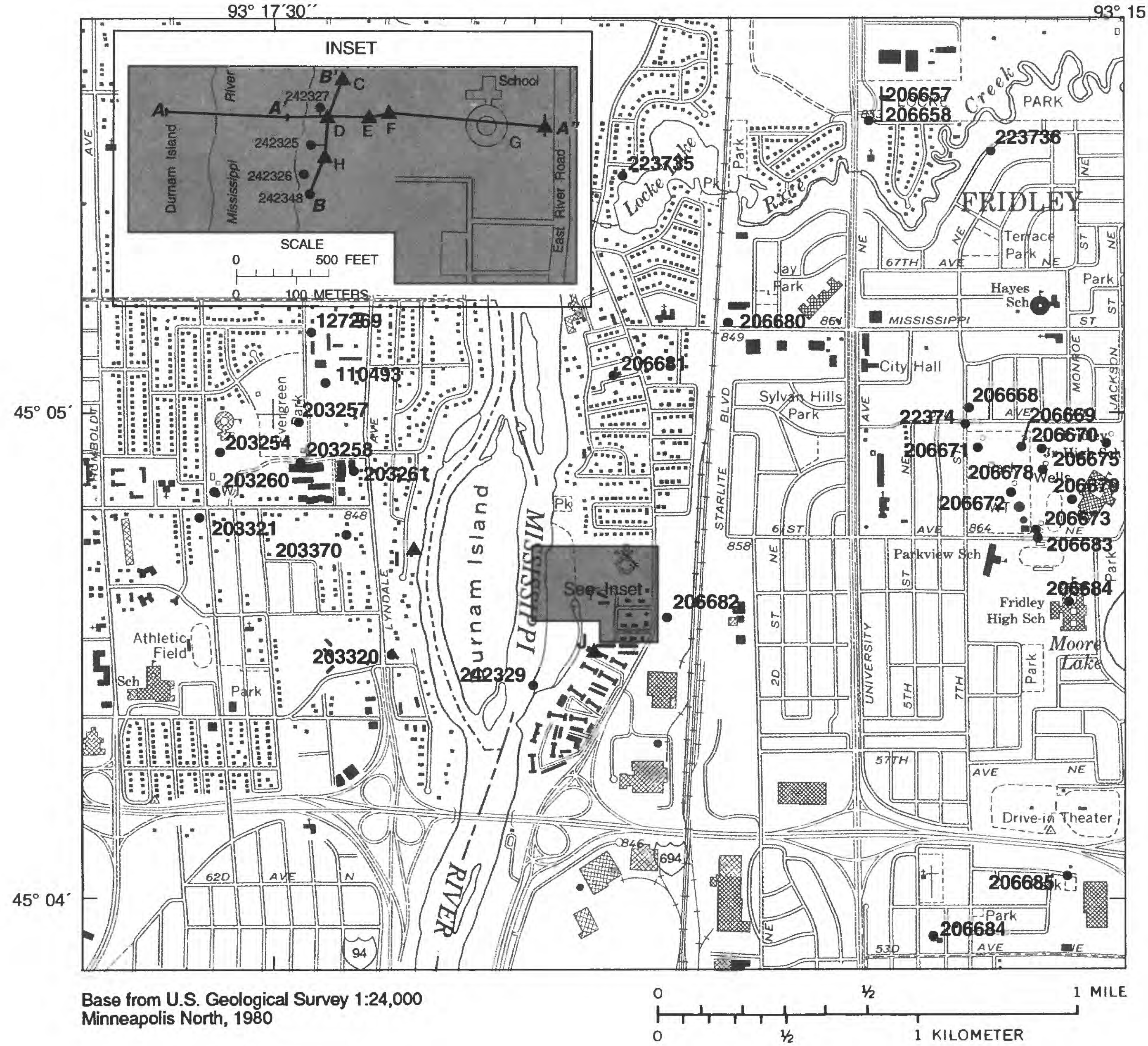
Area 1 is located about 2 mi north of Minneapolis along the Mississippi River between Fridley and Brooklyn Center (fig. 1). Thirty-two test holes were drilled to provide samples of the hydrogeologic units in this area. Twenty-seven wells were installed in eight clusters in those test holes to collect data needed to determine ground-water flow (table 1, fig. 2).

Hydrogeologic framework

Eight unconsolidated hydrogeologic units overlie the bedrock St. Peter and Prairie du Chien-Jordan aquifers. Collectively, the overlying units have been described in the past as undifferentiated glacial drift (table 2). The units are, in descending order, alluvium, terrace deposits, a gray till, an upper red till, a sand and gravel outwash, olive-black till, a lower red till, and a glacial outwash (fig. 3).

Table 1.--Well-cluster label, well-identification number, screened interval, hydrogeologic unit at screened interval, and relative depth in aquifer system for wells drilled for this project, Area 1, at Fridley/Brooklyn Center area near Minneapolis-St. Paul, Minnesota

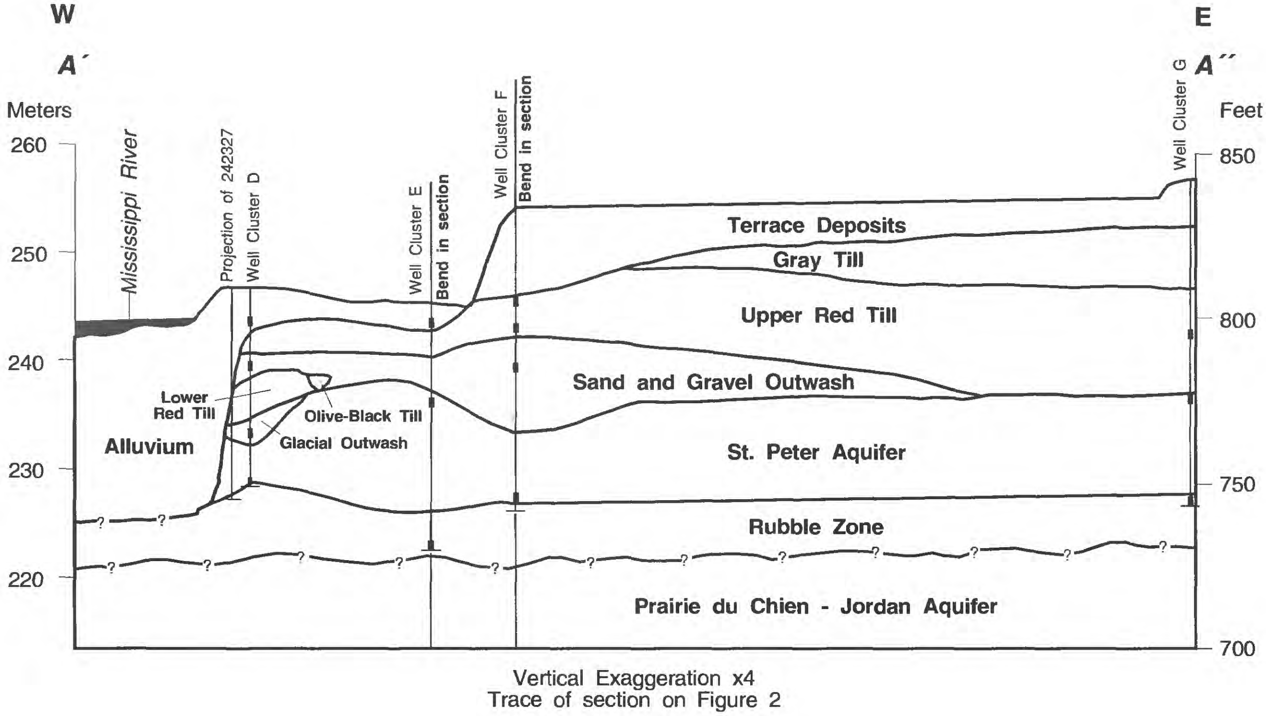
Well cluster label	Well identification number	Screened interval (feet below land surface)	Hydrogeologic unit at screened interval (relative depth in aquifer system)
C	457728	11-14	Upper red till (water table/shallow)
	457727	30-33	St. Peter aquifer (middle)
	457726	56-59	St. Peter aquifer/rubble zone (deep)
D	457742	8-11	Alluvium (water table/shallow)
	457730	23-26	Sand and gravel outwash (shallow)
	457754	42-45	Glacial outwash (middle)
	457729	61-64	St. Peter aquifer/rubble zone (deep)
E	457737	5-8	Alluvium (water table/shallow)
	457736	29-32	St. Peter aquifer (middle)
	457731	73-76	Rubble zone (deep)
F	457745	27-30	Upper red till (water table/shallow)
	457755	36-39	Upper red till (water table/shallow)
	457744	47-50	Sand and gravel outwash (middle)
	457743	88-91	St. Peter aquifer (deep)
G	457735	47-50	Upper red till (water table/shallow)
	457733	64-67	St. Peter aquifer (middle)
	457732	96-99	St. Peter aquifer/rubble zone (deep)
H	457741	8-11	Alluvium (water table/shallow)
	457740	47-50	St. Peter aquifer (middle)
	457750	62-65	St. Peter aquifer/rubble zone (deep)
I	447748	26-29	Alluvium (water table/shallow)
	227985	36-39	Alluvium (water table/shallow)
	447749	48-51	St. Peter aquifer (middle)
	447746	88-91	Rubble zone (deep)
J	457752	31-34	Alluvium (water table/shallow)
	457751	51-54	Alluvium (middle)
	447753	91-94	St. Peter aquifer/rubble zone (deep)

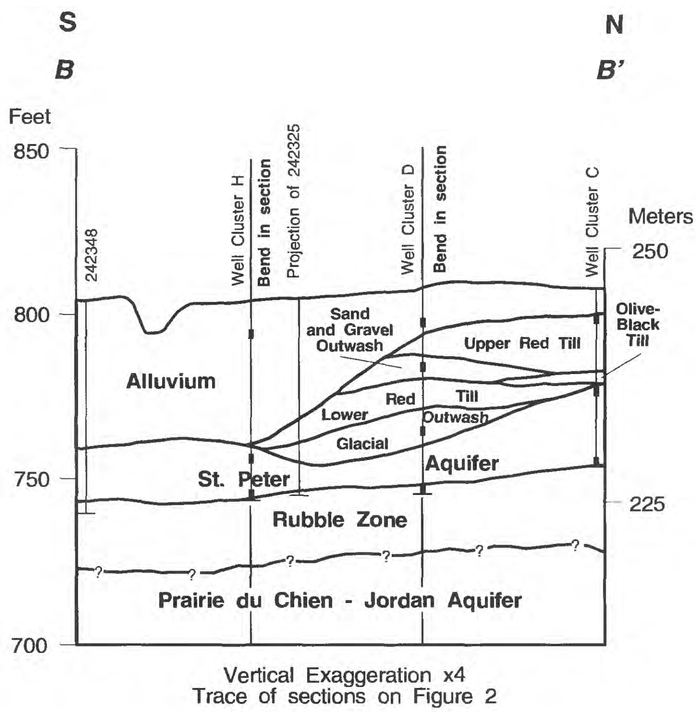


EXPLANATION

A——A′	Trace of section
•——	Line of projection of well or test hole onto trace of section
•203320	Well or test hole (with identification number)
▲J	Well Cluster (with identification letter)

Figure 2. Location of wells, test holes, and hydrogeologic sections, Area 1.





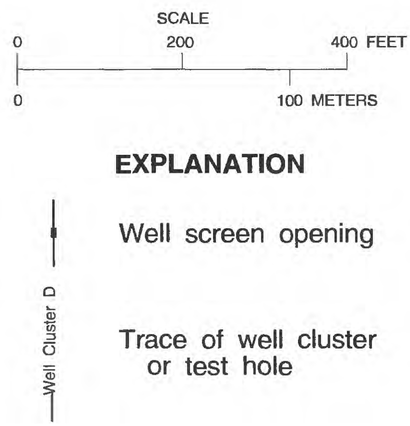


Figure 3. Hydrogeologic sections A´ - A´´ and B - B´, Area 1, Fridley/Brooklyn Center area near Minneapolis-St. Paul, Minnesota.

A buried valley underlying the Mississippi River cuts through the overlying terrace deposits and glacial-drift deposits into two underlying bedrock hydrogeologic units: the St. Peter aquifer, and a rubble zone between the St. Peter and Prairie du Chien-Jordan aquifers (fig. 3). The St. Peter aquifer has been completely eroded in the middle of the buried valley, and is about 30 ft thick along the walls of the buried valley. Data from this project show that a rubble zone, ranging from 10 to 30 ft thick, contains sand from the overlying St. Peter Sandstone and gravel and cobble clasts from the underlying Prairie du Chien Group. Geologically, the rubble zone is the lowermost part of the St. Peter Sandstone in Area 1. Hydrogeologically, it is a separate unit. The thickness of the rubble zone was estimated from a comparison of test-hole data and results of seismic-refraction surveys. In figure 3 question marks reflect the uncertainty about the location of the boundaries of the rubble zone. Mossler (1989) estimated that the Prairie du Chien-Jordan aquifer is 120 ft thick near the transect. Only the top of this aquifer is shown in figure 3. The top of the St. Lawrence-Franconia confining unit, not shown in figure 3, is considered an impermeable base to the Prairie du Chien-Jordan aquifer in this report (table 2).

Hydraulic properties

Hydraulic conductivity of alluvium, upper red till, olive-black till, and St. Peter aquifer were determined with permeameter tests (table 3). Hydraulic conductivity of the alluvium, upper red till, St. Peter aquifer, combined St. Peter aquifer and rubble zone, and rubble zone were determined with slug tests (table 4). The values from the combined St. Peter aquifer and rubble zone reflect the hydraulic conductivity of the bottom of the St. Peter aquifer because of the method of well construction. In this report, wells open to the combined St. Peter aquifer and rubble zone are hereafter referred to as wells open to the St. Peter aquifer/rubble zone. Hydraulic conductivity values were estimated for water-lain sediments from grain-size distributions.

Permeameter tests (table 3) were run on 14 split-spoon samples from well 457726 and one sample each from wells 457732 and 457735. The hydraulic conductivity for alluvium and upper red till ranged from 30 to 50 ft/d and $5x10^{-4}$ to 0.3 ft/d, respectively. Values for the olive-black till and the St. Peter aquifer ranged from $4x10^{-5}$ to 0.8 ft/d and were 0.3 ft/d, respectively. Vertical variations in the moisture content and dry density of the upper red till indicate that the upper red till is composed of three layers (table 3).

Slug tests were performed in 11 wells in Area 1 (table 4) to determine hydraulic conductivities. In wells open to alluvium, hydraulic conductivity ranged from 0.3 to 80 ft/d. A single hydraulic conductivity of 4 ft/d was determined for the top of the upper red till. Hydraulic conductivity for the top of the St. Peter aquifer ranged from 0.6 to 15 ft/d. Hydraulic conductivity for wells screened at the St. Peter aquifer/rubble zone ranged from 20 to 35 ft/d. Hydraulic conductivity of the rubble zone was 10 ft/d.

Estimated values for the hydraulic conductivity of water-lain sediments were obtained from grain-size distributions for 25 split-spoon samples using the methods of Summers and Weber (1984). Medium- to coarse-grained alluvium has a hydraulic conductivity as great as 50 ft/d. Medium- to fine-grained alluvium has a value of about 5 ft/d. Glacial outwash has conductivity as low as 3 ft/d. The estimated hydraulic conductivity of the St. Peter aquifer is about 5 ft/d.

Ground-water flow system

Hydraulic heads from eight well clusters were used to delineate flow through Area 1 (fig. 2). Individual wells in each cluster were open to approximately the water table, the top of the St. Peter aquifer, or the immediately overlying glacial outwash; or sand and gravel outwash, or the bottom of the St. Peter aquifer, or underlying rubble zone, or the St. Peter aquifer/rubble zone. Three clusters were on a line almost parallel to the Mississippi River (section B-B′ in fig. 3). Four clusters were on a line perpendicular to the river (section A′-A″ in fig. 3). The two lines of well clusters share one cluster (Well Cluster D). One cluster was on the west side of the Mississippi River (Well Cluster I) and one was south of the main group of wells (Well Cluster J) (fig. 2). Hydraulic heads were recorded hourly at Well Clusters D, F, and G on the line perpendicular to the river from July 1989 through October 1990. River stage also was recorded hourly from August 1989 through March 1990, and May 1990 through August 1990.

Hydraulic head changes in the wells at Well Cluster D (100 ft east of the river) matched overall changes in river stage (fig. 4). The hydrographs for the well open to the water table in the alluvium (well 457742, shallow) and the well open to the St. Peter aquifer/rubble zone (well 457729, deep) are shown in figure 4. Hydraulic heads in the well open to the water table in the alluvium (well 457742, shallow) and the well open to the sand and gravel outwash (well 457730, shallow) were similar. Hydraulic heads in the well open to glacial outwash (well 457754, middle) and the well open to the St. Peter aquifer/rubble zone (well 457729, deep) also were similar. The differences between wells 457742 and 457730, and wells 457754 and 457729 were too small to show in figure 4.

Table 2.--Hydrogeologic units and hydraulic properties in the Minneapolis-St. Paul area (modified from Stone, 1965)
[ft/d, feet per day]

Period	Geologic formation	Hydrogeologic units defined for this study	Approximate range in thickness and average thickness (feet)	Description	Water-bearing characteristics
Quaternary	Undifferentiated glacial drift	Drift aquifer	0-600 250	Generally well sorted, fine- to coarse-grained deposits in sandplains or outwash plains may overlie, underlie, or be interlayered with poorly sorted, fine- to very coarse-grained, dense tills. Contains deposits from two glacial ice lobes. Superior Lobe deposits tend to be a red homgeneous mixture of sand, clay, gravel, and boulders. Des Moines Lobe deposits are gray and tend to be distinct layers of sand and clay.	Stratified well sorted deposits of sand and gravel yield moderate to large supplies of water to wells. Recharge from and discharge to bedrock aquifers move through layer. Ratio of horizontal to vertical conductivity (K_h/K_v) may be as great as [1]$1x10^5$:1. Average vertical hydraulic conductivity (K_v) for till and for sand and gravel ranges from $1.8x10^{-1}$ to $6.7x10^{-4}$ ft/d and about 2.1 ft/d, respectively[2,3]. Horizontal hydraulic conductivity ranges from 0.002 to 650 ft/d[4].
Ordovician	Decorah shale	Decorah-Platteville-Glenwood confining unit	0-110 50	Decorah: shale, fissile, fossiliferous.	Confining unit where present. Fractures and solution cavities in limestone can yield small supplies to wells. Vertical hydraulic conductivity estimated as [1]$3.5x10^{-6}$ ft/d.
	Platteville Formation			Platteville: limestone, dolomitic, with thin, crinkley beds and massive, finely-crystalline dolomite. Upper few feet interbedded and grades into overlying shale.	
	Glenwood Formation			Glenwood: siltstone, sandy, clayey; sandy shale with minor sandstone layers in upper few feet.	
	St. Peter Sandstone	St. Peter aquifer	0-100 60	Sandstone, fine- to medium-grained massive, quartzose, with well-sorted, uniform, rounded and subrounded grains[5,6]. Grades upward into overlying unit[5,6]. Cut by preglacial bedrock valleys and present-day river valleys.	Water is present under both confined and unconfined conditions. Horizontal hydraulic conductivity ranged from 24 to 50 ft/d for field tests[3], 0.03 to 43.9 ft/d for lab tests[3], and regionally is about [7]15 ft/d.
		Lower St. Peter confining unit	0-50 45	Sandstone, friable, well-sorted, fine-grained[5,6], interlayered with clayey siltstone that thins and disappears southward[7]. Cut by preglacial bedrock valleys and present-day river valleys.	Confining unit is present where not cut by pre-glacial valleys. May be above water table locally. Vertical hydraulic conductivity estimated as [2,3]$1.3x10^{-3}$ ft/d.

Table 2.--Hydrogeologic units and their hydraulic properties--Continued

Period	Geologic formation	Hydrogeologic units defined for this study	Approximate range in thickness and average thickness (feet)	Description	Water-bearing characteristics
Ordovician--Continued	Prairie du Chien Group	Prairie du Chien-Jordan aquifer	0-350 200	Prairie du Chien: dolomite, sandstone and sandy dolomite, thinly to thickly bedded[5,6].	Prairie du Chien: permeability is due to fractures, joints, and solution cavities. Horizontal hydraulic conductivity ranges from 20 to 106 ft/d for field tests[2], with an average of 44 ft/d. Jordan: permeability is mostly intergranular but may be due to joint partings in cemented parts. Horizontal hydraulic conductivity ranged from 19 to 107 ft/d for field tests[2], 4.6 to 166 ft/d for lab tests[2], and regionally is about [1,2,7]50 ft/d. Prairie du Chien-Jordan aquifer: horizontal hydraulic conductivity regionally ranges from 25 to [1]50 ft/d.
Cambrian	Jordan Sandstone			Jordan: sandstone, medium- to coarse-grained, massive to bedded, cross bedded in places, quartzose, loose to well cemented, rarely present without overlying dolomite[5,6].	
	St. Lawrence Formation	St. Lawrence-Franconia confining unit	0-240 200	St. Lawrence: siltstone, dolomitic, interlayered with very-fine-grained sandstones[6].	Confining unit where overlain by Prairie du Chien-Jordan aquifer.
	Franconia Formation			Franconia: sandstone, dolomitic, fine-to coarse-grained; southward, interfingered with upper very fine- to fine-grained silty sandstone and lower fine-grained quartz sandstone[5].	

1 Schoenberg, 1990
2 Larson-Higdem and others, 1975
3 Norvitch and others, 1974
4 Helgesen, 1977; Helgesen and Lindholm, 1977; Lindholm, 1980
5 Austin, 1972
6 Mossler, 1972
7 Woodward, 1986

Table 3.--Hydraulic conductivity determined by permeameter tests[1] and physical properties of selected samples, Area 1, Fridley/Brooklyn Center area near Minneapolis-St. Paul, Minnesota

[ft, feet; ft/d, feet per day; lb/ft^3, pound per cubic foot]

Well or test hole identification number	Hydrogeologic unit name	Sample depth (ft)	Average depth below top of hydro-geologic unit (ft)	Hydraulic conductivity (ft/d)	Moisture content (percent)	Dry density (lb/ft^3)	Gravel (percent)	Sand (percent)	Silt (percent)	Clay (percent)	Comments
457726	Alluvium	2-3	2.5	30	12	79	0.0	71	21.5	7.1	Overbank deposit
		4-6	5	30	3	91	.3	97.7	2.0	0	Overbank deposit
		6-7	6.5	50	6	96	.5	97.0	2.5	0	Overbank deposit
	Upper red till	8-9	.3	.3	12	126	6.0	82.1	11.0	.9	Paleosol horizon on top of till, 8.5 ft below land surface
		10-11	2.1	$4x10^{-2}$	9	130	31.5	58.5	8.8	1.4	Upper layer of upper red till
		12-13	3.9	.2	10	130	9.1	62.8	20.9	7.2	Upper layer of upper red till
		14-16	6.5	.2	9	132	9.3	61.2	21.9	7.6	Upper layer of upper red till
		16-17	8.0	$5x10^{-2}$	6	130	5.2	64.5	21.0	9.3	Upper layer of upper red till
		20-21	12	.2	13	118	4.1	38.2	48.2	9.5	Mixed layer of upper red till
		22-24	14	$5x10^{-4}$	12	124	3.6	40.2	38.6	17.6	Lower layer of upper red till
		25-27	18	$5x10^{-2}$	13	116	8.2	35.0	36.1	20.7	Lower layer of upper red till
	Olive-black till	27-29	2.0	$4x10^{-5}$	18	110	3.2	25.7	40.9	30.2	Color variable; mixed layer
		29-31	4.0	.8	19	111	.2	89.7	6.0	4.1	Color variable; mixed layer
	St. Peter aquifer	35-37	4.0	.3	19	109	0	56.4	43.0	.6	
457732	Upper red till	40-42	.75	$1x10^{-3}$	11	132	14.7	58.5	21.8	5.0	Upper layer of upper red till
457735	Upper red till	47-49	14	.3	14	123	16.0	58.0	19.3	6.7	Possible mixed layer of upper red till

[1] Tests conducted under contract by Twin Cities Testing.

Table 4.--Hydraulic conductivity determined by slug tests at selected wells, Areas 1 and 2, Fridley/Brooklyn Center and Eagan/Bloomington areas near Minneapolis-St. Paul, Minnesota

[ft, feet; ft/d, feet per day; >, greater than]

Well identification number	Hydrogeologic unit name	Depth below surface of top of unit (ft)	Depth below surface of bottom of unit (ft)	Screened interval below land surface (ft)	Location in aquifer	Depth to water, August 1990 (ft)	Displacement (ft)	Hydraulic conductivity (ft/d)
[1]227986	Post-glacial alluvium	0	>12	8-11	Top	2.3	5.4	2
[1,2]227987		0	>12	7-10	Top	3.4	5.5	.01
457737	Alluvium	0	8	5-8	Top	2.7	4.0	10
457741		0	45	8-11	Top	4.3	2.1	80
[3]447751		0	61	51-54	Bottom	29.6	6.0	.3
457728	Upper red till	8	26	11-14	Top	6.7	2.8	4
457727	St. Peter aquifer	30	59	30-33	Top	4.3	5.0	.6
457740		45	62	47-50	Top	2.3	3.4	15
447749		43	71	48-51	Top	28.9	4.9	1
457736		29	63	29-32	Top	.8	5.3	2
457750	St. Peter aquifer/rubble zone[4]	60	65	62-65	Bottom	2.4	3.7	35
447753		50	94	91-94	Bottom	27.4	2.6	20
457746	Rubble zone	84	>91	88-91	Middle	28.1	4.3	10

[1] Area 2 site

[2] Peat

[3] Dislodged block of St. Peter Sandstone in alluvium

[4] Well screen and sand pack hydraulically connect St. Peter aquifer and rubble zone

Hydraulic-head changes in the wells reflected rapid fluctuations of 0.5 ft or less in river stage. The similar response in each of the wells indicates that confining units do not hydraulically separate the ground-water system from the river, at least to a depth of 64 ft. That depth is at the bottom of the hole drilled for the well open to the St. Peter aquifer/rubble zone (well 457729, deep).

Hydraulic-head increases with depth at Well Cluster D (fig. 4). This indicates upward ground-water flow at this site regardless of the rate of change in river stage. Hydraulic head in the well open to the St. Peter aquifer/rubble zone (well 457729, deep) was consistently about 2 to 3 ft higher than hydraulic head in the well open to the water table in the alluvium (well 457742, shallow) and 3 to 4 ft higher than river stage. When data are available at times of rapid river-stage change during January through March 1990, the hydrograph shows that river stage rose more rapidly than hydraulic head in the well open to the St. Peter aquifer/rubble zone (well 457729, deep).

Changes in river stage and hydraulic heads were not always coincident. During mid-September 1989 through early January 1990, the hydrographs of hydraulic head in the well open to the water table in the alluvium (well 457742, shallow) and river stage show two recessions separated by a rise. During the same period, hydraulic heads in the well open to the St. Peter aquifer/rubble zone (well 457729, deep) generally rose. This shows that hydraulic heads in the St. Peter aquifer/rubble zone well (well 457729, deep) did not respond to surface-water changes while hydraulic heads in the well open to the water table in the alluvium (well 457742, shallow) mirrored river stage. The hydrograph for the St. Peter aquifer/rubble zone well (well 457729, deep) shows recovery of hydraulic heads from the effects of summer pumpage in either the regional aquifer system or from nearby (about 2 mi) municipal wells. During early January through early March 1990, when data are available, the hydrographs show that hydraulic heads in all wells responded to flood waves in the Mississippi River. The response decreased with depth. Hydraulic head changes in the well open to the water table in the alluvium (well 457742, shallow) mirrored river-stage changes. Hydraulic head changes in the well open to the St. Peter aquifer/rubble zone (well 457729, deep) were smaller than stage changes.

The hydrograph (fig. 4) shows that, when data are available, some daily fluctuations of hydraulic head in the well open to the St. Peter aquifer/rubble zone (well 457729, deep) exceeded the daily fluctuations of river stage and of hydraulic head in the well open to the water table in the alluvium (well 457742, shallow). The larger fluctuations reflect the effect of pumpage from the regional aquifer system or nearby municipal wells.

Hydrographs for the wells in Well Cluster F (500 ft east of the river) and for river stage (fig. 5) are similar during the mid-August through early September 1989 rains and mid-March 1990 snowmelt. Both are periods of area-wide events of seasonal recharge. Except during times of greatest pumpage from the underlying Prairie du Chien-Jordan aquifer, hydraulic head in the well open to the St. Peter aquifer (well 457743, deep) were higher than hydraulic head in the well open to the sand and gravel outwash (well 457744, middle). The difference in hydraulic head in the well open to the St. Peter aquifer (well 457743, deep), the well open to the sand and gravel outwash (well 457744, middle), and the well open to the water table in the upper red till (well 457755, shallow) indicate that there is a downward component of flow from the shallow well (well 457755) and an upward component of flow from the deep well (well 457743) toward a discharge zone between them, near the middle well (well 457744). This discharge zone could be the seepage face at the foot of the eastern valley wall of the Mississippi River.

Changes in the hydraulic head in the well open to the water table in the upper red till (well 457755, shallow) in Well Cluster F do not always correspond to changes in river stage or hydraulic heads in wells open to the underlying sand and gravel outwash (well 457744, middle) or the St. Peter aquifer (well 457743, deep). The lack of response of hydraulic head in the well open to the water table in the upper red till (well 457755, shallow) to changes in river stage indicates that, at this location, the water table and the river are physically and hydraulically separated. Hydraulic head in the well open to the water table in the upper red till (well 457755, shallow) responded to neither rapid fluctuations of stage nor flood waves. Hydraulic head in the well open to the water table in the upper red till (well 457755, shallow) responded in this manner because outflow from the water table is through a seepage face at the foot of the eastern valley wall of the Mississippi River. This seepage face is higher than the stage of the river. Because the seepage face is above the river stage, fluctuations in river stage are not transmitted directly to the water table east of the seepage face.

Hydrographs, when data are available, show that some hydraulic head changes in the well open to the water table in the upper red till (well 457755, shallow) correspond to changes in river stage. Both the water table in the upper red till (well 457755, shallow) and river stage responded to (1) late summer rains during mid-August to early September 1989, (2) little precipitation during early

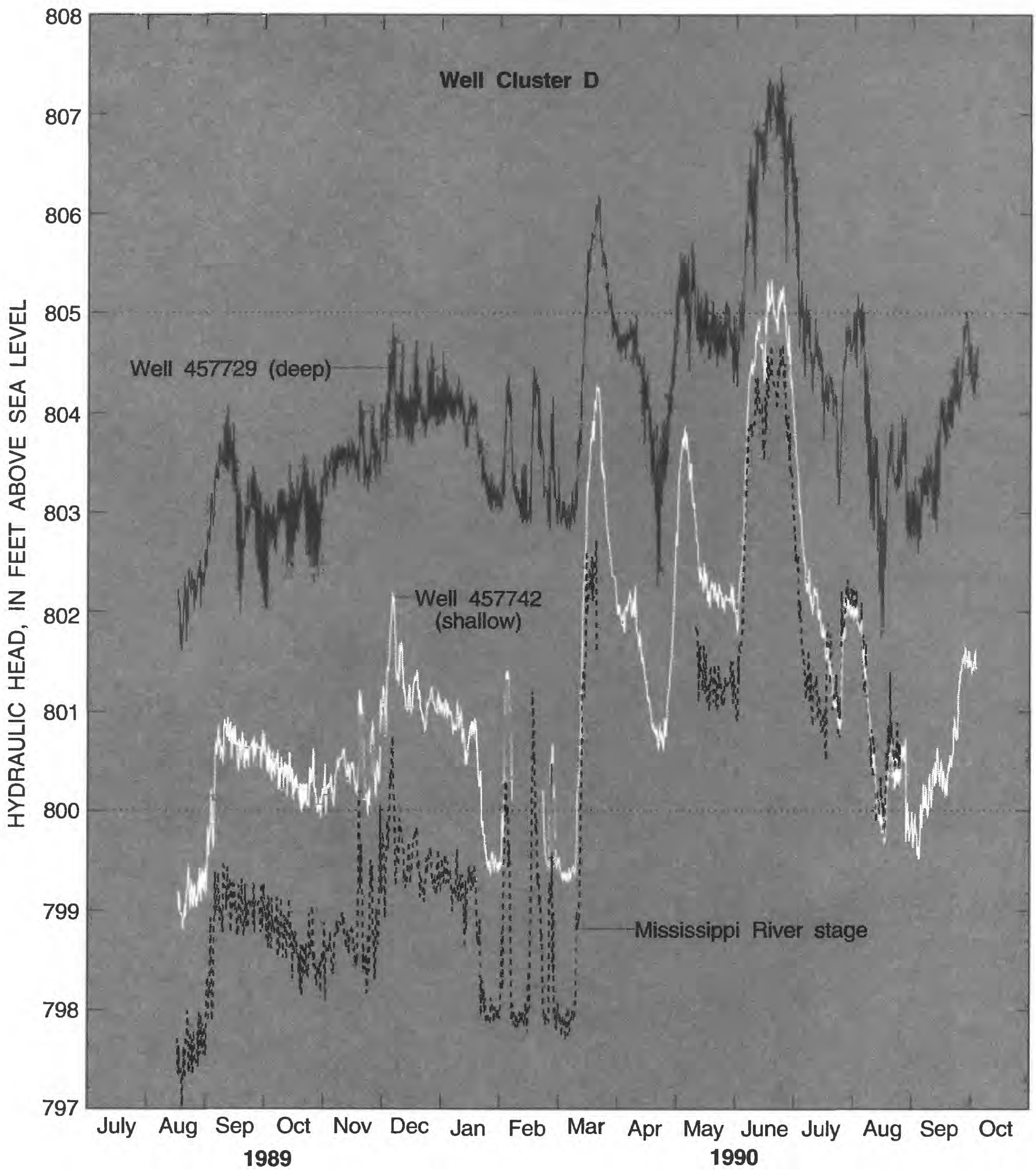


Figure 4. Hydraulic head in well cluster D (100 feet east of the Mississippi River) and Mississippi River stage, Area 1, from July 1989 through October 1990, Fridley/Brooklyn Center area near Minneapolis-St. Paul, Minnesota.

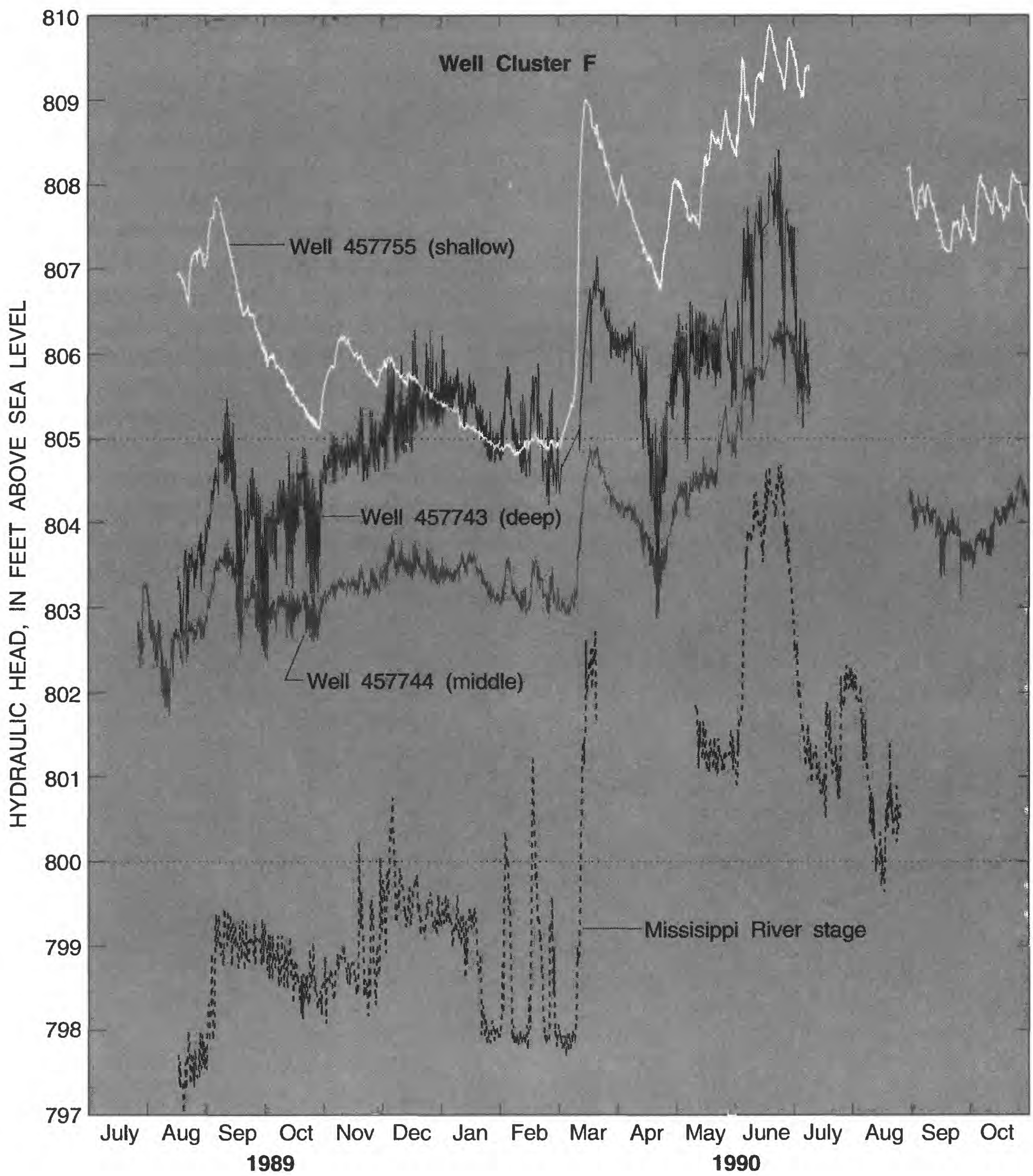


Figure 5. Hydraulic head in well cluster F (500 feet east of the Mississippi River) and Mississippi River stage, Area 1, from July 1989 through October 1990, Fridley/Brooklyn Center area near Minneapolis-St. Paul, Minnesota.

September to late October 1989, (3) spring recharge during mid-March 1990, and (4) precipitation during June 1990. These seasonal hydrologic events affect both the river and the water table.

The hydrograph for the well open to sand and gravel outwash (well 457744, middle) shows daily fluctuations of hydraulic head. During September 1989 through early March 1990, head in this well showed only minor variation except in response to flood waves (George Carlson, 1991, U.S. Geological Survey, written commun.). The response to the flood waves during early January through early March 1990 was damped.

Hydrographs for hydraulic heads in three wells in Well Cluster G (1,500 ft east of the river) and for the river stage show that hydraulic heads and river stage can be affected by the same climatic events and respond differently (fig. 6). The hydraulic heads in all three wells responded simultaneously to short-term changes in the aquifer system. For example, the hydrographs for all three wells for 1990 show matched upward arches between early March and late April and matched downward spikes in late July and mid-August. Seasonal hydraulic head changes in the well open to the water table in the upper red till (well 457735, shallow), however, did not match seasonal hydraulic head changes in the two deeper wells, the well open to the St. Peter aquifer (well 457733, middle) and the well open to the St. Peter aquifer/rubble zone (well 457732, deep). Hydraulic head in the well open to the water table in the upper red till (well 457735, shallow) continued to rise through late August 1990, whereas hydraulic heads in the wells open to the St. Peter aquifer (well 457733, middle) and St. Peter aquifer/rubble zone (well 457732, deep), began to decline in late June 1990.

The hydrograph of the well open to the water table in the upper red till in Well Cluster G (well 457735, shallow) does not resemble the hydrographs of the wells open to the water table in Well Clusters D and F (fig. 7). Changes in the hydraulic head in the well open to the water table in the upper red till (well 457735, shallow) show the dampening and time-delaying effects of the low hydraulic conductivity of till.

The hydrographs of the well open to the St. Peter aquifer (well 457733, middle) and the well open to the St. Peter aquifer/rubble zone (well 457732, deep) in Well Cluster G resemble the hydrographs of the middle and deep wells in Well Clusters D and F (figs. 8 and 9). Some of the hydraulic head changes in the wells open to the St. Peter aquifer (well 457733, middle) and St. Peter aquifer/rubble zone (well 457732, deep) in Well Cluster G probably result from rises in river stage as the river responds to flood waves caused from ice damming and spring snowmelt. Hydraulic head changes more in the well open to the St. Peter aquifer/rubble zone (well 457732, deep) than in the well open to the St. Peter aquifer (well 457733, middle), in Well Cluster G, particularly during the summer. Because the nearby municipal wells are completed in the Prairie du Chien-Jordan aquifer, hydraulic head closer to the bottom of St. Peter aquifer might be more affected by nearby pumping from wells completed in the underlying Prairie du Chien-Jordan aquifer.

The difference in hydraulic head between the stage of the Mississippi River and the well open to the St. Peter aquifer/rubble zone (well 457732, deep) in Well Cluster G varied from about 10 ft in late February 1990 to about 6 ft in June 1990 (fig. 6). A comparison of hydraulic-head changes in each cluster, when data are available, indicate that, over a year, the hydraulic heads in the middle and deep wells in Well Clusters D, F, and G respond primarily to river-stage fluctuations during the winter and to changing regional ground-water pumpage during spring through fall (figs. 4-6). Hydraulic heads in the shallow wells open to the water table in Well Clusters D, F, and G responded to different factors at each well.

A comparison of hydraulic heads in the deep, middle, and shallow wells at Well Clusters D, F, and G show that the horizontal component of ground-water flow is from the highland to the river except for parts of July to August 1990 when the river stage was higher than the hydraulic head in the well open to the water table in Well Cluster D (well 457742, shallow) (figs. 7-9). Hydraulic heads in all wells are generally higher than river stage even during rapid changes in river stage. This head difference prevented river water from flowing into the aquifer system as far as 100 ft from the river, except for July to August 1990.

Potentiometric lines were drawn on hydrogeologic section A'-A" for November 17, 1989 (fig. 10) and March 21, 1990 (fig. 11). They illustrate the two-dimensional distribution of hydraulic head. These days were selected to illustrate hydraulic heads during periods of relatively high and low discharge in the Mississippi River for the water year 1990. The discharges in the river on November 17, 1989 and March 21, 1990 were 3,230 and 16,700 ft^3/sec, respectively (Gunard and others, 1991, p. 83). The maximum and minimum discharges for water year 1990 were 1,730 and 19,800 ft^3/sec, respectively (Gunard and others, 1991, p. 83). Estimated mean daily ground-water discharge per river foot for 1935-87 to the major rivers in the Minneapolis-St. Paul area was 115 ft^3/d per river foot (Schoenberg, 1990, p. 22). A model-calculated ground-water discharge per river foot for

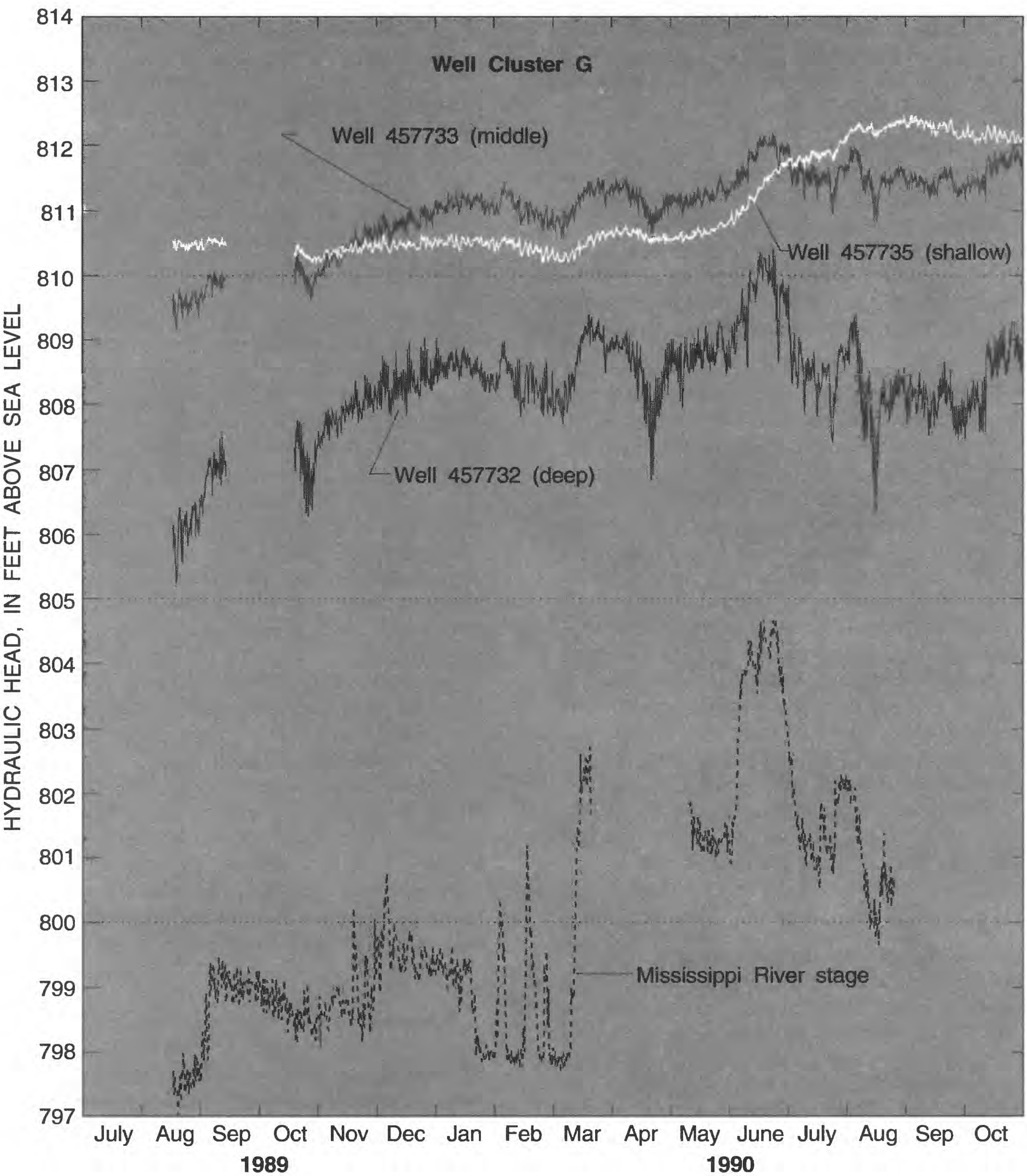


Figure 6. Hydraulic head in well cluster G (1,500 feet east of the Mississippi River) and Mississippi River stage, Area 1, from July 1989 through October 1990, Fridley/Brooklyn Center area near Minneapolis-St. Paul, Minnesota.

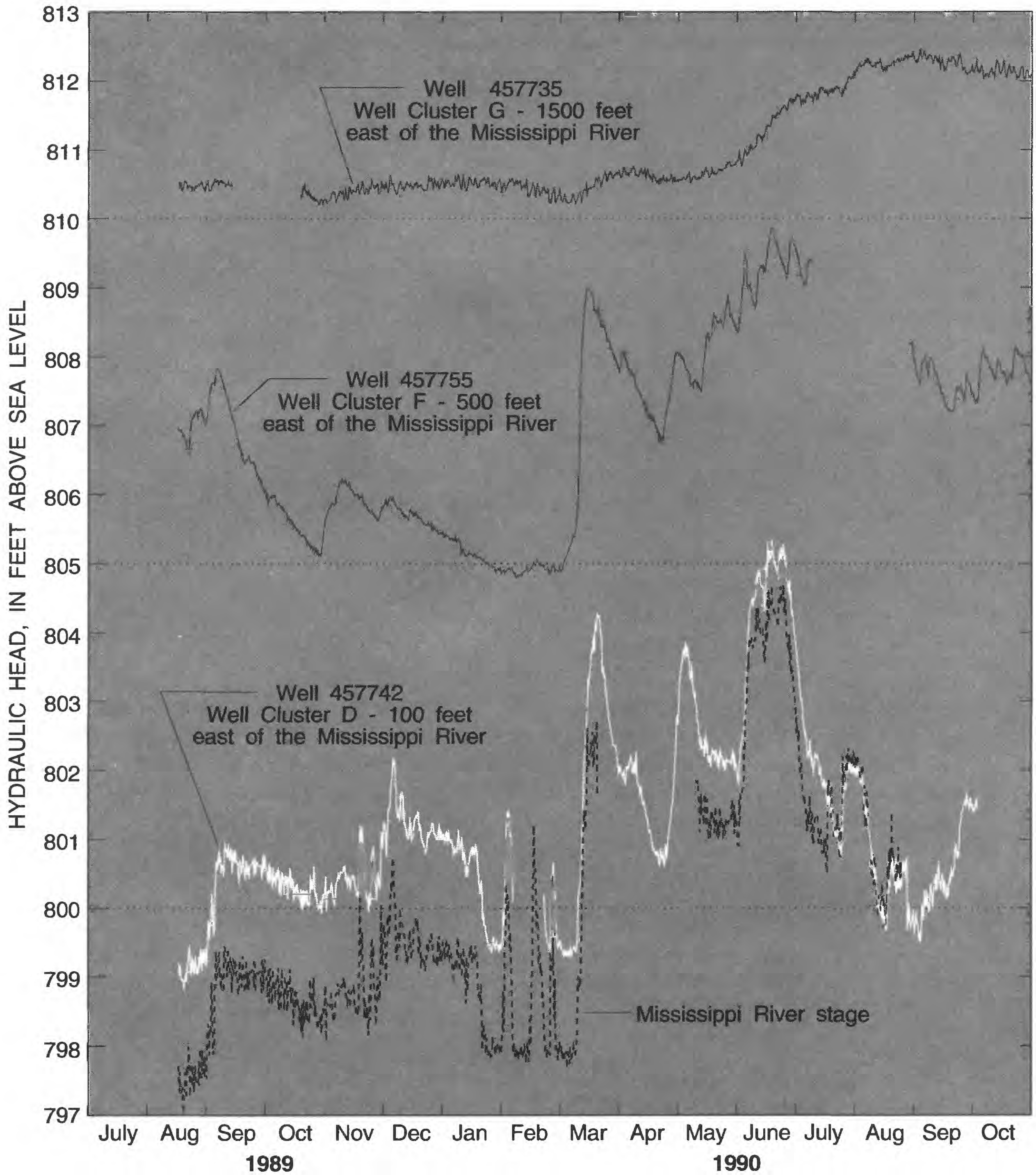


Figure 7. Hydraulic head in shallow wells and Mississippi River stage, Area 1, from July 1989 through October 1990, Fridley/Brooklyn Center area near Minneapolis-St. Paul, Minnesota.

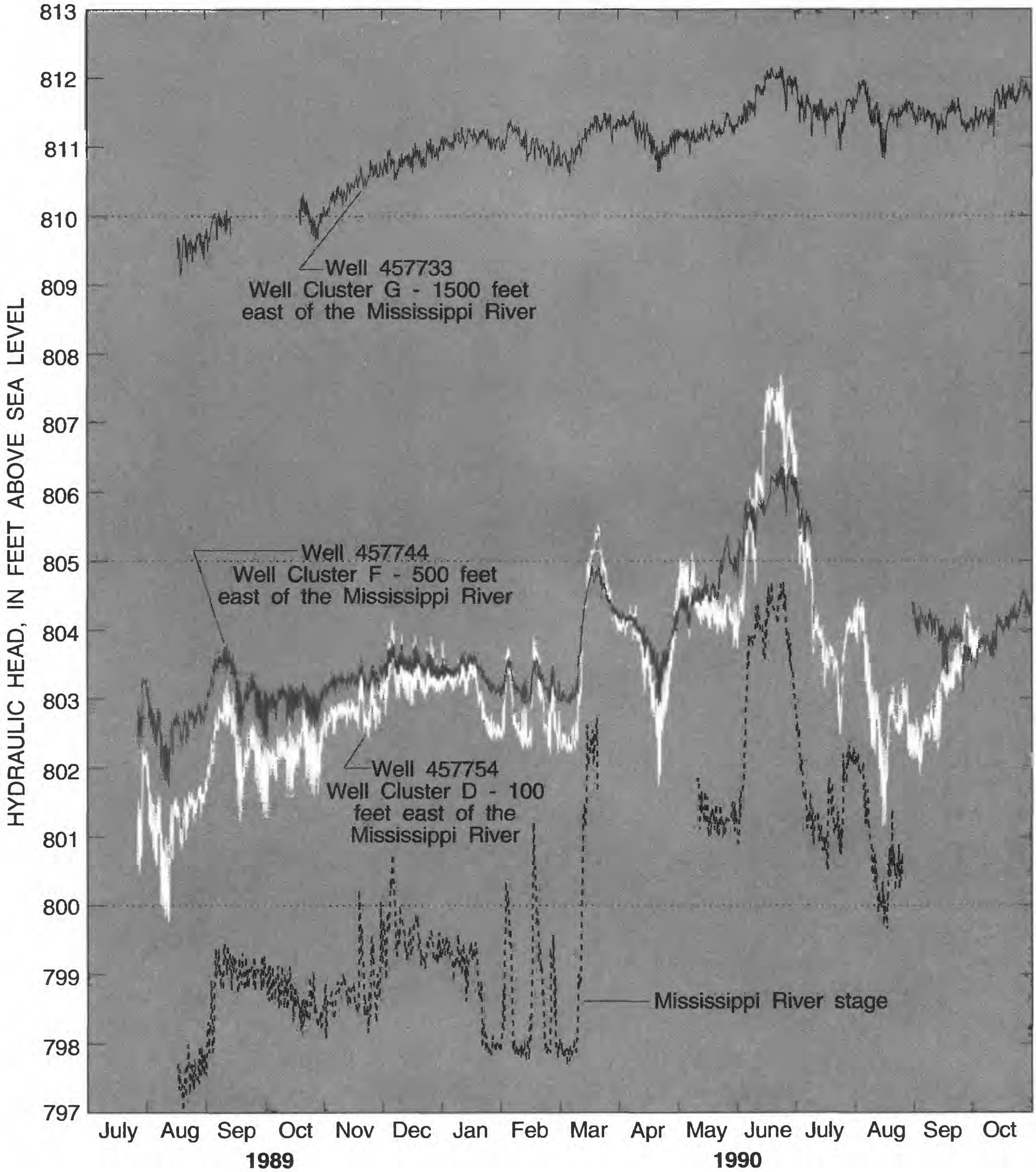


Figure 8. Hydraulic head in middle wells and Mississippi River stage, Area 1, from July 1989 through October 1990, Fridley/Brooklyn Center area near Minneapolis-St. Paul, Minnesota.

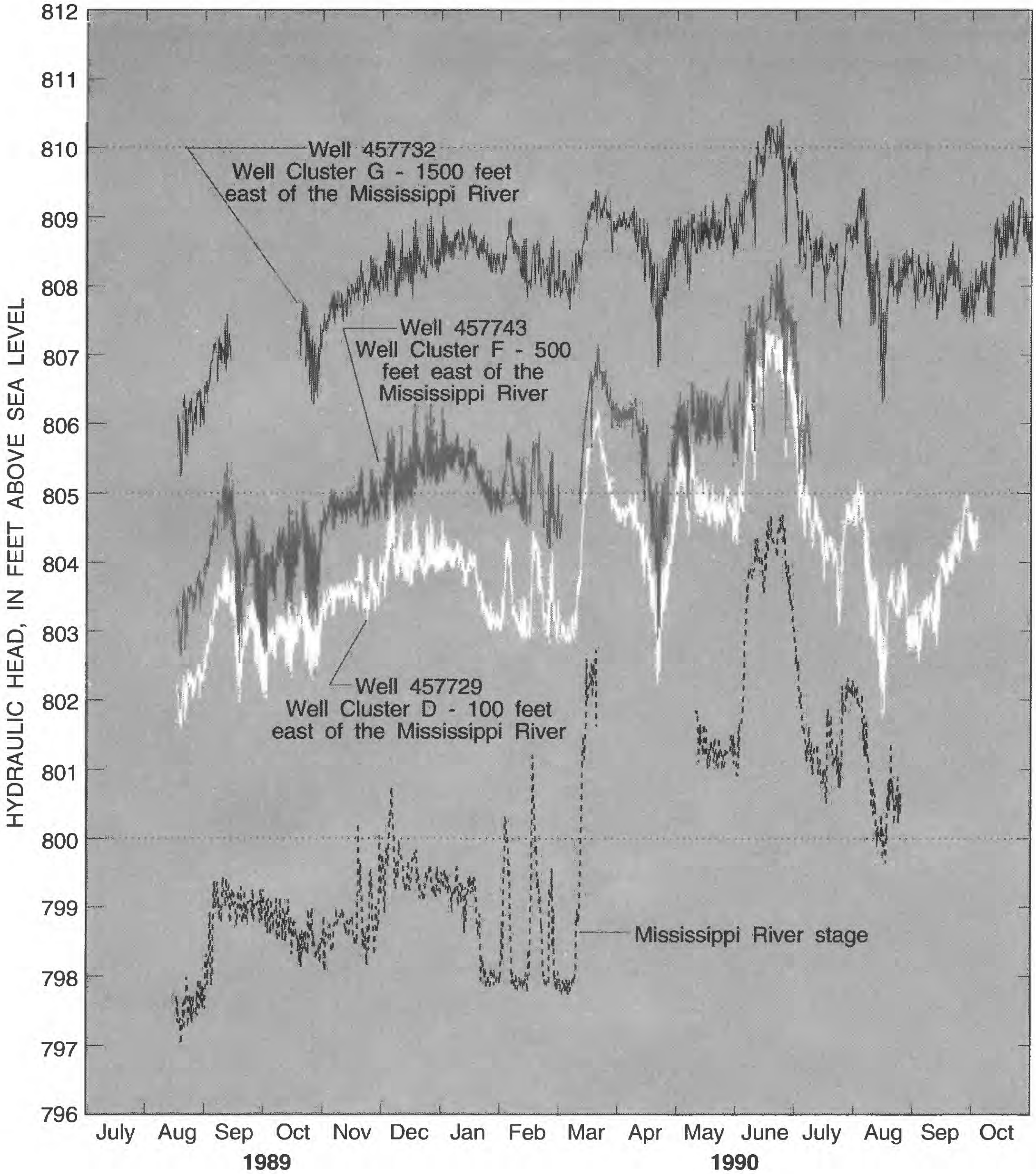
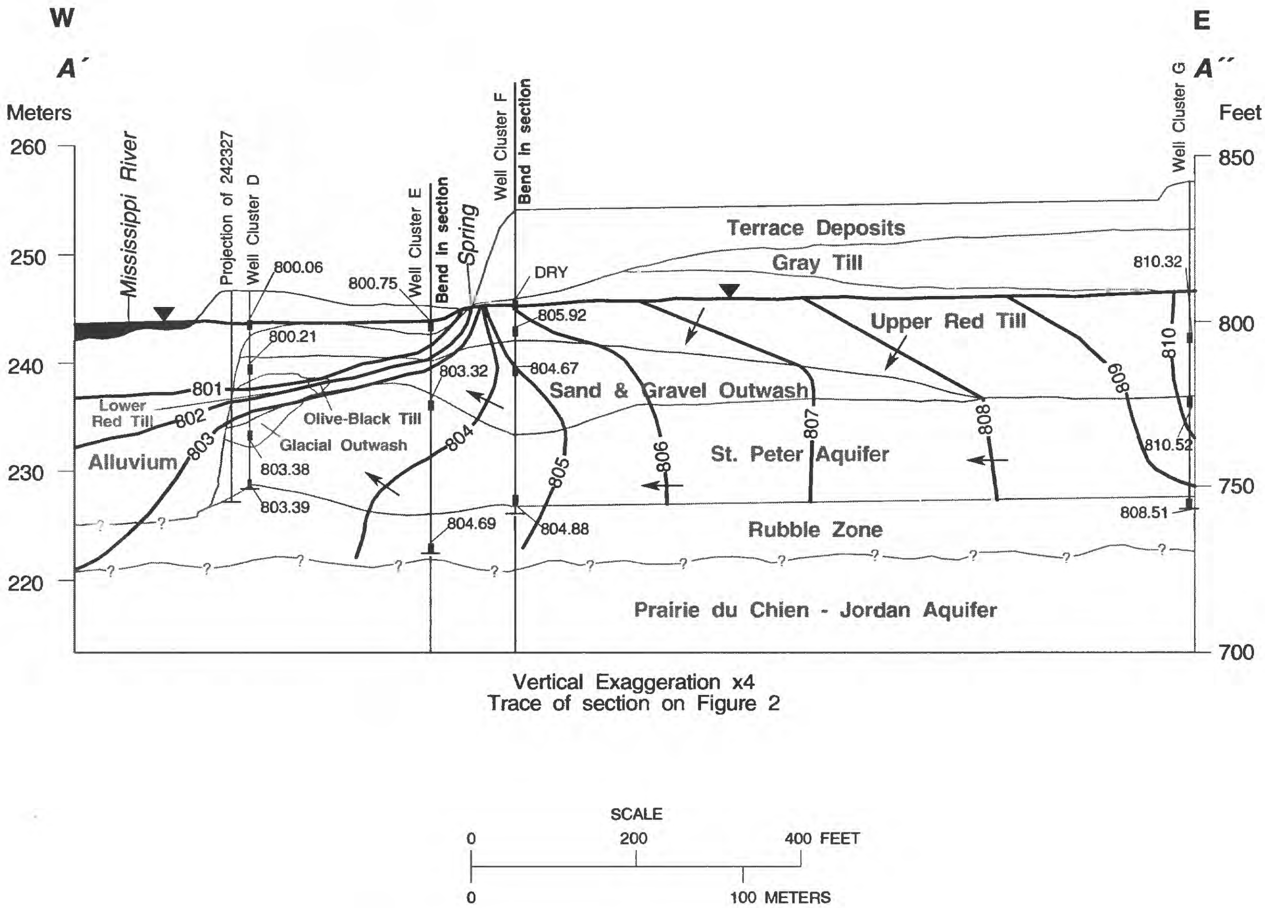


Figure 9. Hydraulic head in deep wells and Mississippi River stage, Area 1, from July 1989 through October 1990, Fridley/Brooklyn Center area near Minneapolis-St. Paul, Minnesota.



EXPLANATION

—806— Line of equal hydraulic head (dashed where approximate)

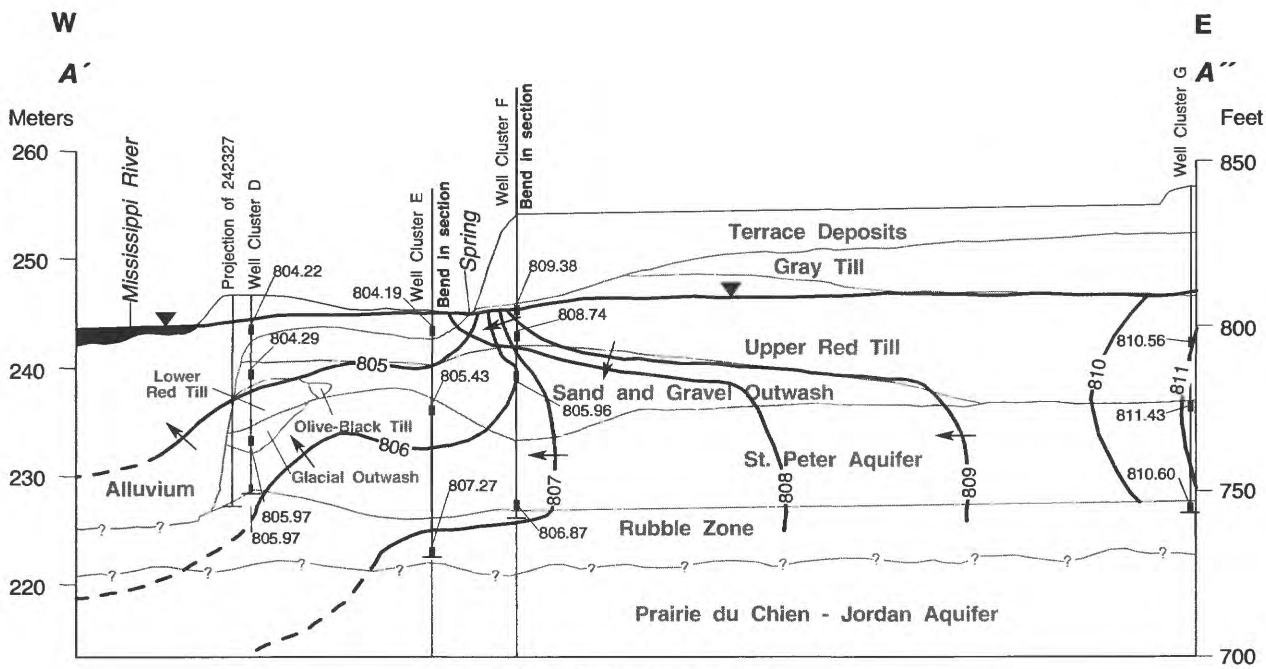
← Direction of ground-water flow

▼ Water table

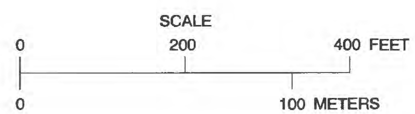
800.75 Well screen opening and measured hydraulic head

Well Cluster D — Trace of well or test hole

Figure 10. Ground-water flow, section A´ - A´´, Area 1, for November 17, 1989, Fridley/Brooklyn Center area near Minneapolis-St. Paul, Minnesota.



Vertical Exaggeration x4
Trace of section on Figure 2



EXPLANATION

—806— Line of equal hydraulic head (dashed where approximate)

← Direction of ground-water flow

▼ Water table

804.22 Well screen opening and measured hydraulic head

Well Cluster D Trace of well or test hole

Figure 11. Ground-water flow, section A´ - A´´, Area 1, for March 21, 1990, Fridley/Brooklyn Center area near Minneapolis-St. Paul, Minnesota.

1970-79 to the Mississippi and Minnesota Rivers is 44 ft^3/d per river foot (Schoenberg, 1990, p. 66).

The distribution of potentiometric lines for both days show that ground water flows from the topographically higher bluff to the topographically lower Mississippi River. Shallow ground-water flow in the near-surface gray and upper red till and sand and gravel outwash aquifer discharges to springs along the edge of the floodplain. The steepest upward hydraulic gradient occurs under the base of the bluff. Water that flows through the combined outwash and St. Peter aquifer discharges through alluvial deposits beneath the river bank to the river. Ground water flowing through the rubble zone and upper part of the Prairie du Chien-Jordan aquifer probably discharges to the river through alluvial deposits beneath the river.

Ground-water-flow model

Ground-water flow for November 17, 1989 along a transect in Area 1 was simulated with a steady-state, cross-sectional, numerical model. The numerical model is based on a conceptual model of the flow system. The numerical model was used to test concepts of ground-water flow between the river and bedrock aquifers.

The steady-state, cross-sectional, numerical model provides qualitative insights into the ground-water-flow system. As a steady-state model, it ignores the time-dependent transfer of ground water into and out of storage. The model provides an estimate of ground-water flow assuming that conditions for November 17, 1989 do not change. As a cross-sectional model, it assumes no flow normal to the model. This assumption is reasonable because the section approximately follows the direction of ground-water flow. Hydraulic head data were available only for part of the modeled section. The model is calibrated only for that part of the section. Ground-water flow into the river, against which the model is calibrated, can only be estimated using area-wide discharge measurements. Ground-water discharge into a river the size of the Mississippi River, when compared to the total discharge of the river, is too small to be directly measured over the length of the study area. The calibrated numerical model is a non-unique representation of the ground-water-flow system. Other combinations of values for the physical properties represented in the model might produce equally as good matches between measured hydraulic data and computer-calculated values.

Relation of model to the ground-water-flow system

The numerical model simulates a longer and deeper cross-section than shown in hydrogeologic section A′-A″ (fig. 12). Most of the terrace deposits that form the bluff above the Mississippi River were not simulated because they are unsaturated and are hydraulically separated from the underlying aquifers by the gray till. The section represented in the numerical model extends 80 ft east of section A′-A″. Well Cluster G is represented in the numerical model. The section in the numerical model extends 560 ft west of section A′-A″. The boundary of the model is the center of Durnam Island. The center of the island is a ground-water divide for shallow ground-water flow. Durnam Island also divides the Mississippi River into low- and high-flow channels. The low-flow channel is represented in the numerical model. The high-flow channel is not represented in the numerical model because the high-flow channel received water from shallow ground-water systems outside of the modeled sections. The lower boundary of the model represents the top of the St. Lawrence-Franconia confining unit.

The major assumptions associated with the conceptual and ground-water-flow models are the following:

1. There is no ground-water flow perpendicular to the transect.
2. Ground-water levels do not fluctuate.
3. Stage in the Mississippi River does not fluctuate.
4. Ground-water storage does not change.
5. There is no evapotranspiration from ground water.
6. There is no recharge.
7. No ground water flows into the modeled area as horizontal flow through gray till from east.
8. Ground water from the east flows through the upper red till, St. Peter aquifer, rubble zone, and Prairie du Chien-Jordan aquifer and is simulated as entering the model through a head-dependent-flux boundary.
9. The low-flow channel of the Mississippi River is simulated by leaky-river cells.
10. The center of Durnam Island is a no-flow boundary from the water table to the top of the rubble zone.
11. Ground water from the west flows through the rubble zone and the Prairie du Chien-Jordan aquifer and is simulated as entering the model through a head-dependent-flux boundary.
12. A seepage face represents the spring at the foot of the eastern edge of the river floodplain.
13. There are no ground-water withdrawals.

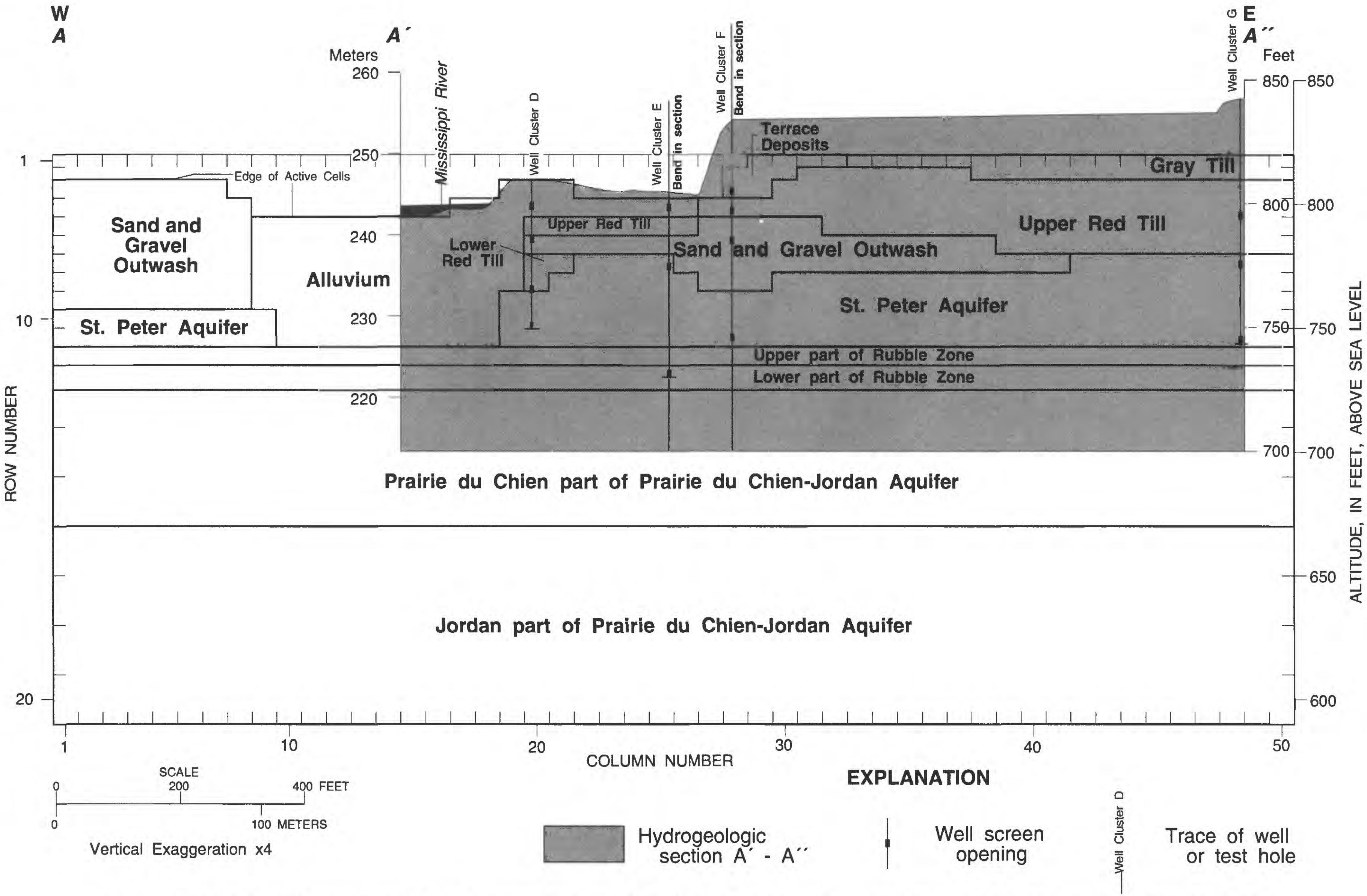


Figure 12. Finite-difference grid and discretization of hydrogeologic units used in model analysis, section A - A´´, Area 1, Fridley/Brooklyn Center area near Minneapolis-St. Paul, Minnesota.

14. The hydrogeologic material within each cell is homogeneous and hydraulic conductivity is horizontally isotropic.
15. Heterogeneity in aquifer and confining unit properties are simulated by using more than one row of cells for each hydrogeologic unit.
16. Vertical anisotropy of hydraulic conductivity within the aquifer system is constant for the whole model.

The modeled cross section is represented by a grid that has 20 rows and 50 columns (fig. 12), for a total of 1,000 cells. Each column represents a length of 40 ft. The rows represent thickness ranging from 5 ft at the top to 20 ft at the bottom of the model.

The thin cells in rows 1 to 11 represent thin hydrogeologic units that were present in the area represented by columns 17 to 50. The rubble zone at the base of the St. Peter aquifer was simulated with two rows (12 and 13). The Prairie du Chien and Jordan parts of the Prairie du Chien-Jordan aquifer were simulated with multiple rows.

Smaller hydrogeologic units were grouped together with nearby hydraulically similar units. The olive-black till was combined with the lower red till (row 7, column 21). The glacial outwash (row 8, column 21 and row 9, columns 19 and 20) was combined with the St. Peter aquifer. Hydraulic conductivity values are the principal model input. Uniform values of hydraulic conductivity were initially assigned for each hydrogeologic unit (table 5), based on a combination of measured values (tables 3 and 4) and reported values (Schoenberg, 1990). The hydraulic boundaries assigned to the modeled section are shown in figure 13.

Ground water flows into the model at general-head boundaries. The flow rates were calculated by the model from a conductance multiplied by the difference between the hydraulic head at the edge of the model and a known hydraulic head at a point outside the model. Conductance is a quantity that combines hydraulic conductivity, cross-sectional area of flow, and length of flow path (MacDonald and Harbaugh, 1988). Beginning values of conductances were determined by assuming Darcian flow from a known hydraulic head at a well. Ground-water fluxes into the model were adjusted during model calibration by adjusting conductance values. Table 6 contains the final values of conductances used in the calibrated model.

Ground water flows out of the model at leaky river boundaries. The flow rates were calculated by the model from a conductance multiplied by the difference between hydraulic head in the river and the model-calculated hydraulic head in the cell. For a leaky river cell the cross-sectional area of flow is the product of the length and width of the cell. In this model, the length of each cell was

Table 5.--Initial and final values of hydraulic conductivity of hydrogeologic materials used in the numerical model, section A'-A'', Area 1, Fridley/Brooklyn Center area near Minneapolis-St. Paul, Minnesota

Hydrogeologic materials	Hydraulic conductivity (in feet per day) Initial values	Final values in calibrated model
Alluvium	10-30	20-30
Terrace deposits	10	1-20
Gray till	.01	.01
Upper red till	.01	.01-.1
Sand and gravel outwash	20	20
Lower red till	.01	1
St. Peter aquifer	4	1-20
Upper part of rubble zone	.1	.05-10
Lower part of rubble zone	10	10
Prairie du Chien part of the Prairie du Chien-Jordan aquifer	50	50
Jordan part of the Prairie du Chien-Jordan aquifer	20	20

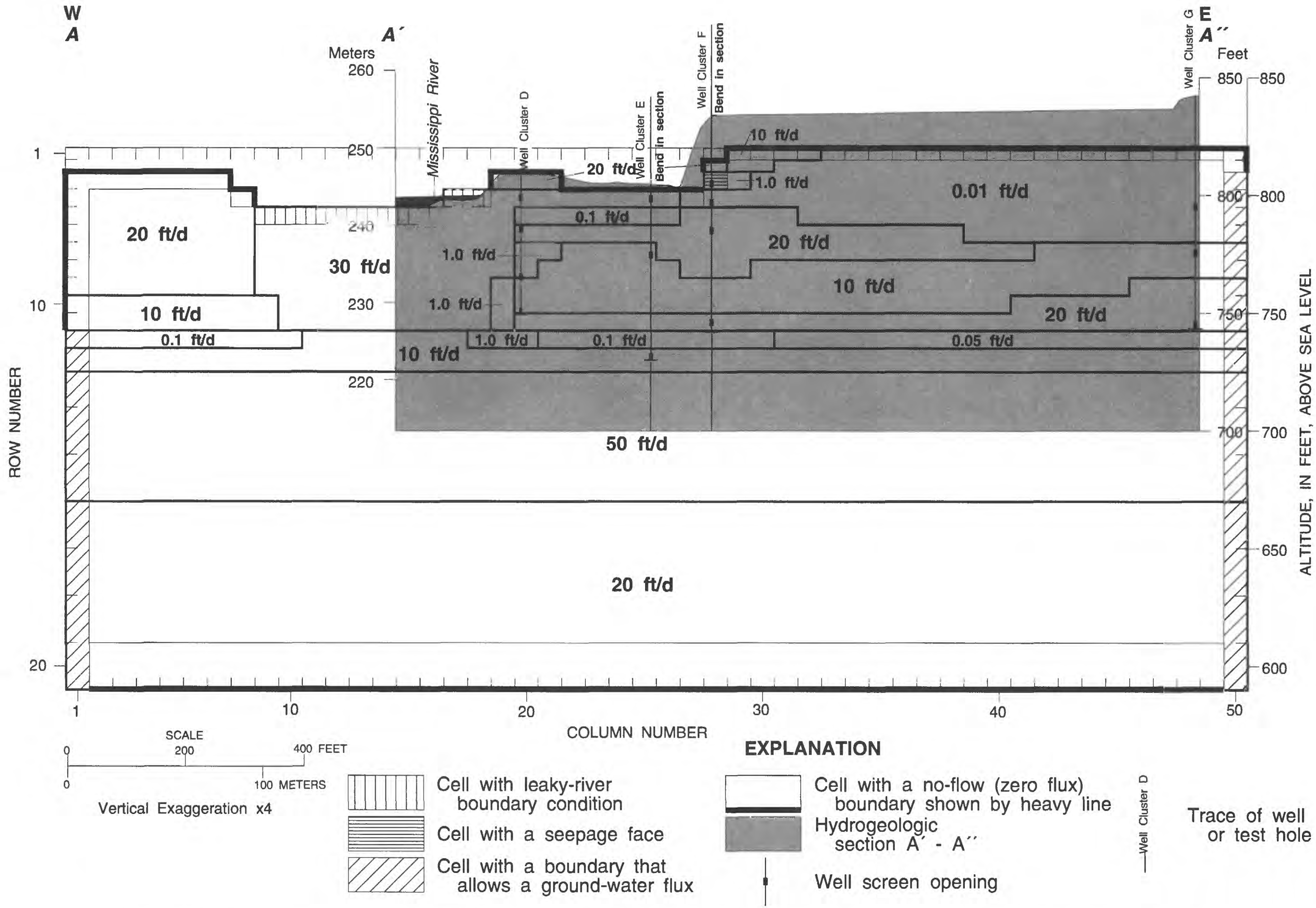


Figure 13. Boundary conditions and distribution of final hydraulic conductivities used in numerical-model analysis, section A - A´´, Area 1, Fridley/Brooklyn Center near Minneapolis-St. Paul, Minnesota.

Table 6.--Final conductance values for all boundaries in the numerical model, section A-A", Area 1, Fridley/Brooklyn Center area near Minneapolis-St. Paul, Minnesota
[ft^2/d, feet squared per day]

Boundary type	Location		Conductance[1] (ft^2/d)	Description of controlling elevation	Controlling elevation(s) (in feet above sea level)
	Row	Column			
Seepage face	3	28	0.0375	Bottom of seepage face	804.0
Leaky riverbeds	5	9	5.000	River stage	798.6
	5	10	5.000		798.6
	5	11	5.000		798.6
	5	12	5.000		798.6
	5	13	5.000		798.6
	5	14	5.000		798.6
	5	15	5.000		798.6
	5	16	5.000		798.6
	4	17	5.000		798.6
	4	18	5.000		798.6
Ground-water flux dependent on hydraulic head outside of the model	3	50	.05	Hydraulic head of an external source of ground water	812.0
	4	50	.05		812.5
	5	50	.05		813.0
	6	50	.05		813.5
	7	50	.075		830.0
	8	50	.075		830.0
	9	50	.03		830.0
	1	50	.03		820.0
	1	50	.03		820.0
	1	50	.0075		820.0
	1	50	.075		820.0
	1	50	.1008		820.0
	1	50	.1008		820.0
	1	50	.1008		820.0
	1	50	.1008		820.0
	1	50	.1008		820.0
	1	50	.1008		820.0
	2	50	.1008		820.0
	1	1	.0075		830.0
	1	1	.075		830.0
	1	1	.1000		863.0
	1	1	.1000		863.0
	1	1	.1000		863.0
	1	1	.1000		863.0
	1	1	.1000		863.0
	1	1	.1000		863.0
	2	1	.1000		863.0

[1] Conductance combines grid dimensions and hydraulic conductivity into a single constant. It is the "product of hydraulic conductivity and cross-sectional area of flow divided by the length of the flow path." (MacDonald and Harbaugh, 1988, p. 2-11)

40 ft. The width of a cell in a cross-sectional model is unit thickness, or 1 ft. The length of the flow path in a leaky river cell is the thickness of the streambed. The streambed was assumed to be 1 ft thick. For the model, the hydraulic conductivity of the streambed (in ft/d) is the value of conductance (in ft^2/d) divided by 40 ft, the length of the cell.

Model calibration

The function of model calibration is to produce a numerical model that, having reasonable initial and boundary conditions, can adequately approximate measured hydraulic heads and ground-water discharges. Model calibration does not produce a unique representation of a ground-water-flow system. It produces one that, given the assumptions embedded in the model, fits the known data. Because data are limited, the interpretation of model results are constrained.

The model was considered calibrated in that part of the modeled section where measured hydraulic heads were available (fig. 14) when the model-calculated hydraulic heads approximately matched measured hydraulic heads (table 7) and the model-calculated ground-water flux reasonably represented the estimated ground-water flux (tables 8 and 9). Model-calculated flux to the river was compared to an estimated ground-water flux of 44 to 115 ft^3/d per foot of river. Schoenberg (1988) estimated that variations in discharge to the Mississippi River can vary from 50 to 150 ft^3/d. The ground-water flux for the calibrated model of 54 ft^3/d (rounded) was near the low end of these ranges. Flow to the river, however, is mostly independent of the model calibration because most of the flow occurs from the west where there are no measured hydraulic-head data for calibration. Consequently, the model is not predictive. The model, however, can be used to illustrate the interaction of different hydrogeologic factors and ground-water flow between the river and bedrock aquifers.

Table 7.--Comparison of measured and model-calculated hydraulic heads for the numerical model, section A-A", Area 1, Fridley/Brooklyn Center area near Minneapolis-St. Paul, Minnesota

Well cluster label	Well identification number	Location: Row	Location: Column	Hydraulic head (in feet above sea level): Measured	Hydraulic head (in feet above sea level): Computed	Difference between computed and measured heads (in feet)
D	457742	4	20	800.06	800.51	0.45
	457730	6	20	800.21	800.78	.57
	457754	8	20	803.38	801.91	-1.47
	457729	11	20	803.39	802.81	-.58
E	457737	4	25	800.75	800.57	-.18
	457736	7	25	803.32	803.61	.29
	457731	13	25	804.69	805.09	.40
F	457755	4	28	805.92	804.20	-1.72
	457744	6	28	804.67	804.31	-.36
	457743	11	28	804.88	804.31	-.57
G	457734	5	48	810.32	809.96	.36
	457733	7	48	810.52	809.41	-1.11
	457732	11	48	808.51	809.34	.83

Mean error = -0.29 feet

Root of the mean square error = 0.82 feet

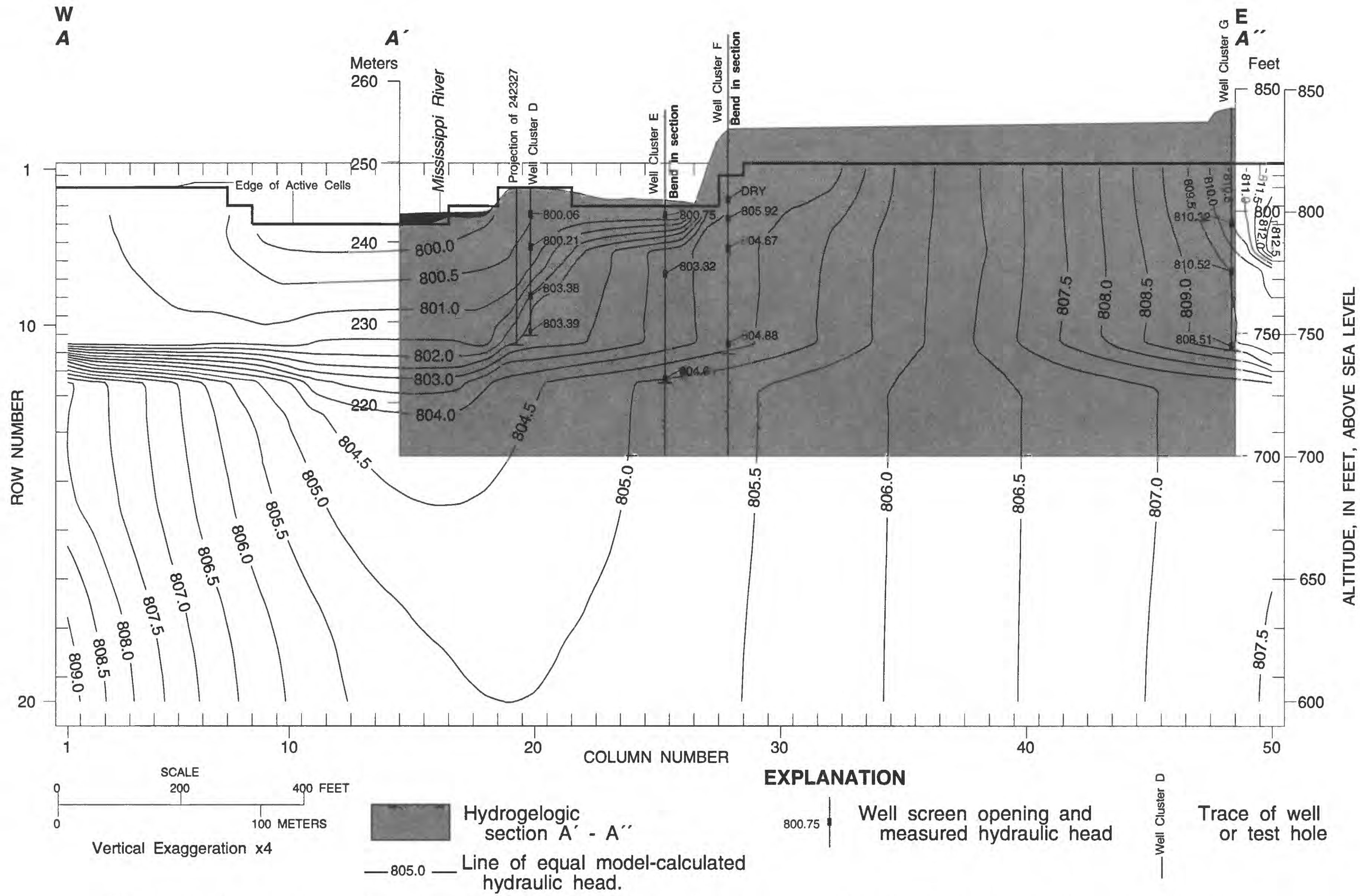


Figure 14. Comparison of model-calculated hydraulic head and measured hydraulic head, for November 17, 1989, section A - A´´, Area 1, Fridley/Brooklyn Center area near Minneapolis-St. Paul, Minnesota.

Table 8.--Volumetric ground-water budget for the numerical model, section A-A", Area 1, Fridley/Brooklyn Center area near Minneapolis-St. Paul, Minnesota

Model boundary	Flow rate (cubic feet per day)
Inflow to the system	
Ground-water flow at eastern boundary of model	
Upper red till =	0.04
St. Peter aquifer =	4.19
Rubble zone between St. Peter and Prairie du Chien part of the Prairie du Chien-Jordan aquifers =	1.02
Prairie du Chien part of the Prairie du Chien-Jordan aquifer =	3.81
Jordan part of the Prairie du Chien-Jordan aquifer =	5.04
Ground-water flow at western boundary of model	
Rubble zone between St. Peter and Prairie du Chien part of the Prairie du Chien-Jordan aquifers =	1.82
Prairie du Chien part of the Prairie du Chien-Jordan aquifer =	16.50
Jordan part of the Prairie du Chien-Jordan aquifer =	21.60
Total inflow =	54.02
Outflow from the system	
Seepage face =	.01
Net leakage to rivers =	54.01
Total outflow =	54.02

Interpretation of simulation results

Model results indicate that most ground-water flow in the modeled section moves through the Prairie du Chien-Jordan aquifer to the Mississippi River. Model-calculated fluxes from the eastern and western boundaries of the model are directly related to the differences between the hydraulic heads at the recharge areas and the hydraulic heads at the eastern and western boundaries of the model. The greater the difference between hydraulic head at the recharge area and the hydraulic head at the model boundary, the greater the model-calculated flux into the model. For example, the differences between the hydraulic heads at the recharge areas to the west and east (863 and 820 ft above sea level) and the hydraulic heads at the model boundary (about 808 to 810 ft above sea level) are about 55 and 10 ft, respectively. About 71 and 16 percent of the 54 ft^3/d (rounded) of model-calculated discharge come from general head boundaries in the Prairie du Chien-Jordan aquifer along the western and eastern model boundaries, respectively.

The model was used to test the relation of model-calculated hydraulic head and flow to specific characteristics represented in the model. The response to variation in seven characteristics were explored: (1) continuity of the upper part of the rubble zone; (2) vertical hydraulic conductivity of the riverbed; (3) hydraulic conductivity of the upper red till; (4) hydraulic conductivity of the St. Peter aquifer; (5) hydraulic conductivity of the Prairie du Chien part of the Prairie du Chien-Jordan aquifer; and (6) conductance values along the western and eastern model boundaries.

Simulated flow through the modeled section was sensitive to the continuity of the upper part of the rubble zone. The best match between measured and model-calculated hydraulic heads occurs when the upper part of the rubble zone is simulated as having a hydraulic conductivity of 10 ft/d, similar to that in the lower part of the rubble zone or the overlying alluvium. This could indicate that the upper part of the rubble zone is absent under the river. The effect of the hydraulic conductivity of the upper part of the rubble zone (row 12, columns 11 to 17) was investigated by changing the value of hydraulic conductivity from 10 to 1 ft/d. This change produced two successive simulations with a difference in the mean error between measured and computed heads of 0.52 ft and a change in the net ground-water flux through the aquifer system of 9 percent from 54 to 49 ft^3/d (rounded).

Table 9.--Calculated seepage, river leakage, and ground-water flux for the calibrated numerical model, section A-A", Area 1, Fridley/Brooklyn Center area near Minneapolis-St. Paul, Minnesota

Boundary type	Location		Rate[1] (in cubic feet per day)
	Row	Column	
Seepage out (-) of model	3	28	-0.01
River leakage out (-) of model	5	9	-6.06
	5	10	-5.38
	5	11	-5.17
	5	12	-5.12
	5	13	-5.13
	5	14	-5.20
	5	15	-5.33
	5	16	-5.62
	4	17	-5.10
	4	18	-5.90
Ground-water flux into model	3	50	.001
	4	50	.003
	5	50	.006
	6	50	.03
	7	50	1.48
	8	50	1.49
	9	50	.60
	10	50	.31
	11	50	.31
	12	50	.08
	13	50	.94
	14	50	1.27
	15	50	1.27
	16	50	1.27
	17	50	1.26
	18	50	1.26
	19	50	1.26
	20	50	1.26
	12	1	.18
	13	1	1.64
	14	1	5.50
	15	1	5.50
	16	1	5.50
	17	1	5.44
	18	1	5.41
	19	1	5.38
	20	1	5.37

[1] Rounded to two decimal places or first non-zero digit.

The lower the simulated hydraulic conductivity of the riverbed, the lower the simulated discharge from the alluvium and the Prairie du Chien-Jordan aquifer. Model-calculated fluxes out of the leaky-river cells changed in response to variations of the vertical hydraulic conductivity of the riverbed. Halving the hydraulic conductivity of the riverbed from 0.125 ft/d to 0.0625 ft/d changed the calculated flux discharging through the riverbed from 54.0 to 52.6 ft^3/d (rounded). The mean error between the measured and computed heads changed from -0.29 to 0.54 ft. Multiplying the hydraulic conductivity of the riverbed from 0.125 ft/d to 1.25 ft/d changed the calculated flux discharging through the riverbed from 54.0 to 55.4 ft^3/d (rounded). The mean error between the measured and computed heads changed from -0.29 to -1.11 ft.

Model-calculated hydraulic heads were not sensitive to a change of the hydraulic conductivity value of upper red till (row 5, columns 20 to 26). Changing the value of hydraulic conductivity from 0.01 to 10 ft/d resulted in an absolute change of the mean error between the measured and calculated heads of 0.35 ft and a change of the root mean square error of 0.53 ft.

Model-calculated fluxes through the St. Peter aquifer on the east side of the Mississippi River were not sensitive to representing the St. Peter aquifer (on the east side of the Mississippi River) with a single value for its hydraulic conductivity (10 or 20 ft/d) compared to representing that aquifer with an upper layer (10 ft/d) and a lower layer (20 ft/d). Representing the hydraulic conductivity of the St. Peter aquifer solely as 10 or 20 ft/d changed the model-calculated flux through the St. Peter aquifer on the east side of the Mississippi River from 4.19 ft^3/d (calibration simulation) to 3.97 ft^3/d (3 percent decrease) and 4.46 ft^3/d (6 percent increase), respectively.

The effect of increasing transmissivity for the most transmissive hydrogeologic unit in the section was simulated by increasing the value of hydraulic conductivity of the Prairie du Chien part of the Prairie du Chien-Jordan aquifer from 50 to 75 ft/d. The model was not sensitive to this change. The absolute change in the mean error between measured and computed heads was 0.02 ft. Simulated discharge through the aquifer system changed from 54 to 55 ft^3/d (rounded).

The availability of ground water to flow through the section was simulated by varying conductance values along the western and eastern model boundaries. Halving all conductances (50 percent decrease) resulted in a 43 percent simulated decrease in the ground-water flux (54 to 31 ft^3/d, rounded). About 67 and 18 percent of the 31 ft^3/d (rounded) of model-calculated discharge came from general head boundaries along the western and eastern boundaries of the model, respectively.

Simulated ground-water flow through the modeled section was not sensitive to reducing hydraulic conductivity of the erosional face of the St. Peter aquifer (rows 9 to 11, column 19). Model-calculated hydraulic fluxes through the St. Peter aquifer on the east side of the Mississippi River changed from 4.19 to 4.25 ft^3/d when the erosional edge of the St. Peter aquifer (rows 9 to 11, column 19) was represented as not case hardened. Case hardening refers to a zone of reduced hydraulic conductivity (1 ft/d compared to 10 or 20 ft/d) on the erosional face of the St. Peter aquifer that could be caused by the precipitation of minerals similar to that observed on present-day (1994) exposed faces of this aquifer in the Mississippi River valley near St. Paul, Minnesota.

Discharge to the Minnesota River at Eagan/Bloomington

Area 2 is located along the Minnesota River between Eagan and Bloomington (fig. 15). Four water-table wells were drilled in the study area. Two test holes were drilled into bedrock in the valley of the Minnesota River, but outside of the study area (MV05 and MV06 shown in figure 1). Samples obtained from these test holes are considered to represent deposits in Area 2 because they were deposited under the same conditions at the same time as parts of the valley fill in this study area.

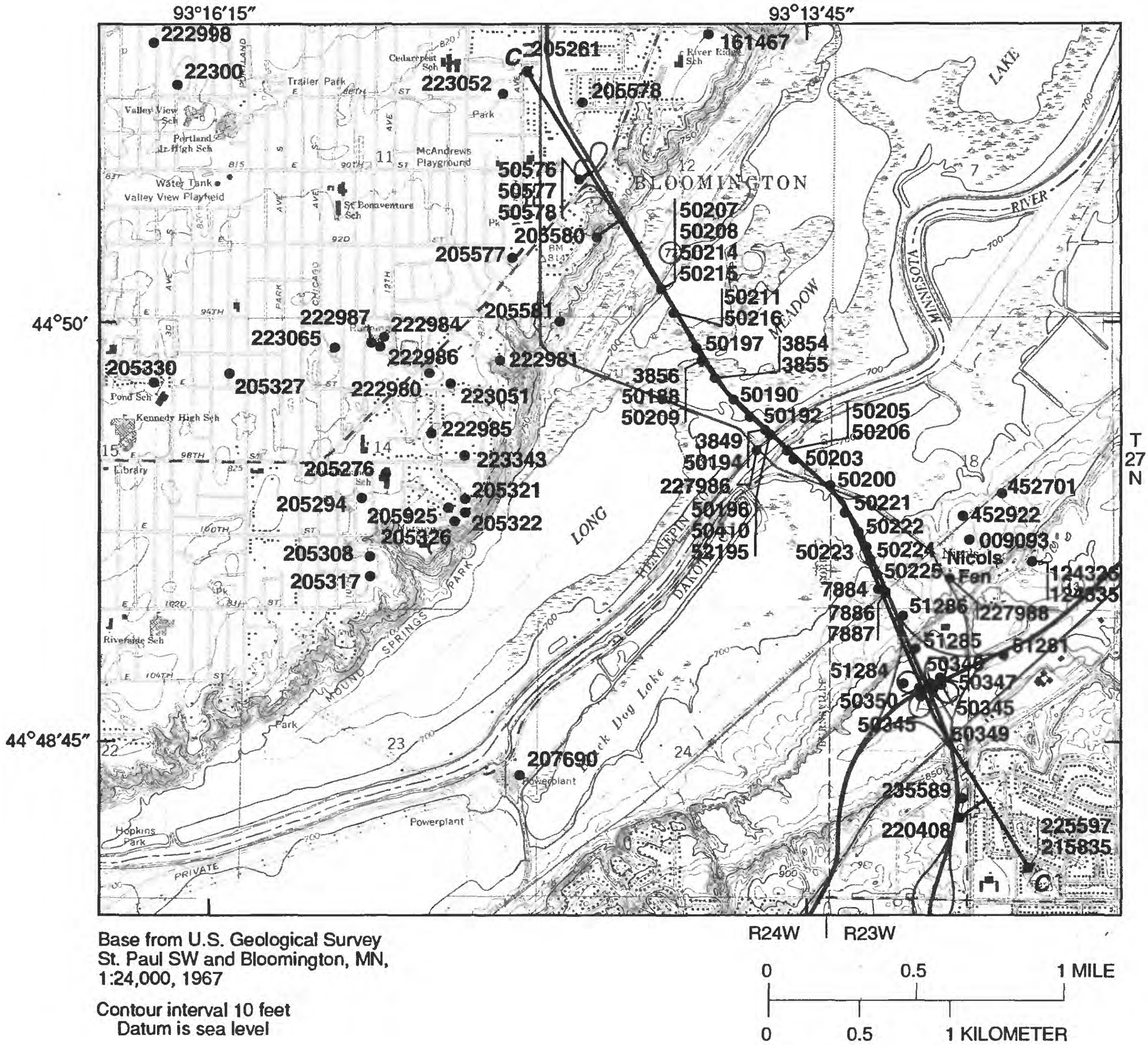
Hydrogeologic framework

Almost 200 ft of post-glacial alluvium, glaciofluvial sand and gravel, Pleistocene lake deposits, and peat fill a bedrock valley under the present-day Minnesota River. The valley is cut into terrace deposits, till, sand and gravel, and the Prairie du Chien-Jordan aquifer (fig. 16). As much as 40 ft of post-glacial peat, silty clay, clay, and muck lie near the river-valley walls.

Hydraulic properties

Hydraulic conductivity for post-glacial alluvium, and Pleistocene lake deposits were estimated from grain-size data and slug tests. Grain-size data are available from two test holes in the Minnesota River valley, MV05 (fig. 17) and MV06 (fig. 18). Hydraulic conductivity values for post-glacial alluvium were obtained from the analysis of slug-test data (table 4).

Estimated hydraulic conductivity of post-glacial alluvium based on grain-size analyses for samples from test hole MV05 (fig. 17), using the method of Summers and Weber (1984), ranged from 0.001 to 2 ft/d. Most layers in the post-glacial alluvium are mostly silt and clay



Base from U.S. Geological Survey
St. Paul SW and Bloomington, MN,
1:24,000, 1967

Contour interval 10 feet
Datum is sea level

LOCATION MAP

EXPLANATION

C——C' Trace of section

●—— Line of projection of well or test hole onto trace of section

●7884 Well or test hole (with identification number)

Figure 15. Location of wells, test holes, and hydrogeologic section, Area 2.

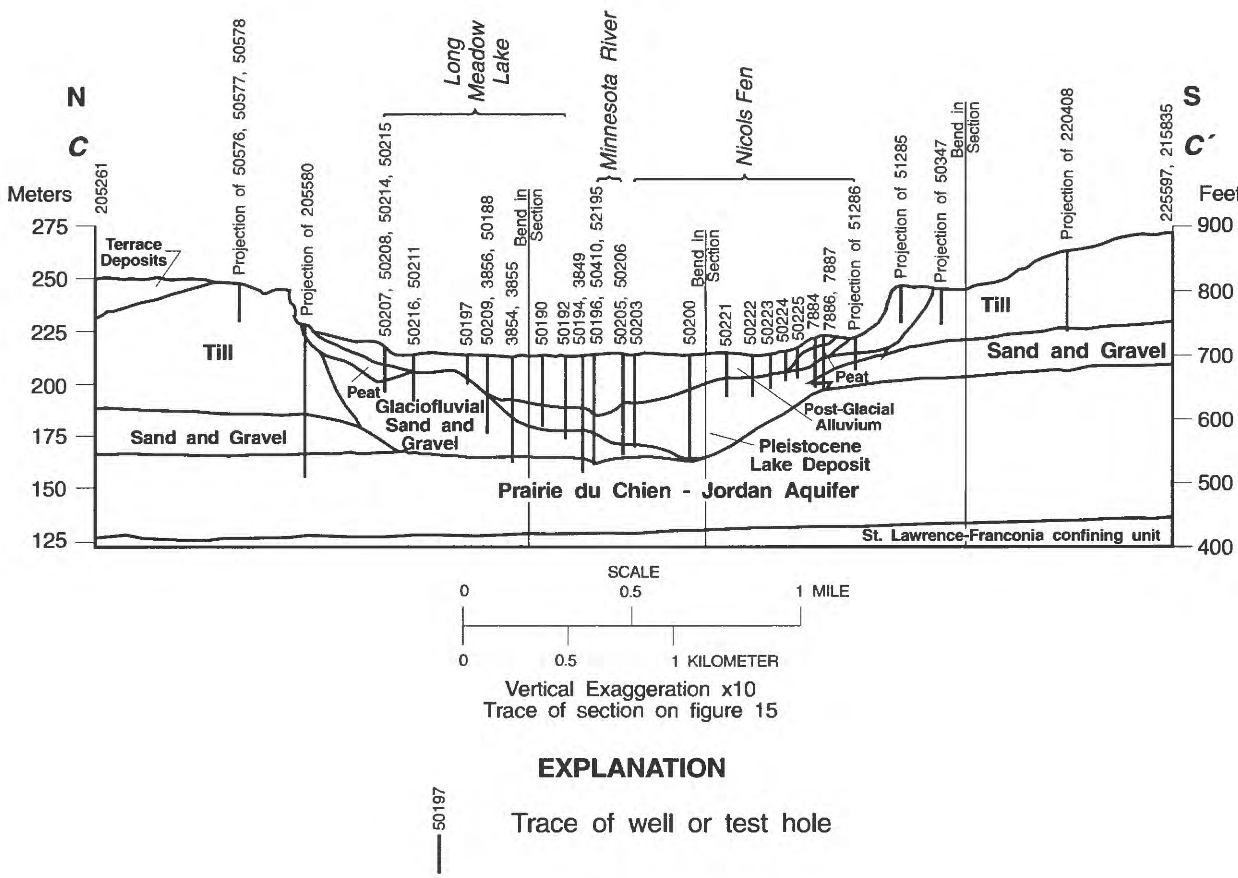


Figure 16. Hydrogeologic section C - C′, Area 2, Eagan/Bloomington area near Minneapolis-St. Paul, Minnesota.

and have conductivities of about 0.001 ft/d. Hydraulic conductivity is greatest (2 ft/d) in layers that contain 25 to 50 percent sand (with less than 10 percent clay).

Pleistocene lake deposit sediments are almost all silt and clay. The percentage of clay generally increases with depth. The hydraulic conductivity of this material is estimated to be less than 0.001 ft/d, using the method of Summers and Weber (1984). Fractures observed in cores from the lower part of this unit, however, indicate that secondary permeability may be present.

In test hole MV06 (fig. 18) the silt and clay content of the post-glacial alluvium increases toward land surface through three broad zones. The lowermost zone is between 28 ft below land surface and bedrock at 55 ft below land surface. The hydraulic conductivity of this zone ranges from 1 to 2 ft/d. In the middle zone, from 18 to 28 ft below land surface, sand and clayey silt layers are interlayered. The hydraulic conductivity ranged from about 10 ft/d for coarser layers to about 0.001 ft/d for finer layers. The uppermost saturated zone, from 4 to 18 ft below land surface contains mostly silt and clay. It has a hydraulic conductivity of 0.001 ft/d or less. All estimated values of hydraulic conductivity are based on the method of Summers and Weber (1984).

Based on the results of slug tests, the hydraulic conductivity of peat near the southern bluff was 0.01 ft/d (well 227987) and the hydraulic conductivity of post-glacial alluvium adjacent to Long Meadow Lake was 2

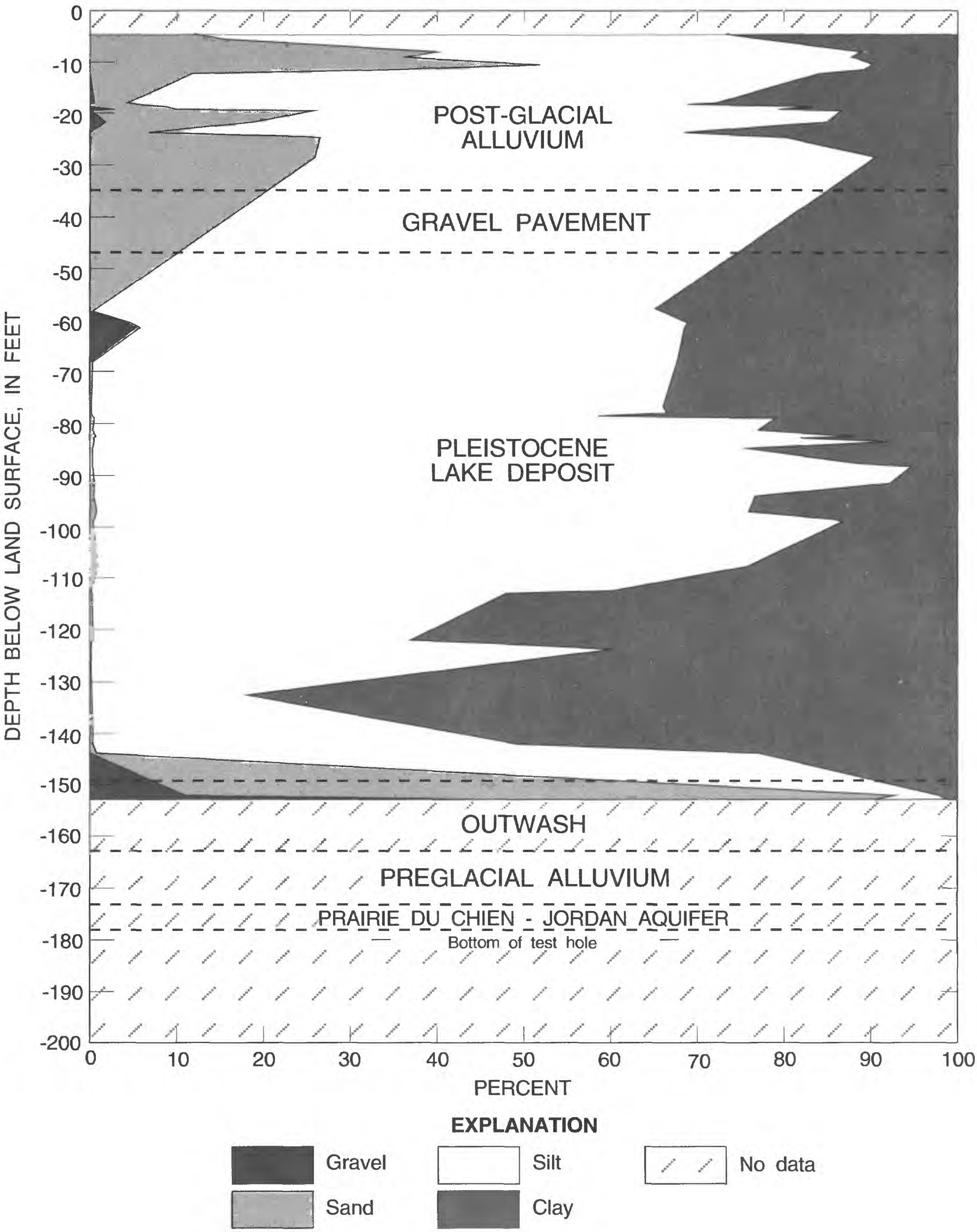


Figure 17. Graphic log of grain-size analyses from test hole MV05 showing percentage of gravel, sand, silt, and clay near Chaska, Minnesota.

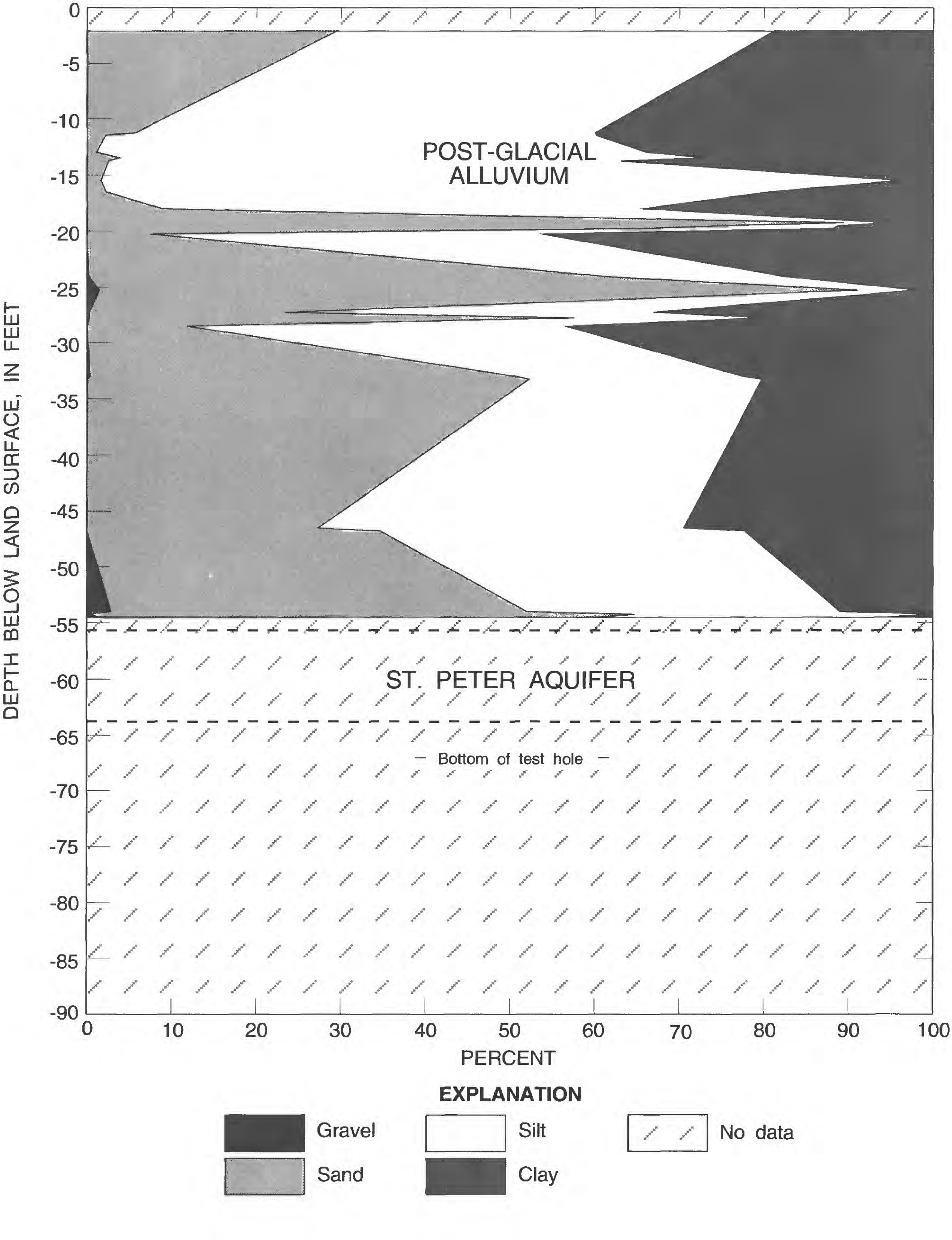


Figure 18. Graphic log of grain-size analyses from test hole MV06 showing percentage of gravel, sand, silt, and clay near St. Paul, Minnesota.

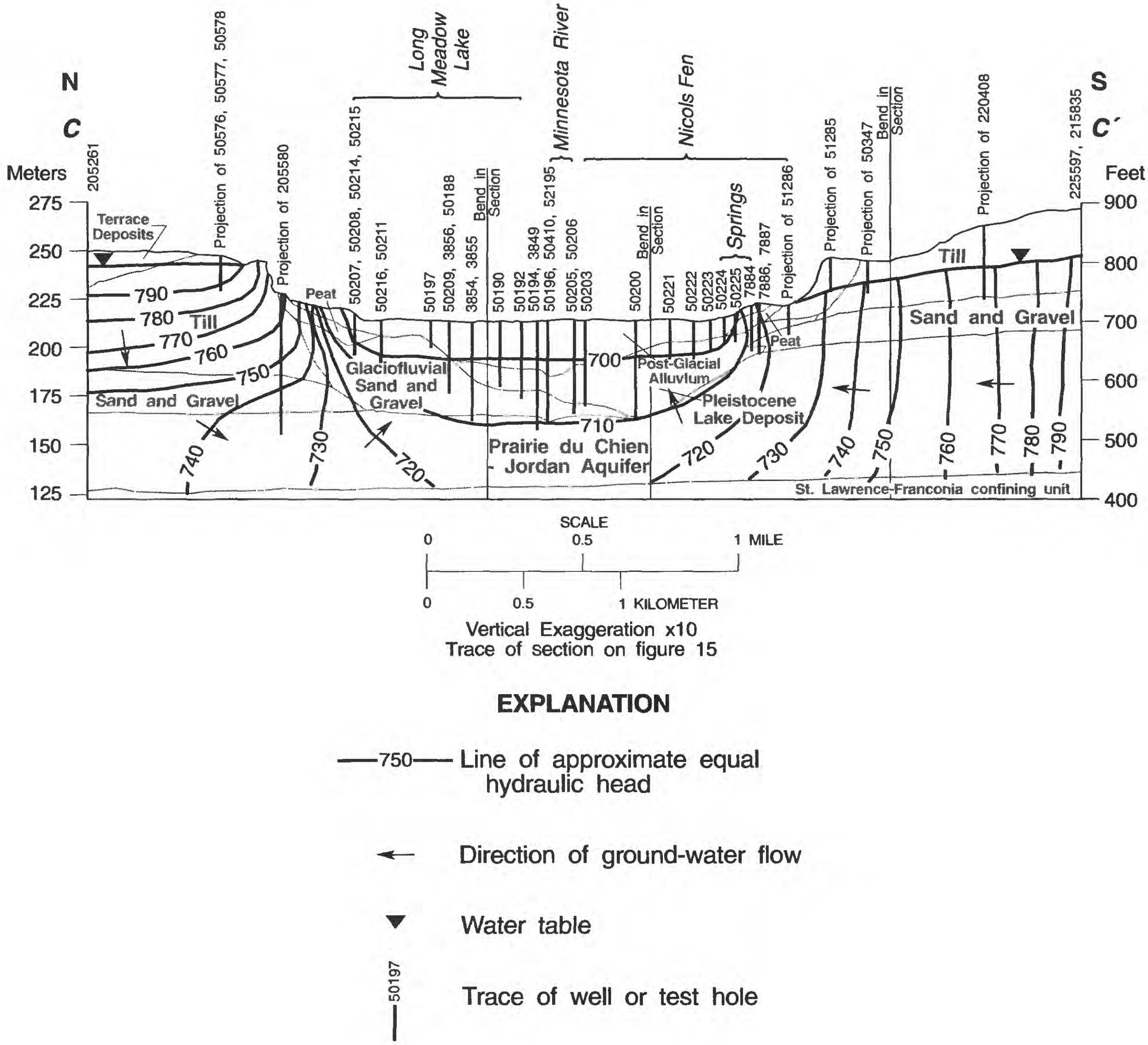


Figure 19. Ground-water flow, section C - C´, Area 2, Eagan/Bloomington area near Minneapolis-St. Paul, Minnesota.

ft/d (well 227986) (table 4). In both cases the data were analyzed with the Bouwer-Rice method (Bouwer and Rice, 1976; Bouwer, 1989).

Ground-water flow system

At the Eagan/Bloomington transect in Area 2, ground water flows toward the Minnesota River from the bluffs north of the river and through the underlying Prairie du Chien-Jordan aquifer from north and south of the river (fig. 19). It is assumed that no ground water flows normal to the hydrogeologic section shown in figure 19 because the section is approximately perpendicular to potentiometric contours in the Prairie du Chien-Jordan aquifer shown by Schoenberg (1984). Precipitation percolates from the bluff north of the river to the water table and flows to seepage faces along the river banks or leaks into the Prairie du Chien-Jordan aquifer. The hydraulic head changes from greater than 790 ft under the northern bluff to less than 700 ft under the river. The fine-grained tills on the southern bluff probably impede vertical leakage from the water table to the Prairie du Chien-Jordan aquifer near the river. Much of the water that flows through the Prairie du Chien-Jordan aquifer from the south, therefore, probably starts as underflow into Area 2 south of the transect. The top of the St. Lawrence-Franconia confining unit, which underlies the Prairie du Chien-Jordan aquifer, is the bottom of the ground-water-flow system. Only the top of the St. Lawrence-Franconia confining unit is shown in figure 19.

Confining units beneath the river channel impede the direct discharge of ground water from the underlying Prairie du Chien-Jordan aquifer to the river. Ground water discharges to wetlands, lakes, and springs along both the north and south side of the river. Along the southern bluff, ground-water discharge coalesces to form Black Dog Lake and Nicols Fen; along the northern bluff, it forms Long Meadow Lake (fig. 15). Water discharging into Black Dog Lake and Nicols Fen along the southern bluff face probably flows through the upper part of Prairie du Chien-Jordan aquifer and the overlying sand (fig. 19). The rate of discharge from a 1,600 ft^2 section of Nicols Fen to the Minnesota River, measured with a calibrated Parchall flume, was about 1 ft^3/s during 1988. Ground water discharges from the northern bluff face through the till into Long Meadow Lake.

Discharge to the Mississippi River at Minneapolis

Area 3 is located along the Mississippi River at Minneapolis about 5 mi upstream of the confluence of the Minnesota and Mississippi Rivers (fig. 20). No test holes or wells were installed in Area 3 for this project. One test hole was drilled into bedrock outside of the study area (MV07 shown in figure 1) to obtain samples of valley-fill deposits, which were deposited under similar conditions to those in Area 3.

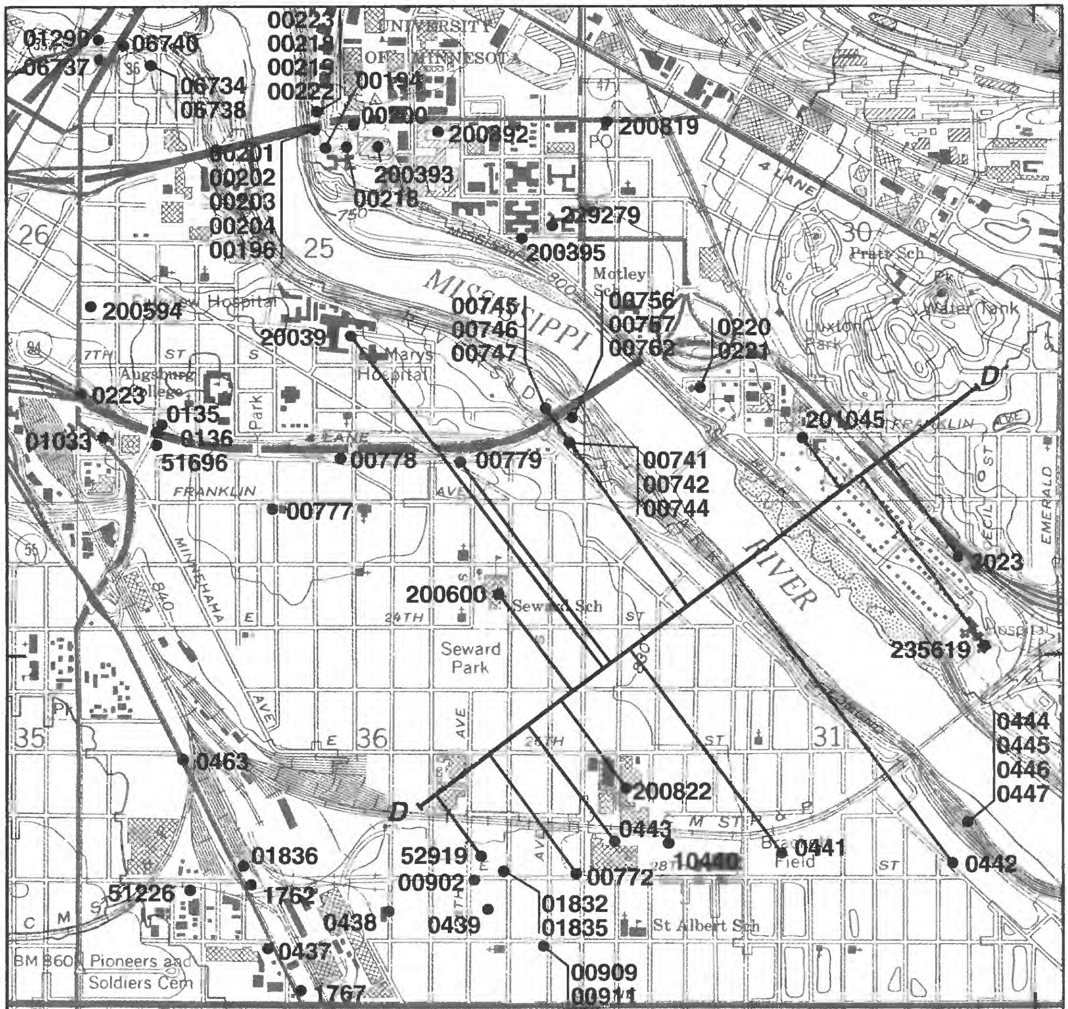
Hydrogeologic framework

The Mississippi River lies in a post-glacial valley cut through thin glacial drift into the St. Peter aquifer (fig. 21). The drift is a terrace deposit (Hobbs and Goebel, 1982) that contains layers of medium to fine sand, sand and gravel, and fine sand. On the west side of the river, there also is a lower sand layer (not shown) (0 to 15 ft thick). The drift was deposited on the eroded surface of the Decorah-Platteville-Glenwood confining unit (fig. 21) (Norvitch and Walton, 1979). Post-glacial alluvium in the valley is mostly well-washed sand. This sand comes locally from the drift aquifer and the St. Peter aquifer, or was transported by the Mississippi River from bedrock and drift deposits further upstream. The post-glacial alluvium in the river valley is as much as 20 to 100 ft thick. The hydrogeologic section generalizes the hydrology of Area 3 by using data projected from wells and test holes that are off the line of section (figs. 20 and 21).

The Decorah-Platteville-Glenwood and St. Lawrence-Franconia confining units bound the bedrock ground-water-flow system in Area 3. The Decorah-Platteville-Glenwood confining unit is absent in the river valley. This confining unit crops out in the valley walls. The confining unit thins from about 75 ft thick along the northeastern side of the transect to being absent near the southwestern side of the transect. The St. Peter aquifer underlies the Decorah-Platteville-Glenwood confining unit and is continuous along the entire transect, ranging from about 25 to 125 ft thick. The St. Peter aquifer is thinnest in areas where the underlying Prairie du Chien-Jordan aquifer is thickest. It is thickest where the underlying Prairie du Chien-Jordan aquifer was eroded prior to deposition of the St. Peter aquifer. The lower St. Peter confining unit underlies most of the transect, but is absent above the thickest parts of the underlying Prairie du Chien-Jordan aquifer. The Prairie du Chien-Jordan aquifer underlies the whole transect. Only the top of this aquifer is shown in figure 21. The Prairie du Chien-Jordan aquifer is hydraulically connected to the Mississippi River through the St. Peter aquifer where the lower St. Peter confining unit is absent. The St. Lawrence-Franconia confining unit (not shown) is the lower boundary of the Prairie du Chien-Jordan aquifer and forms the bottom of the ground-water-flow system.

Hydraulic properties

Hydraulic conductivity of the post-glacial alluvium in Area 3 was estimated from grain-size data from test hole MV07 (fig. 22). Similar sediment sources and depositional processes affected the alluvium in Area 3 and the site of test hole MV07. The hydraulic conductivity of post-glacial alluvium, estimated using the method of Summers and Weber (1984), at MV07 ranged from about 5 to 200 ft/d. Hydraulic conductivities greater than 100 ft/d are typically associated with 25 percent or more gravel and less than 10 percent silt and clay. Samples that contain 50 percent gravel and between 10 and 20 percent silt and clay have an estimated hydraulic conductivity of about 100 ft/d. Samples with less than 5 percent gravel, but mostly sand, have hydraulic conductivity of about 5 ft/d to 20 ft/d. In comparison, disaggregated samples of the St. Peter aquifer from a location 3.3 mi downstream of the transect (not shown)



LOCATION MAP

EXPLANATION

D——D′ Trace of section

●—— Line of projection of well or test hole onto trace of section

• 1767 Well or test hole (with identification number)

Figure 20. Location of wells, test holes, and hydrogeologic section D - D´, Area 3.

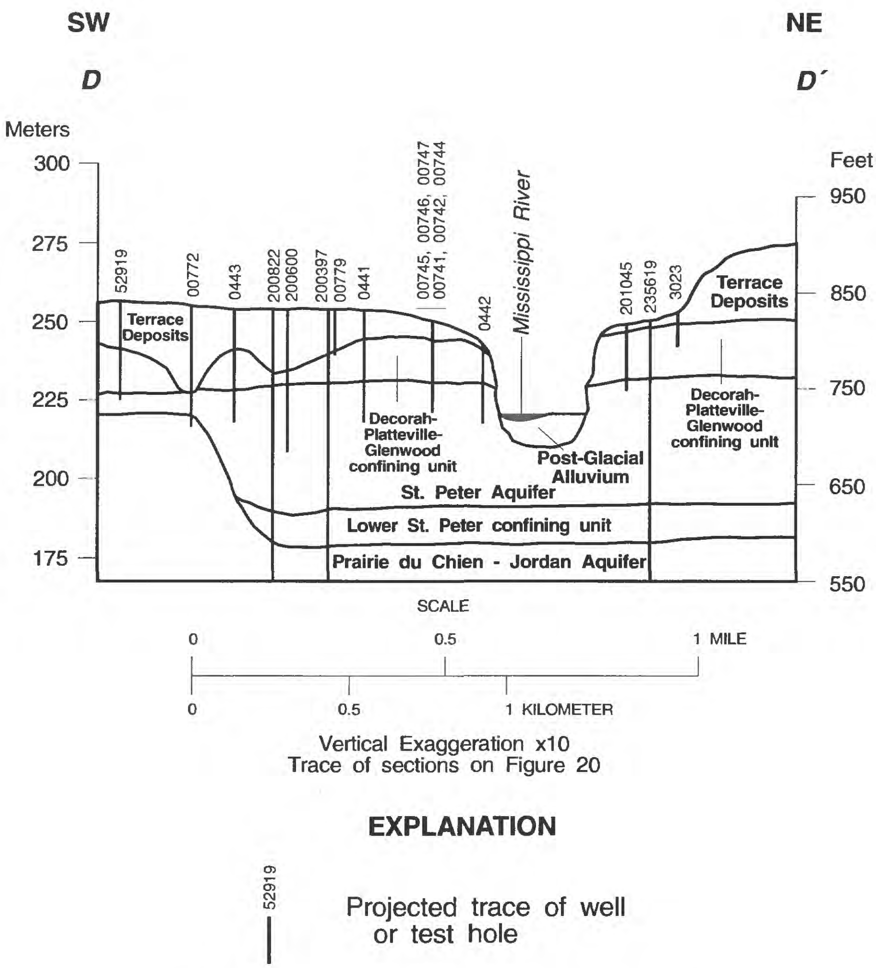


Figure 21. Generalized hydrogeologic section D - D′, Area 3, at Minneapolis, Minnesota.

had hydraulic conductivity values ranging from about 20 to 40 ft/d (U.S. Army Corps of Engineers, 1939).

Permeability tests on intact blocks of the St. Peter aquifer (U.S. Army Corps of Engineers, 1939) from a site 3.3 mi downstream of Area 3 indicate that the St. Peter aquifer has a hydraulic conductivity that ranges from about 3 ft/d for unfractured blocks to about 17 ft/d for heavily fractured blocks. More specifically, the hydraulic conductivity of unfractured blocks ranged from about 3 to 10 ft/d. The hydraulic conductivity of fractured blocks ranged from about 10 to 17 ft/d. Tests on one specimen in three mutually perpendicular directions indicate that the St. Peter aquifer might be locally isotropic (U.S. Army Corp of Engineers, 1939).

Ground-water-flow system

Ground water discharges from a continuous line of springs and seeps along the steep bluff face on the northeast side of the river where the water table intercepts the bluff face (fig. 23). On the west side of the river, ground-water discharge along the bluff face is limited to a few springs and seeps. Beneath the river, ground water flows from the St. Peter aquifer through the overlying post-glacial alluvium to the Mississippi River. No confining unit separates the St. Peter aquifer and the river. Beneath the river, ground-water flow from the Prairie du Chien-Jordan aquifer to the Mississippi River is impeded by the lower St. Peter confining unit. Water-table data used to construct figure 23 came from static water levels

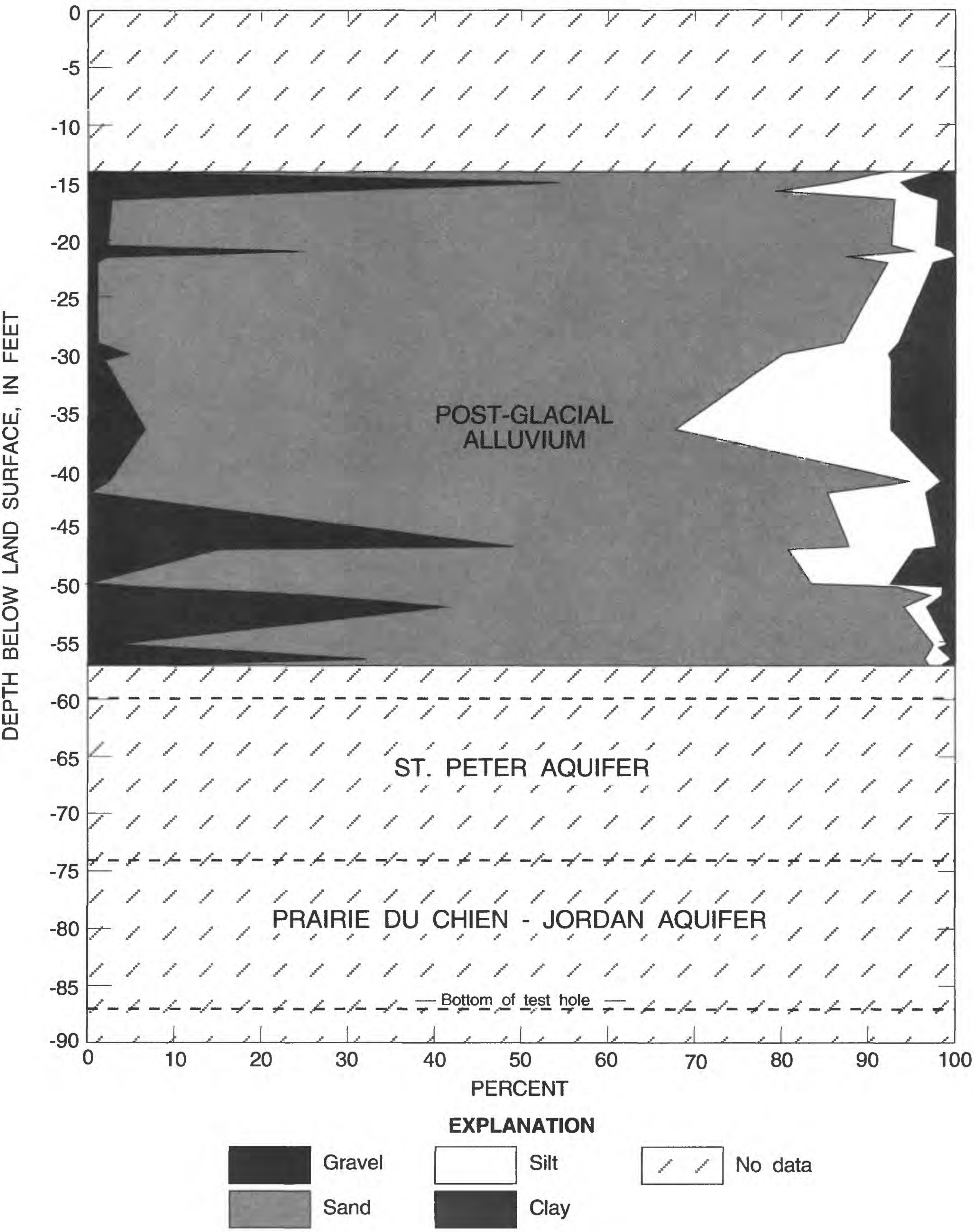


Figure 22. Graphic log of grain-size analyses from test hole MV07 showing percentage of gravel, sand, silt, and clay, near St. Paul, Minnesota.

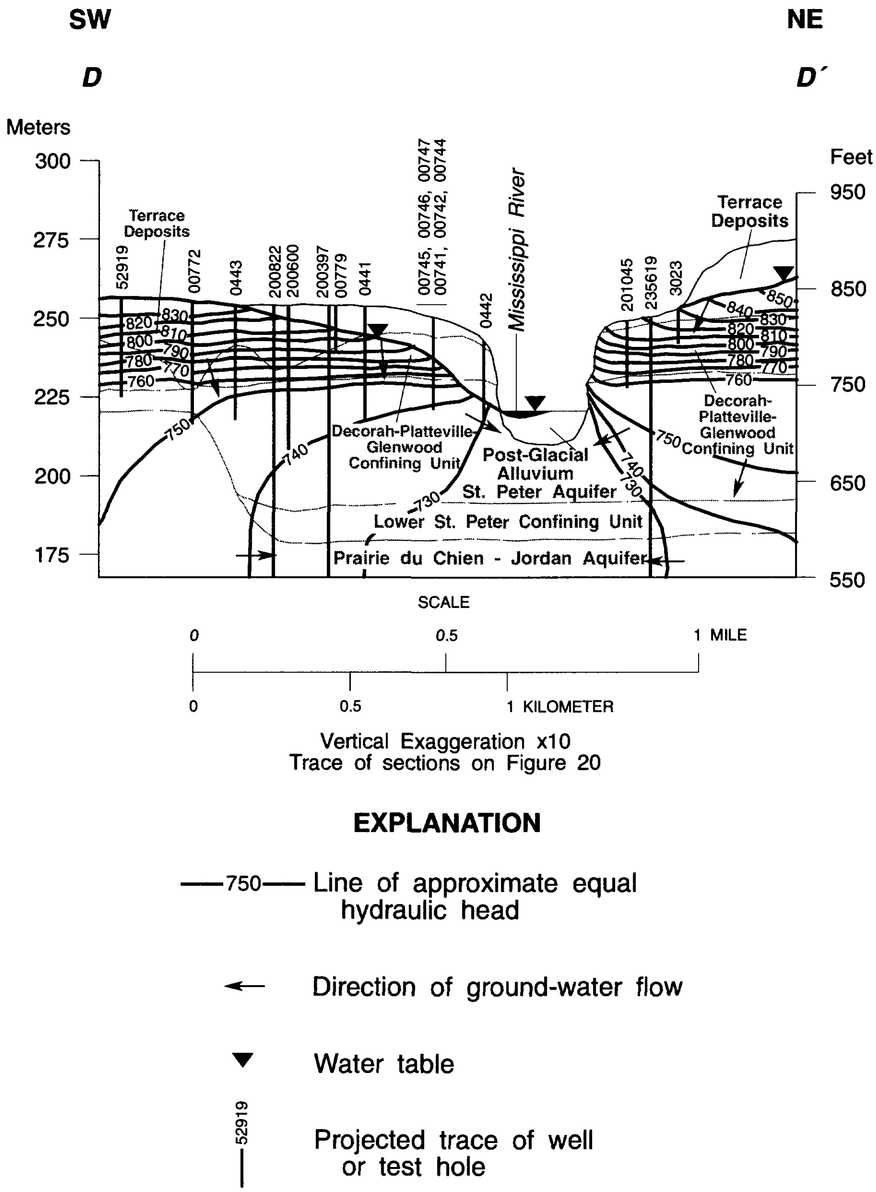


Figure 23. Ground-water flow, section D - D′, Area 3, at Minneapolis, Minnesota.

in test holes open to the water table. Hydraulic-head data for the Prairie du Chien-Jordan aquifer used to construct figure 23 came from a potentiometric map of that aquifer (Schoenberg, 1984). It is assumed that no ground water flows normal to the hydrogeologic section shown in figure 23 because the section is approximately perpendicular to potentiometric contours in the Prairie du Chien-Jordan aquifer shown by Schoenberg (1984).

Summary

Ground water connections between bedrock aquifers and the Mississippi and Minnesota Rivers depend on the types of fill in the river valleys. Ground-water discharge from bedrock aquifers to the rivers is characterized along transects across the rivers at three study areas in the Minneapolis-St. Paul area. Potentiometric maps of the Prairie du Chien-Jordan and St. Peter aquifers were used to select one transect in each area. The transects lay along lines of ground-water flow, perpendicular to potentiometric contours. Area 1 lies along the Mississippi River between Fridley and Brooklyn Center; Area 2 is in the Eagan/Bloomington area along the Minnesota River; and Area 3 is in Minneapolis along the Mississippi River.

At the transect in Area 1, eight unconsolidated hydrogeologic units overlie the bedrock St. Peter and Prairie du Chien-Jordan aquifers. A buried valley underlying the Mississippi River cuts through the overlying terrace deposits and glacial-drift deposits into two underlying bedrock hydrogeologic units: the St. Peter aquifer, and a rubble zone between the St. Peter and Prairie du Chien-Jordan aquifers.

Hydraulic conductivity of hydrogeologic units was determined with the permeameter tests, slug tests, and from grain-size distributions. The hydraulic conductivity determined with permeameter tests ranged from 30 to 50 ft/d for alluvium, from 5×10^{-4} to 0.3 ft/d for upper red till, from 4×10^{-5} to 0.8 ft/d for olive-black till, and was 0.3 ft/d for the St. Peter aquifer. Hydraulic conductivities determined with slug tests ranged from 0.3 to 80 ft/d in wells open to alluvium, was 4 ft/d for the top of the upper red till, ranged from 0.6 to 15 ft/d for the St. Peter aquifer, ranged from 20 to 35 ft/d for the St. Peter aquifer/rubble zone, and was 10 ft/d for the rubble zone. Estimated hydraulic conductivity based on grain-size distributions were as great as 50 ft/d for medium- to coarse-grained alluvium, about 5 ft/d for medium- to fine-grained alluvium, as low as 3 ft/d for glacial outwash, and about 5 ft/d for the St. Peter aquifer.

Hydraulic heads from eight clusters of wells were used to delineate ground-water flow through Area 1. Individual wells in each cluster were open to approximately the water table, the top of the St. Peter aquifer, or the immediately overlying glacial outwash or sand and gravel outwash aquifer, or the bottom of the St. Peter aquifer or underlying rubble zone, or the St. Peter aquifer/rubble zone. Hydrographs from the three well clusters on a line perpendicular to the Mississippi River showed that, when data are available, the hydraulic head in the shallow wells open to the water table responded primarily to seasonal factors throughout the year. A comparison of hydraulic-head changes in each well cluster, when data are available, indicate that, over a year, the hydraulic heads in the middle and deep wells in the same three well clusters responded primarily to river stage fluctuations during the winter and to changing regional ground-water pumpage during spring through fall. Hydraulic heads increased with depth in the St. Peter aquifer for at least 100 ft east of the Mississippi River, indicating upward flow regardless of river stage. In contrast, at a distance 1,500 ft east of the river, hydraulic heads generally decreased with depth in the aquifer, indicating ground-water recharge generally occurs at this location.

The distribution of potentiometric lines for November 17, 1989 and March 21, 1990 for Area 1 show that ground water flows from the topographically higher bluff to the topographically lower Mississippi River. Shallow ground-water flow in the near-surface gray and upper red tills and sand and gravel outwash aquifer discharges to springs along the edge of the river. Ground water flowing through the rubble zone and upper part of the Prairie du Chien-Jordan aquifer probably discharges directly to the river.

Ground-water flow for November 17, 1989 along the transect in Area 1 was simulated with a steady-state, cross-sectional, numerical model. The model was calibrated by comparing values of model-calculated hydraulic head and discharge (flux) to measured hydraulic head and estimated river discharge. The model was considered calibrated when the model-calculated hydraulic heads closely matched measured hydraulic heads and the model-calculated ground-water flux reasonably represented the estimated ground-water flux.

After model calibration, values of selected model parameters were varied to test the sensitivity of simulated hydraulic heads and flows to the values of parameters used in simulating the aquifer system (sensitivity analysis).

Results from the model simulation indicate that two important controls on the discharge to the river are the continuity of the upper part of the rubble zone and the hydraulic conductivity of the riverbed. The best match between measured and model-calculated hydraulic heads occurs when the upper part of the rubble zone was simulated as having a hydraulic conductivity of 10 ft/d, similar to that in the lower part of the rubble zone or the overlying alluvium. This could indicate that the upper part of the rubble zone is absent under the river. The lower the simulated hydraulic conductivity of the riverbed, the lower the simulated discharge from the alluvium and the Prairie du Chien-Jordan aquifer.

Calibrated-model results indicate that most ground-water flow moves through the Prairie du Chien-Jordan aquifer to the Mississippi River. About 71 and 16 percent of the 54 ft^3/d of (rounded) model-calculated discharge come from general-head boundaries along the western and eastern ends of the model, respectively.

In Area 2, along the Minnesota River between Eagan and Bloomington, almost 200 ft of post-glacial alluvium, glaciofluvial sand and gravel, Pleistocene lake deposits, and peat fill a bedrock valley under the present-day Minnesota River. As much as 40 ft of post-glacial peat, silty clay, clay, and muck lie near the river-valley walls.

In Area 2, hydraulic conductivity for post-glacial alluvium was estimated to range from 0.001 to 2 ft/d on the basis of grain-size analyses for samples from a test hole. Layers containing silt and clay have hydraulic conductivities of about 0.001 ft/d. Hydraulic conductivity is greatest (2 ft/d) in layers that contain 25 to 50 percent sand (with less than 10 percent clay). Based on grain-size analyses for samples from test hole MV06, sediments that contain mostly silt and clay and almost no sand have hydraulic conductivities less than 0.001 ft/d. The hydraulic conductivity of coarser layers in the alluvium is about 10 ft/d. Slug-test results indicate that peat has a hydraulic conductivity of 0.01 ft/d and post-glacial alluvium has a hydraulic conductivity of 2 ft/d.

At the transect in Area 2, confining units beneath the river channel impede the direct discharge of ground water from the underlying Prairie du Chien-Jordan aquifer to the river. Ground water discharges to wetlands, lakes, and springs along both the north and south side of the river.

Area 3 is along the Mississippi River at Minneapolis, about 5 mi upstream of the confluence of the Minnesota and Mississippi Rivers. The Mississippi River lies in a post-glacial valley cut through thin glacial drift into the St. Peter aquifer. Post-glacial alluvium in the river valley is mostly well-washed sand and is as much as 20 to 100 ft thick. This sand comes locally from the drift aquifer and the St. Peter aquifer, or was transported by the Mississippi River from bedrock and drift deposits further upstream. Estimated hydraulic conductivity of post-glacial alluvium ranged from about 5 to 200 ft/d. Estimated hydraulic conductivity of disaggregated samples and intact blocks of the St. Peter aquifer ranged from about 20 to 40 ft/d and 3 to 17 ft/d, respectively. Beneath the river, ground-water flows from the St. Peter aquifer through the overlying post-glacial alluvium to the Mississippi River. No confining unit separates the St. Peter aquifer and the river.

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