HYDROGEOLOGY AND WATER QUALITY OF THE GALENA-PLATTEVILLE AQUIFER AT THE PARSON'S CASKET HARDWARE SUPERFUND SITE, BELVIDERE, ILLINOIS, 1991

By Patrick C. Mills

U.S. GEOLOGICAL SURVEY

Open-File Report 93-403

Prepared in cooperation with the

U.S. ENVIRONMENTAL PROTECTION AGENCY

Urbana, Illinois

1993

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Robert M. Hirsch, Acting Director

For additional information
write to:

District Chief
U.S. Geological Survey
102 E. Main St., 4th Floor
Urbana, IL 61801

Copies of the report can be
purchased from:

U.S. Geological Survey
Earth Science Information Center
Open-File Reports Section
Box 25286, MS 517
Denver Federal Center
Denver, CO 80225

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS

TABLES

CONVERSION FACTORS, ABBREVIATED WATER-QUALITY UNITS, AND VERTICAL DATUM

Multiply	By	To Obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
acre	0.4047	hectare
foot per foot (ft/ft)	0.3048	meter per meter
foot per day (ft/d)[1]	0.3048	meter per day
foot squared per day (ft^2/d)	0.09290	meter squared per day
gallon (gal)	3.785	liter
gallon per minute (gal/min)	3.785	liter per minute
pound per square inch (lb/in^2)	6.895	kilopascal
degree Celsius (°C)	°F = 1.8 x °C + 32	degree Fahrenheit (°F)
part per billion (ppb)	1.00	microgram per liter
part per million (ppm)	1.00	milligram per liter

Abbreviated water-quality units used in this report:

microsiemen per centimeter at 25°C (μS/cm)

millivolt (mv)

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.

[1]Foot per day is the mathematically reduced term of cubic foot per day per square foot of aquifer cross-sectional area.

HYDROGEOLOGY AND WATER QUALITY OF THE GALENA-PLATTEVILLE AQUIFER AT THE PARSON'S CASKET HARDWARE SUPERFUND SITE, BELVIDERE, ILLINOIS, 1991

by Patrick C. Mills

ABSTRACT

The U.S. Geological Survey, in cooperation with the U.S. Environmental Protection Agency, investigated the hydrogeology of the Galena-Platteville aquifer and its relation to contaminant migration at the Parson's Casket Hardware Superfund site in Belvidere, Ill. This report presents the results of the second phase of the investigation, which lasted from March through October 1991.

The uppermost bedrock units beneath the study site are the Galena and Platteville Groups[1]; these bedrock units immediately underlie a glacial drift aquifer. The Galena and Platteville Groups, which consist predominantly of dolomite, compose the Galena-Platteville aquifer, and extend from about 40 to 320 feet below land surface. The unconfined Galena-Platteville aquifer is partitioned into five hydrogeologic units. The uppermost unit, the weathered surface of the bedrock, has a horizontal hydraulic conductivity that ranges from about 1 to 200 feet per day. The four underlying units have hydraulic conductivities that range from about 0.01 to 1 foot per day. Vertical hydraulic gradients in the aquifer are typically downward. Horizontal ground-water flow generally is southward to southeastward from the site toward the Kishwaukee River.

Three notable bedding-plane solution fissures and three fractures that crosscut the bedding planes are identified within the dolomite bedrock. The inclined fractures are assumed to function as conduits that connect high conductivity horizontal fissures, thus allowing more rapid vertical movement of ground water and contaminants than would be expected in the generally low conductivity dolomite matrix.

A multiple-well, constant-discharge aquifer test confirms the heterogeneity and anisotropy of the dolomite aquifer. The hydraulic characteristics of the uppermost part of the bedrock aquifer are somewhat different than the characteristics of the deeper part(s) of the aquifer. This is because the principal conduits for water movement are in the deeper part(s) of the aquifer.

Ground-water flow in the Galena-Platteville aquifer beneath the study site is affected by pumping of Belvidere Municipal Wells No. 4 and No. 6. Water levels in wells screened near the vertical midpoint of the aquifer are affected by the municipal-well pumping substantially more than are water levels in wells screened near the top of the aquifer.

[1]Stratigraphic nomenclature is that of the Illinois State Geological Survey.

The highest specific conductances and the highest sodium, chloride, and nitrite-nitrate concentrations were present within the shallowest test interval (about 41 to 57 ft below land surface) in the aquifer. Volatile organic compounds (VOC's) were detected throughout the vertical extent of the Galena-Platteville aquifer beneath the site and there was a positive correlation between VOC concentrations and specific conductances. The predominant VOC's were trichloroethylene (TCE), 1,300 ppb (parts per billion), and 1,1,1-trichloroethane (1,1,1-TCA), 900 ppb.

INTRODUCTION

The Parson's Casket Hardware site, encompassing about 2 acres at the northern edge of Belvidere, Boone County, Ill. (fig. 1), is designated a Superfund site under the U.S. Environmental Protection Agency (USEPA) Comprehensive Environmental Response, Compensation, and Liability Act program. The history of the site, as compiled by the Illinois Environmental Protection Agency (1989), indicates that, from 1898 until 1982, the Parson's Casket Hardware Company manufactured metal fittings for caskets by use of an electroplating process. Wastes generated by the manufacturing process included electroplating sludge, cyanide solutions, and assorted metal sludges. Waste products were stored in steel drums, electroplating tanks, four underground storage tanks, and an unlined waste-disposal pond (fig. 2). Organic solvents, acidic and alkaline cleaning solutions, cyanide, and arsenic have been identified in storage-drum, soil, and water samples collected at the site. Additionally, an oil layer has been detected at the water-table surface near the previous location of the waste-disposal pond (Science Applications International Corporation, 1990a). During 1982-85, the Illinois Environmental Protection Agency (IEPA) coordinated the removal of waste materials from the site; part of that effort included the removal of contaminated water and soil from the waste-disposal pond and filling of the pond with clean soil.

Hydrogeology and contaminant distribution at the site have been investigated by the IEPA and USEPA since 1984 (Science Applications International Corporation, 1990a). The most recent investigation was in 1990 as part of the remedial investigation/feasibility study, phase 2 site investigation (Science Applications International Corporation, 1990a). These investigations have focused primarily on soils in the unsaturated zone and the glacial drift aquifer that immediately underlies the site. In 1990, the USEPA requested that the U.S. Geological Survey (USGS) investigate the hydrogeology and contaminant distribution in the uppermost bedrock aquifer, the dolomite Galena-Platteville aquifer. Results of the USGS investigation will be used by the IEPA and USEPA to develop strategies for effective aquifer remediation. The USGS investigation is being done in several phases. This report presents the results of the second phase.

The first phase of the Galena-Platteville aquifer investigation described the vertical distribution of horizontal hydraulic conductivity (hereafter referred to as hydraulic conductivity) and volatile organic compound (VOC) concentrations in three 150-ft-deep boreholes (G115BD, G125BD, G126BD; fig. 2) (Mills, 1993a). In that investigation, hydraulic conductivities of the

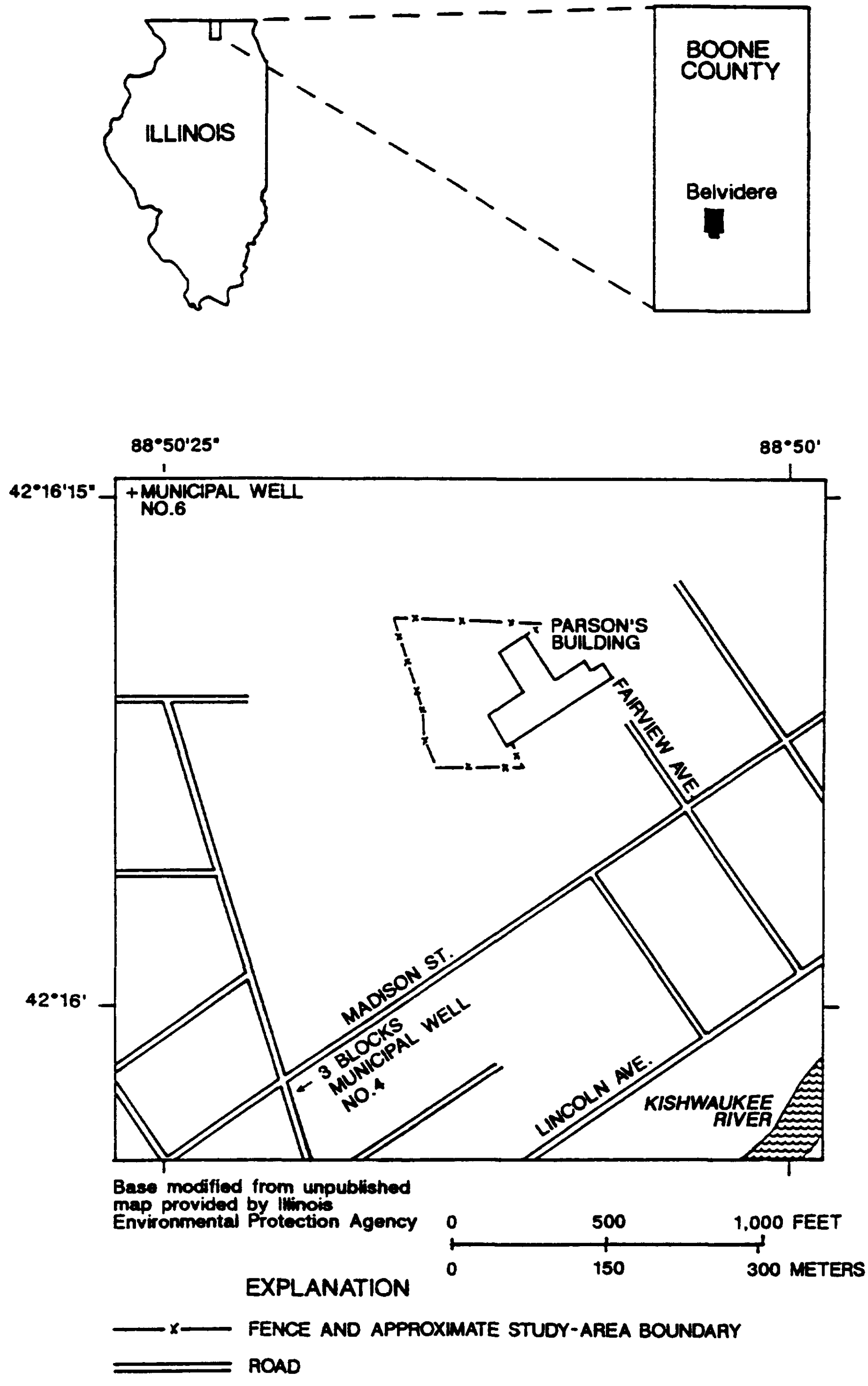
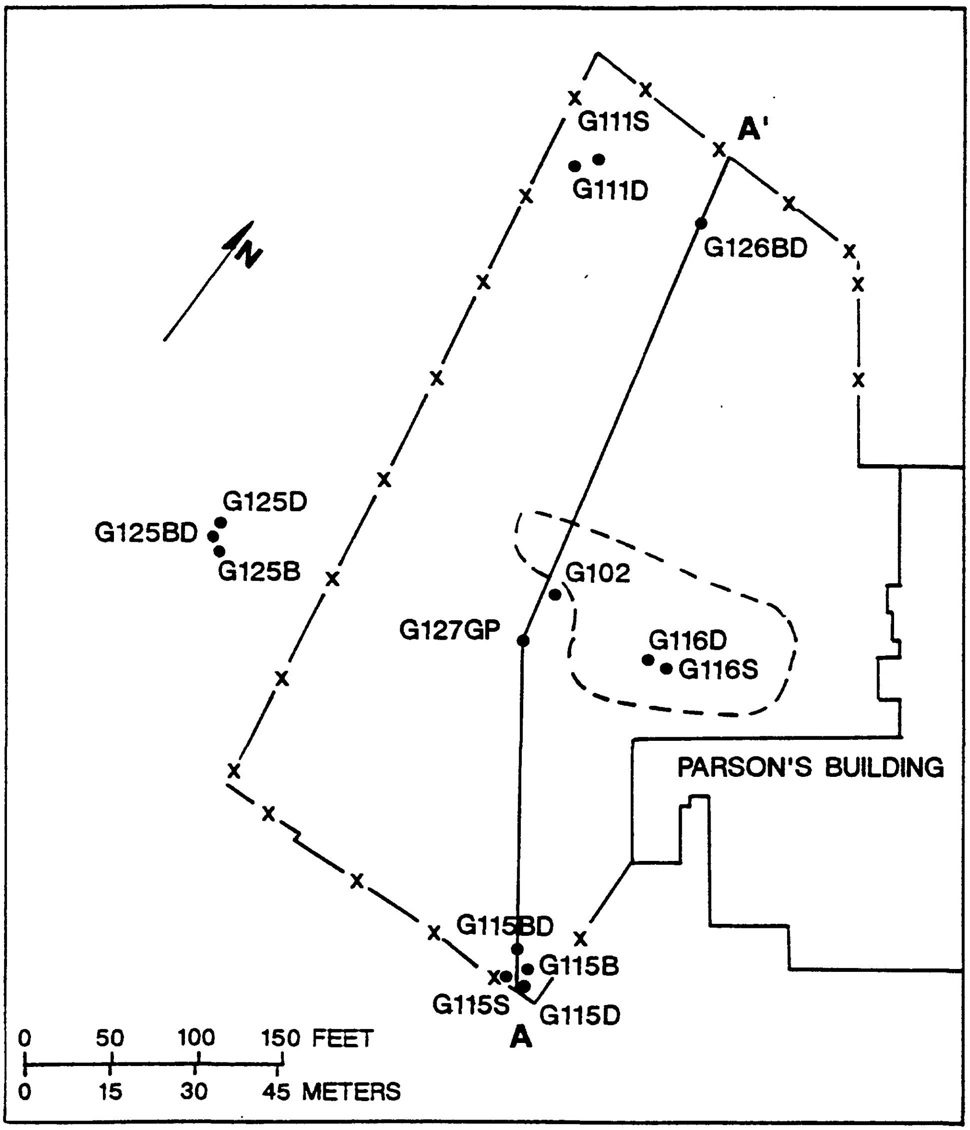


Figure 1.--Location of Parson's Casket Hardware Superfund site.



Base modified from unpublished map provided by Illinois Environmental Protection Agency

EXPLANATION

—x—	FENCE AND APPROXIMATE STUDY-AREA BOUNDARY
- - - - - -	APPROXIMATE LOCATION OF FORMER WASTE-DISPLOSAL POND
A——A'	LINE OF SECTION
G115BD ●	BOREHOLE OR OBSERVATION WELL AND DESIGNATION

Figure 2.--Location of borehole, observation wells, and line of section A-A' at the study site.

aquifer were determined to range from about 0.01 to 200 ft/d. The highest hydraulic conductivities were associated with the weathered surface of the bedrock. Elevated hydraulic conductivities also were associated with an interval of strata between about 115 and 125 ft below land surface that seems to be horizontally continuous across the site. Detectable concentrations of VOC's (up to 570 ppb trichloroethylene) were identified throughout the vertical extent of the three test boreholes.

The second phase of the investigation had three objectives: (1) to determine if pumping of nearby municipal wells affects flow of water in the aquifer beneath the study site, (2) to refine the hydrogeologic characterization of the aquifer, and (3) to determine the vertical distribution of inorganic-constituent and VOC concentrations in water in the lower half of the dolomite aquifer.

The third and final phase of the investigation, as described in Mills (1993b), provided additional information on the vertical distribution of hydraulic conductivity and water quality in the upper half of the dolomite aquifer and evaluated water quality in the uppermost part of the underlying St. Peter Sandstone aquifer.

Several factors determined the objectives of the second phase of the investigation. Trace concentrations of chlorinated hydrocarbons similar to those detected in ground water beneath the study site have periodically been detected in Belvidere Municipal Wells No. 4 and No. 6 (Voelker and others, 1988), located within 0.5 mi of the study site (fig. 1). Both wells derive water from the Galena-Platteville aquifer (are open to about 60 to 75 percent of the aquifer thickness), as well as several underlying bedrock aquifers, including the St. Peter Sandstone aquifer (Woller and Sanderson, 1974, p. 7,8). There has been concern that the Parson's Casket Hardware site may be a source of the low concentrations of VOC's (below the USEPA established maximum contaminant levels) detected in the municipal-well water. The USEPA investigated this possibility by monitoring water levels in two Parson's Casket Hardware site wells (a shallow dolomite-aquifer well and a glacial-drift-aquifer well) to determine if the water levels were responding to municipal-well pumping; no response was detected (Douglas Yeskis, U.S. Environmental Protection Agency, written commun., 1990). During subsequent site investigations, water-level changes that were not attributable to natural recharge cycles were detected in some of the site wells. The unexplained water-level changes prompted additional evaluation of the effects of municipal-well pumping on ground-water flow and contaminant migration beneath the study site.

Existing hydrogeologic characterization of the dolomite aquifer (Mills, 1993a) was limited to determination of the vertical distribution of hydraulic conductivity above the 150-ft depth limit of three boreholes (hereafter all depths are referenced to land surface, unless otherwise noted). In order to effectively characterize the hydrogeology of the aquifer, investigators required more data regarding (1) lithologic composition of the aquifer material, (2) potential preferential pathways for ground-water flow and contaminant movement within the aquifer, (3) spatial distribution of hydraulic conductivity through the full vertical extent of the aquifer, and (4) average hydraulic properties of the aquifer.

In the first phase of the investigation, VOC's were detected in ground water throughout the 150-ft depth of the three test boreholes (Mills, 1993a). Additional sampling below that depth was necessary to determine the vertical extent of VOC migration in the dolomite aquifer.

In the first phase of the investigation, VOC's also were detected in a dolomite-bedrock well upgradient and beyond the property limits of the Parson's Casket Hardware site (Mills, 1993a). The inorganic chemistry of ground water beneath the study site was characterized to aid in delineation of what seems to be multiple source areas of ground-water contamination in the vicinity of the Parson's Casket Hardware site.

Purpose and Scope

This report provides results of the second phase of the USGS investigation of the Galena-Platteville aquifer, which lasted from March through October 1991. The report presents and interprets (1) rock-core and geophysical data collected to assist the hydrogeologic characterization of the aquifer; (2) water-level data collected to evaluate the hydraulic relation of the aquifer to the saturated glacial deposits that overlie the aquifer and to evaluate the effect of municipal-well pumpage on ground-water flow and contaminant migration in the aquifer; (3) aquifer-test data collected at borehole G127GP (fig. 2) to determine the vertical distribution of hydraulic conductivity in the lower half of the aquifer; (4) aquifer-test data collected from a multiple-well aquifer test to determine the average hydraulic properties of the aquifer; and (5) water-quality data collected at borehole G127GP to determine the vertical distribution of inorganic-constituent and VOC concentrations in the lower half of the aquifer.

Hydrogeologic Setting

The hydrogeology of Quaternary deposits at the study site has been described by the IEPA (Science Applications International Corporation, 1990a). A number of investigators have described the geology (Willman and others, 1975; Willman and Kolata, 1978) and the hydrogeology (Berg and others, 1984; Schumacher, 1990) of the bedrock deposits in the vicinity of the study site. Geologic and hydrogeologic descriptions included in the above-referenced reports provide the basis for the following description of the hydrogeologic setting of the study site. The stratigraphic nomenclature used in this report is that of the Illinois State Geological Survey (Willman and others, 1975, p. 61-80 and 211-231) and does not necessarily follow the usage of the USGS.

The Parson's Casket Hardware site is in a broad lowland valley that overlies the Troy Bedrock Valley. The valley axis is about 3 mi west of the site. Land surface at the site is virtually flat; land-surface altitudes in the vicinity of the site range from about 782 to 785 ft (fig. 3). Surface drainage is to the Kishwaukee River, which is about 0.5 mi south of the site (fig. 1).

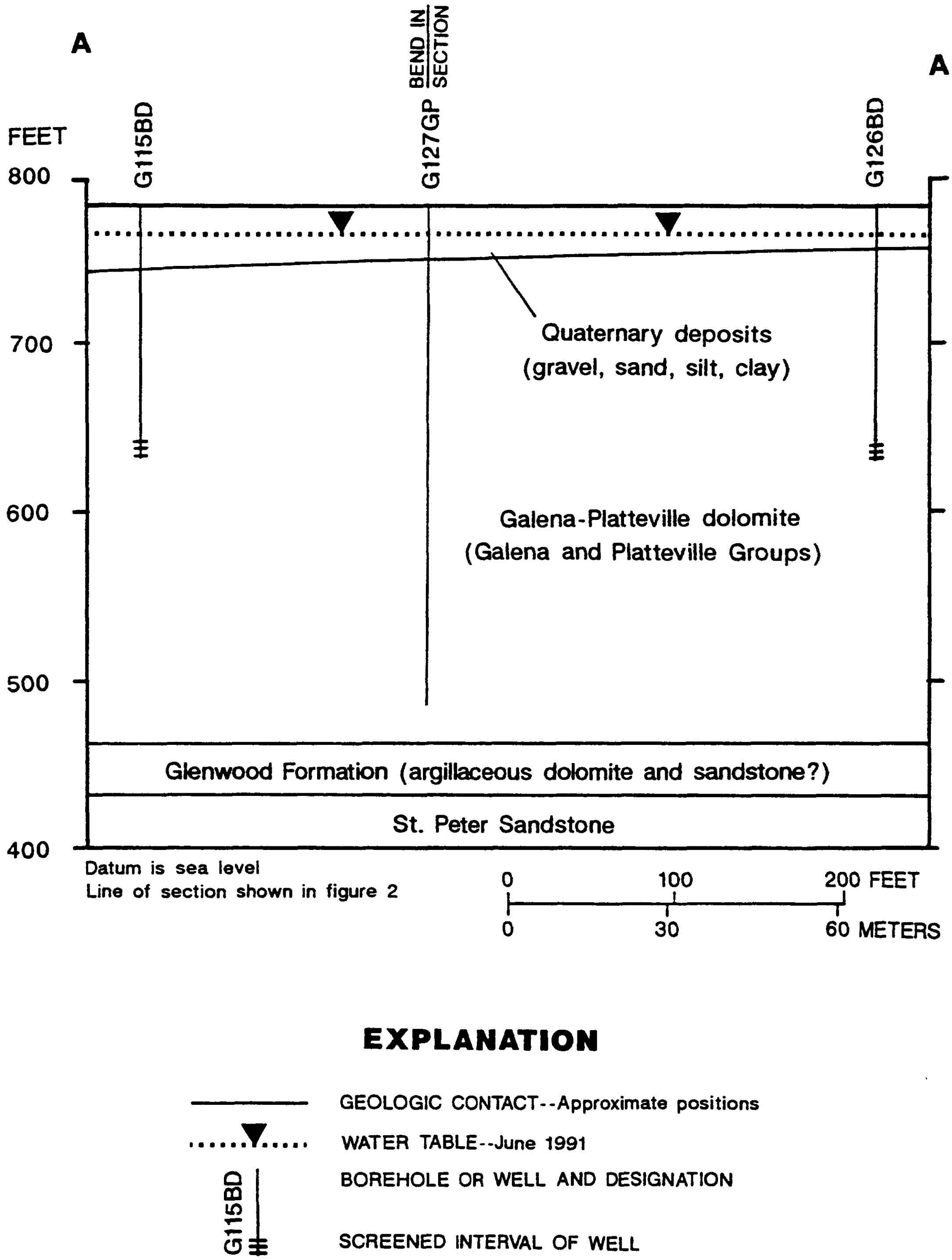


Figure 3.--Hydrogeologic section A-A' through the study site.

The surficial geologic deposits at the study site are glacial-drift deposits of Quaternary age (fig. 3). The 25- to 40-ft-thick unconsolidated glacial-drift deposits are composed of the Belvidere Till Member of the Glasford Formation, the Nimitz Till Member of the Winnebago Formation, the Mackinaw Member of the Henry Formation, the Grayslake Peat, and the Cahokia Alluvium (Science Applications International Corporation, 1990a). Clayey silt fill is present in the site of the excavated waste-disposal pond.

Fluvioglacial silt, sand, and gravel associated with the Belvidere Till Member and the Mackinaw Member compose a single glacial drift aquifer that immediately overlies the bedrock Galena-Platteville aquifer. Where deposits of the Nimitz Till Member are present, localized semiconfined conditions can exist within the glacial drift aquifer (Science Applications International Corporation, 1990a).

The Galena Group of Ordovician age is the uppermost bedrock unit beneath the study site (fig. 3). The Platteville Group of Ordovician age immediately underlies the Galena Group. Because of the similar lithologic and hydraulic properties of the two geologic units, they generally are considered a single aquifer, referred to as the "Galena-Platteville aquifer" (and, where appropriate, the "Galena-Platteville dolomite"). Physical description of the Galena-Platteville aquifer is presented in the report section "Hydrogeologic Framework."

The Glenwood Formation of Ordovician age underlies the Platteville Group (fig. 3). The Glenwood Formation generally is composed of interbedded shale, dolomite, and sandstone (Willman and others, 1975, p. 63, 64; Berg and others, 1984, p. 10). The lowermost beds of the formation typically are more sandy than the uppermost beds and are often indistinguishable from the underlying St. Peter Sandstone; the uppermost beds generally are composed of impure dolomite (argillaceous, silty, sandy).

Driller's logs of Belvidere Municipal Wells No. 4 and No. 6 (well locations shown in fig. 1) indicate that, beneath the study site, the Glenwood Formation consists of dolomite and sandstone and that the depth to the top of the formation is about 320 ft (Woller and Sanderson, 1974, p. 7, 8). The thickness of the formation ranges from 27 ft at Well No. 4 to 65 ft at Well No. 6.

In some northern Illinois localities, the Harmony Hill Shale Member may be the uppermost unit of the Glenwood Formation; where present, this shale unit is commonly about 5 ft thick (Willman and others, 1975, p. 63, 64). Because of the presence of the Harmony Hill Shale Member between the overlying Galena-Platteville aquifer and the underlying St. Peter Sandstone aquifer, the St. Peter Sandstone aquifer can be semiconfined (Kay and others, 1989, p. 14). The hydraulic properties of the Glenwood Formation are unknown in the vicinity of the site, but it is assumed that either the Harmony Hill Shale Member (if present) or the argillaceous dolomite of the Glenwood Formation functions as a semiconfining unit at the base of the Galena-Platteville aquifer.

The St. Peter Sandstone of Ordovician age underlies the Glenwood Formation (fig. 3). This generally fine- to coarse-grained, friable sandstone (Willman and others, 1975, p. 61-63) is one of the principal water-yielding units of the regional Cambrian-Ordovician aquifer (Woller and Sanderson, 1974, p. 3). Depth to the top of the St. Peter Sandstone is approximately 345 to 380 ft in the vicinity of the site (Woller and Sanderson, 1974, p. 3, 7, 8).

METHODS OF STUDY

The methods of study used to evaluate the effects of municipal-well pumping on the Galena-Platteville aquifer and to determine the hydrogeologic properties and distribution of contaminants in the aquifer are presented in the following report sections. Included are descriptions of the construction and distribution of boreholes and wells and the application of water-level measurements to various aspects of the investigation. The techniques used in aquifer testing and water-quality sampling also are described.

Borehole and Well Network

One borehole open to the Galena-Platteville aquifer (G127GP), six observation wells screened in the Galena-Platteville aquifer (G115BD, G125BD, G126BD, G111D, G115B, and G125B) and three observation wells screened in the glacial drift aquifer (G102, G116S, and G116D) were used in different combinations for the separate objectives of the study. Locations of the borehole and wells are shown in figure 2. The methods used to construct borehole G127GP and well G125B, installed for this study, are presented below. Construction of wells G111D, G115BD, G125BD, and G126BD has been described in a previous report (Mills, 1993a). At the time of that report, wells G115BD, G125BD, and G126BD were open boreholes; 2-in.-diameter[2] stainless-steel risers (casings) and screens have since been installed in the boreholes. Construction data for all wells used in the study are summarized in table 1.

Borehole G127GP was constructed by first drilling through the surficial glacial-drift deposits by use of the mud-rotary method. An 8-in.-diameter black-steel surface casing was grouted into the uppermost 9 ft of the bedrock (to a depth of about 41 ft). A 6-in.-diameter borehole was then drilled into the bedrock to a depth of about 301 ft by use of the air-hammer method. Although the intent was to have a borehole that fully penetrated the Galena-Platteville aquifer, drilling was terminated about 20 ft above the apparent base of the aquifer. Because the exact depth of the base of the aquifer was not known, caution was taken to ensure that the underlying Glenwood Formation was not penetrated and that the integrity of the potential semiconfining unit was not compromised. Because the borehole was open to about 90 percent of the thickness of the aquifer, it was assumed to fully penetrate the aquifer during subsequent analyses.

The borehole was developed on two occasions before data collection in order to remove silt- and clay-sized drill cuttings from the borehole. The first occasion was immediately after completion of drilling, 1 month before

[2]Unless otherwise noted, well-casing and other pipe sizes mentioned in this report are nominal inside diameters.

Table 1.--Description of borehole and observation wells

[--, no data]

Borehole or well number	Installation date	Land-surface altitude, in feet above sea level	Top of well-riser altitude, in feet above sea level	Total depth of hole, in feet below land surface[1]	Open or screened interval, in feet below land surface	Aquifer that well or borehole is open to
G102	05-31-84	783.4	786.11	29.5	23.5- 28.5	Glacial drift
G111S	06-01-89	782.6	785.36	25.0	13.9- 24.4	Glacial drift
G111D	05-11-89	782.8	784.47	35.4	30.4- 35.4	Galena-Platteville
G116S	06-06-89	784.7	787.08	25.0	19.6- 24.6	Glacial drift
G116D	05-25-89	784.4	787.17	35.0	28.6- 33.6	Glacial drift
G115S	06-06-89	782.3	784.45	20.6	9.6- 20.1	Glacial drift
G115D	05-15-89	782.2	785.16	37.8	32.8- 37.8	Glacial drift
G115B	05-23-89	782.3	785.14	49.0	43.6- 48.6	Galena-Platteville
G115BD	11-20-90	782.5	784.48	150.8	140.6-150.6	Galena-Platteville
G125D	08-28-90	783.0	783.02	28.9	23.4- 28.4	Glacial drift
G125B	06-05-91	783.0	782.90	37.0	31.2- 36.2	Galena-Platteville
G125BD	12-09-90	783.0	782.90	149.9	137.4-147.7	Galena-Platteville
G128BD	11-30-90	783.9	784.98	151.3	141.0-151.3	Galena-Platteville
G127GP[2]	04-27-91	783.8	--	301.0	41.0-301.0	Galena-Platteville

[1] Total depth at time of sampling; depth may differ slightly from depth at time of drilling.
[2] Borehole; data entry represents open-borehole interval.

data collection. The second occasion was 1 day before data collection. On the first occasion, the pump was lowered to a depth of about 60 ft below the water surface and pumped at a rate of about 30 gal/min; about eight well volumes of water were removed from the borehole. On the second occasion, the pump was lowered to a depth of about 100 ft below the water surface and pumped at a rate of about 30 gal/min; about six well volumes of water were removed from the borehole. On both occasions, the pump was decontaminated before it was placed in the borehole by brushing with soapy tap water and then rinsing with tap water followed by deionized water.

Well G125B was constructed by first drilling through the surficial glacial drift with a 6-in. outside-diameter hollow-stem auger. A 4-in.-diameter polyvinyl chloride (PVC) surface casing was then grouted into the uppermost 5 ft of the bedrock to a depth of about 31 ft. A 3.9-in.-diameter borehole was drilled into the bedrock to a depth of 37 ft by use of the water-rotary method. A 2-in.-diameter stainless-steel riser with a 5-ft-long screen was installed in the borehole.

Water-Level Measurements

Water levels were measured in two pairs of vertically nested observation wells (G111S-G111D and G115D-G115B; fig. 2, table 1) to evaluate the hydraulic relation between the Galena-Platteville aquifer and the overlying glacial drift aquifer and in three pairs of vertically nested observation wells (G115B-G115BD, G111D-G126BD, and G125B-G125BD; fig.2, table 1) to evaluate the hydraulic relation between shallow and deep parts of the Galena-Platteville aquifer. The water levels were used to calculate vertical hydraulic gradients. The method used to calculate the hydraulic gradients has been described previously (Mills, 1993a).

Water levels were measured in six observation wells in the Galena-Platteville aquifer in June and October 1991 to determine the direction and gradient of horizontal ground-water flow beneath the study site. Measurements were made in three wells (G111D, G115B, G125B; fig. 2) screened near the top of the aquifer (table 1) and in three wells (G126BD, G115BD, and G125BD) screened near the vertical midpoint of the aquifer (about 150 ft below land surface). Measurements were made by use of a steel measuring tape.

Ground-water-flow directions were determined from the water-level measurements by means of the three-point method described by Compton (1962, p. 31, 32). Because of apparent heterogeneity and anisotropy of the Galena-Platteville aquifer, the three-point method may be inappropriate for determination of flow directions in the aquifer at the study site. The method was used because of the limited number of wells available from which to determine flow directions and because the method provides at least an approximation of horizontal ground-water-flow direction.

Water levels were measured at short time intervals (10 minutes to 1 hour) in borehole G127GP and observation wells G111D, G115B, G115BD, and G126BD to determine if there was a water-level response to pumping of Belvidere Municipal Wells No. 4 and No. 6. The water levels were measured for periods ranging from 17 hours to 26 days between June 9 and July 8, 1991. Records of total daily pumpage for the two municipal wells also were obtained for comparison with the site water-level data.

Water levels in the site wells were measured with pressure transducers rated in a range of 0-10 lb/in^2 and were automatically recorded with a data logger. The pressure-transducer-measured water levels were calibrated against steel-tape measurements.

Water levels also were measured in the borehole and wells in conjunction with the aquifer tests and water-quality sampling. Specifics concerning water-level measurements made as part of those study objectives will be discussed in the report sections "Aquifer Tests" and "Water-Quality Sampling."

Aquifer Tests

Two approaches were taken in the study to analyze the hydraulic properties of the Galena-Platteville aquifer. Single-well aquifer tests were done at discrete depth intervals in borehole G127GP (fig. 2). These data, along with similar data collected in three boreholes shallower than borehole G127GP (Mills, 1993a), were used to characterize the spatial (vertical and horizontal) variability of the hydraulic properties of the bedrock aquifer. A multiple-well aquifer test also was done. The data from this test allowed quantification of the average hydraulic properties of the aquifer, as well as additional evaluation of aquifer heterogeneity and anisotropy.

Discrete-Interval Tests in Borehole G127GP

Use of a packer assembly (shown schematically in fig. 4) allowed slug testing and constant-discharge testing (and water-quality sampling) at discrete vertical intervals in borehole G127GP. The packer assembly and its use in ground-water investigations at the study site have been described previously (Mills, 1993a); the reader is referred to that report for details regarding the packer assembly.

Several modifications were made to the packer assembly and packer-test procedures between the first and second phases of the USGS site investigation. For the first-phase investigation, packer-test intervals were about 10 ft in length. On the basis of data from the first-phase investigation, it was determined that lengthened packer-test intervals would still allow adequate aquifer characterization. For the tests in borehole G127GP, packer-test intervals were about 20 ft long. For the two deepest test intervals (253.0-273.4 ft and 273.4-301.0 ft), an upper 10-ft-long section of stainless-steel pipe connected to a lower 10-ft-long section of slotted stainless-steel screen was assembled between the packers. Mechanical problems with the packer assembly required that the remainder of the tests be made with an upper 10-ft-long section of perforated aluminum pipe and a lower 10-ft-long section of galvanized-steel pipe between the packers.

After packers are inflated in a test interval, it is generally desirable to allow pressures within the packed interval and the intervals above and below to reach equilibrium before starting the aquifer tests. Equilibrium is reached when the water levels equal or approximate the original static level. During the second-phase investigation, this approach was not possible because water levels in the test intervals constantly changed, apparently in response to municipal-well pumping. To ensure that the effects of packer inflation, such as transient water levels approaching hydrostatic equilibrium, would not interfere with the aquifer tests, investigators started all tests at least 30 minutes after the packers were inflated. For intervals in which previous discrete-interval aquifer tests indicated comparatively low permeabilities might be expected (Mills, 1993a), the tests were delayed for as much as 120 minutes after packer inflation. Data from the previous tests indicated that the 30- to 120-minute delay in starting tests was a reasonable length of time to allow near equilibration of pressures in the packed borehole.

To evaluate the hydraulic isolation of the packed interval, investigators monitored packer-inflation pressures throughout the tests. Water levels were also monitored above the packed interval, in the packed interval, and below the packed interval; this approach, however, generally proved unsuccessful because of the water-level changes attributed to nearby municipal-well pumping. Packer leakage was detected during several tests; on these occasions the tests were terminated, the cause of the leakage was corrected, the collected data were discarded, and the tests were redone.

Slug tests and constant-discharge tests were done in each packed interval to estimate horizontal hydraulic conductivity. With the packer assembly removed, a constant-discharge test also was done in the open borehole to estimate transmissivity and hydraulic conductivity. The slug tests were done and interpreted by the method described by Bouwer and Rice (1976); the constant-discharge tests were done and interpreted by the time-drawdown method described

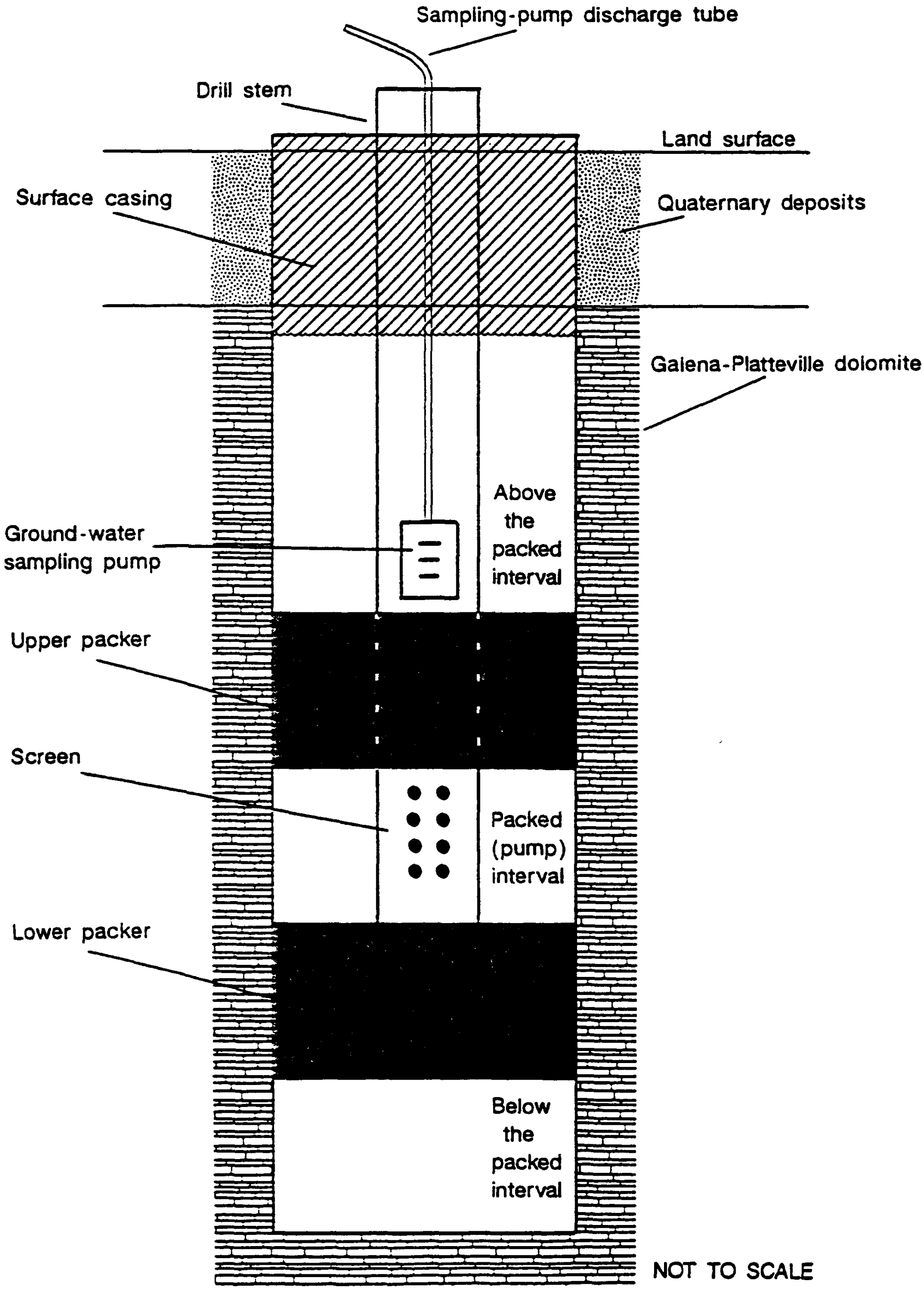


Figure 4.--Generalized view of the packer assembly and ground-water-sampling pump in a borehole.

by Cooper and Jacob (1946). Discussion of the controlling assumptions of the tests and the suitability of the tests to the hydrologic conditions at the Parson's Casket Hardware site are presented in the report section "Results of Aquifer Tests in Borehole G127GP." The reader is referred to the report by Mills (1993a) for a description of the methodology of the tests at the study site.

Multiple-Well Test

A multiple-well, constant-discharge aquifer test was done at the site in order to estimate transmissivity, hydraulic conductivity, and specific yield of the Galena-Platteville aquifer. The aquifer test was done June 11-12, 1991. A discussion of the conceptual and analytic models used to interpret the test data is presented in the report section "Results of Multiple-Well Aquifer Test."

For the test, the fully penetrating borehole G127GP was pumped at a constant rate of 28.6 gal/min for 17 hours. Water levels were monitored in the pumped borehole and in nine observation wells throughout the pumping phase and the recovery phase, which also lasted about 17 hours. The observation wells included three wells screened in the glacial drift aquifer (G102, G116S, G116D), three wells screened in about the top 10 ft of the Galena-Platteville aquifer (G111D, G115BD, G125BD), and three wells screened near the vertical midpoint of the Galena-Platteville aquifer (G115BD, G125BD, G126BD). The locations of the borehole and wells are shown in figure 2; the depths at which the wells are screened are listed in table 1. The nests of shallow and deep wells in the dolomite aquifer were located approximately equidistant from the pumped well. The pumped well was located slightly off-center to avoid drilling through the site of the former waste-disposal pond. Water levels in the glacial-drift wells were monitored during the aquifer test to identify possible hydraulic connection between the dolomite and the glacial drift aquifers.

Investigators followed several procedures to account for potential sources of error in the aquifer test to ensure the reliability of the test results. A description of those procedures follows.

Throughout the aquifer test, water levels in most of the site wells were measured by use of pressure transducers typically rated in a range from 0 to 10 lb/in^2. Water levels in two wells screened in the glacial drift aquifer, where minimal water-level change was anticipated, were measured by use of pressure transducers rated in a range from 0 to 5 lb/in^2. Water levels in the pumped borehole, where the most significant water-level change was anticipated, were measured by use of a pressure transducer rated in a range from 0 to 15 lb/in^2. The water levels were recorded automatically on a data logger. A logarithmic sampling schedule was used. The maximum sampling interval of 10 minutes occurred after 100 minutes of the test had elapsed. Water levels were measured manually at about 3-hour intervals with steel or electric tapes to ensure the accuracy of the pressure-transducer-measured water levels. Differences between manually and automatically measured water levels, which generally did not exceed 0.04 ft, were considered insignificant.

Because water levels in the Galena-Platteville aquifer beneath the study site were apparently affected by pumping of nearby municipal wells, it was arranged for the pumping schedules of the municipal wells to be regulated during the aquifer test. About 31 hours before the start of the pumping phase of the aquifer test, Belvidere Municipal Well No. 4 was started on a regulated on-off pumping schedule, and a steady, continuous pumping rate was established for Well No. 6. The actual time interval between pumping cycles for Well No. 4 is not known. Because of municipal water demand, pumping of the nearby wells could not be terminated or held fully constant during the test, and the regulation of pumping was limited to about a 55-hour period. The time limit imposed on the regulation of municipal-well pumping established a limit to the duration of the aquifer test.

Water levels in borehole G127GP and observation wells G111D and G126BD were measured for about 48 hours before the start of the pumping phase of the aquifer test to determine background trends (figs. 5a, b). Water levels in wells G115B, G115BD, G125B, and G125BD were measured for about 90 minutes before the start of the test (fig. 5b). Water levels in well G126BD and borehole G127GP declined by about 7 ft to more than 8 ft, respectively, during the initial 24 hours of regulated municipal-well pumping. After about 24 hours, water-level declines in all observation wells generally had ceased (fig. 5b). During the 90-minute measuring period before the start of the aquifer test, the maximum decline was about 0.5 ft, recorded in well G115BD. Declines in the other wells, including well G126BD, generally were less than 0.1 ft.

The water level in borehole G127GP seemed to stabilized after about 24 hours of regulated pumping (fig. 5b), but an additional decline of about 4.5 ft occurred a little over an hour before the start of the aquifer test. By the start of the aquifer test, the water level in borehole G127GP was finally beginning to stabilize.

An attempt was made to correct for the apparent municipal-well pumping interference to the aquifer test by use of the method described by Rushton (1985). Because this method produced unrealistic drawdown corrections, interference by off-site pumping was not corrected for in the aquifer-test results. The unsatisfactory results of the Rushton (1985) method are attributed to the variations in municipal-well pumping and to the hydraulic complexity of the heterogeneous and anisotropic aquifer.

As will be subsequently discussed in the report section "Results of Multiple-Well Aquifer Test," municipal-well pumping seemed to interfere with drawdown and recovery during the test. The extent of interference, however, is uncertain. Drawdown in site-well water levels attributed to municipal-well pumping seemed to have stabilized generally by the time the aquifer test began, and, in most site wells, the municipal-well-induced drawdown seemed to represent only a small fraction of the total drawdown that was associated with the aquifer test.

Barometric pressure was measured throughout the aquifer test by use of a drum-type recording barometer. Background trends in barometric pressure were analyzed to determine potential effects on ground-water levels. During the course of the test, barometric pressure increased about 0.3 ft (fig. 6). Drawdown and recovery data in wells G115B and G125B, where drawdowns were

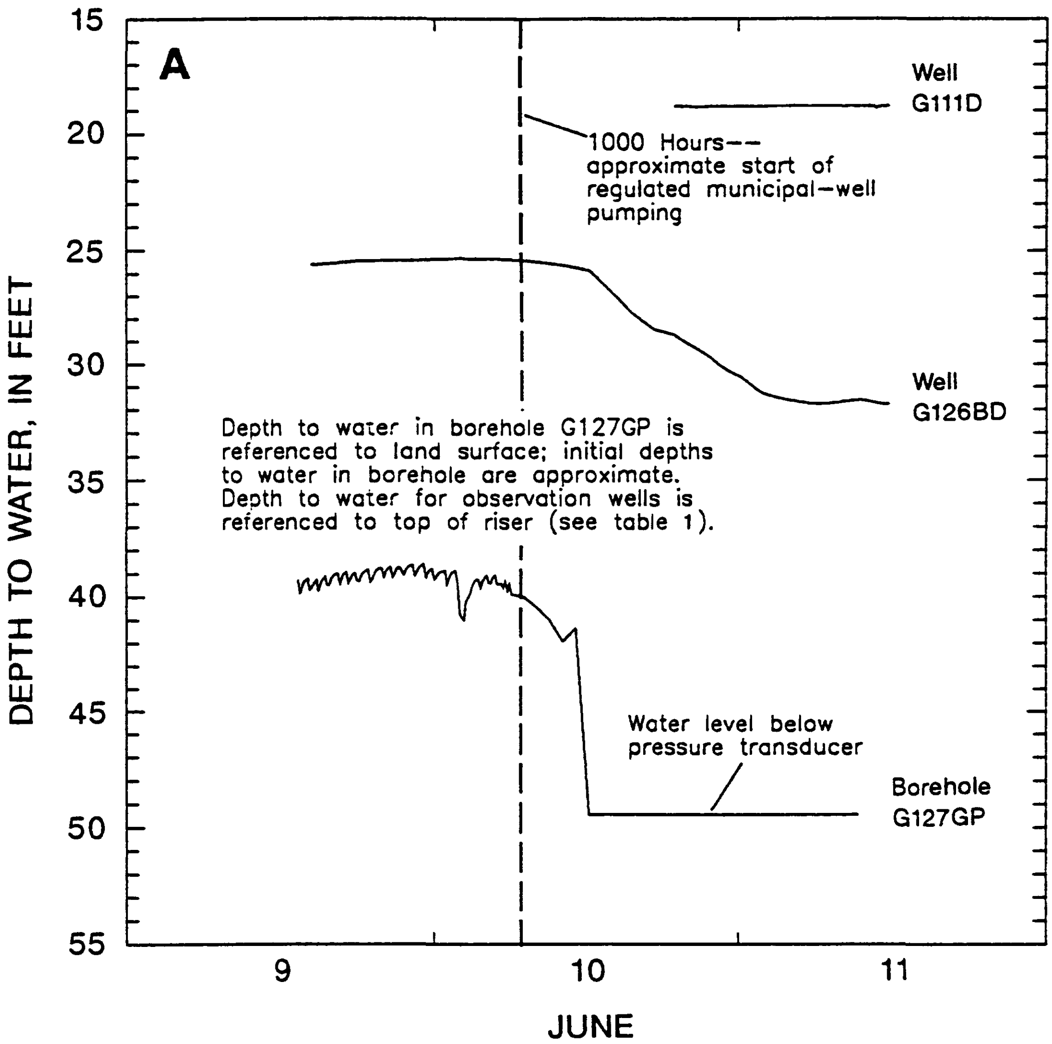


Figure 5.--Water levels in a borehole and observation wells in the Galena-Platteville aquifer, June 9-11, 1991.

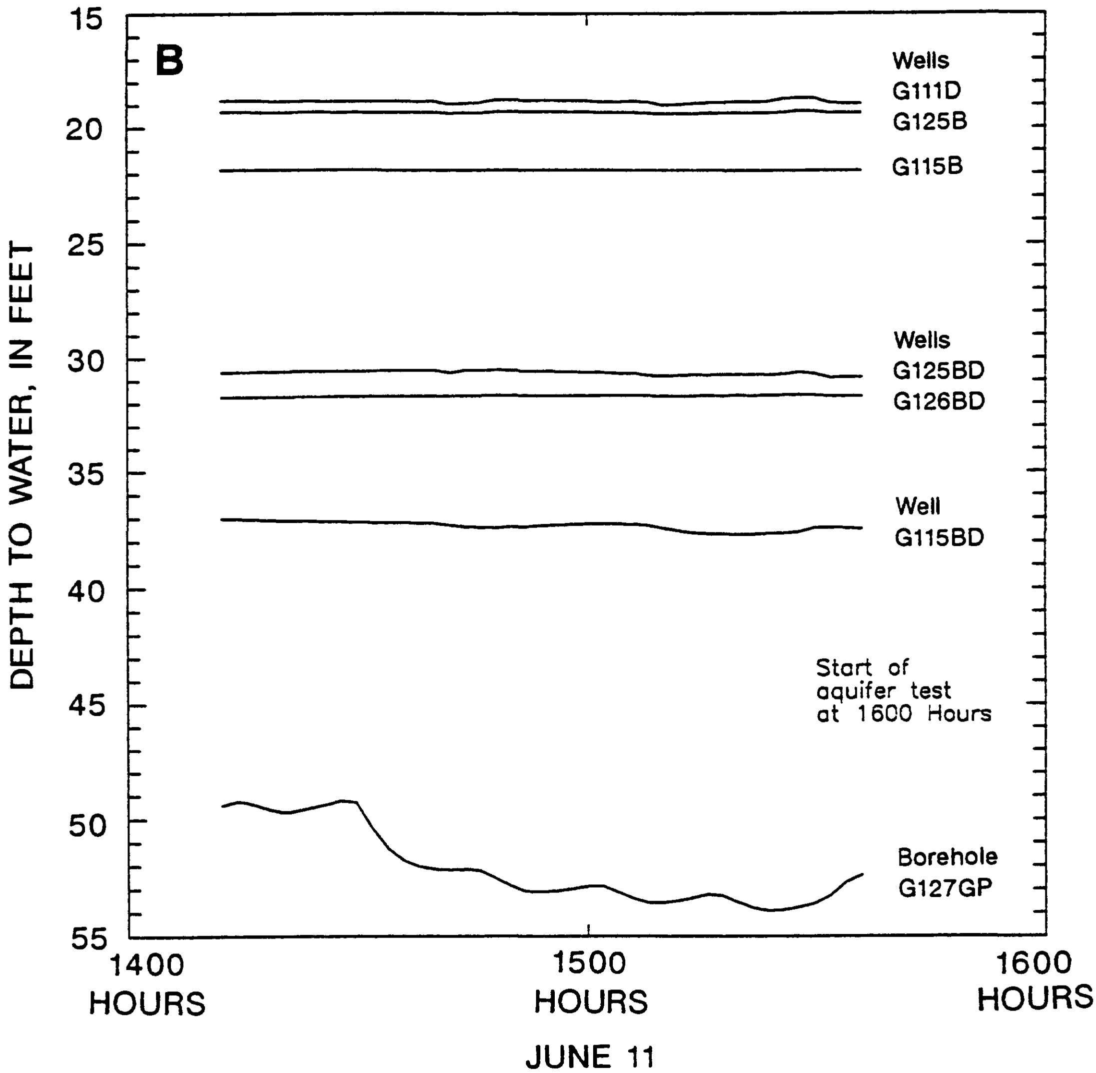


Figure 5.--Water levels in a borehole and observation wells in the Galena-Platteville aquifer, June 9-11, 1991--Continued.

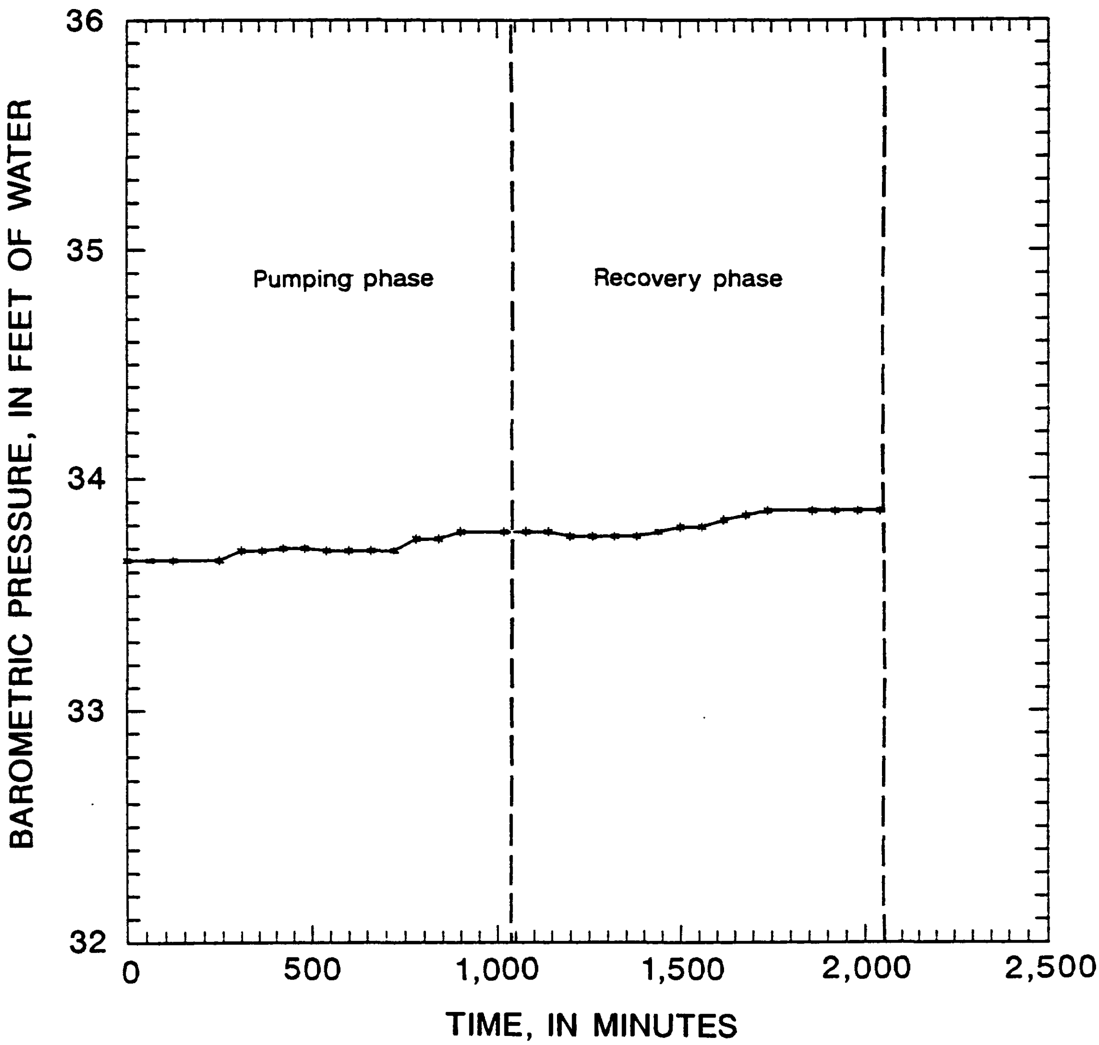


Figure 6.--Barometric pressure during the Galena-Platteville aquifer constant-discharge test, June 11-12, 1991.

small relative to barometric-pressure-induced water-level changes, were corrected. A barometric efficiency of 50 percent for the wells was assumed for the corrections. Barometric pressures in confined aquifers typically range from about 25-75 percent (Freeze and Cherry, 1979, p. 234).

A flowmeter attached to the water-discharge line was regularly monitored to ensure that pumping discharge was constant during the aquifer test. Discharge also was recorded by periodically timing the filling of a 3-gal bucket. Pumping rates varied by less than 5 percent during the extent of the test and, therefore, were assumed to be constant. Pumped water was discharged to a storm sewer several hundred feet offsite by previous arrangement with the city of Belvidere.

Water-Quality Sampling

Water samples were obtained from borehole G127GP (fig. 2) from each packed interval and from the open borehole within 30 minutes of the start and end of pumping during the multiple-well aquifer test. A submersible, positive-displacement sampling pump consisting of a stainless-steel pump head and Teflon[3] tubing was used to obtain water samples from the packed intervals. The pumping rate during sampling was less than 0.5 gal/min. A submersible, positive-displacement sampling pump consisting of a stainless-steel pump head and nylon hosing was used to obtain water samples during the multiple-well aquifer test. The pumping rate during sampling was 28.6 gal/min.

Two methods were used to ensure that representative aquifer water was obtained during packer-interval sampling. In the first method, well volumes were computed with the goal of purging at least three well volumes before sampling. Well volumes were determined by measuring the depth to water in the drill stem, which was open to the packed interval (fig. 4). The calculation of water volume included the 20 ft of water in the 6-in.-diameter packed interval and the height of the water column in the 2-in.-diameter drill stem above the packed interval. In the second method, pH, temperature, specific conductance, and Eh were monitored at the wellhead as water was purged from the boreholes. A water-quality monitor with a flow-through cell was used to measure these water-quality characteristics. The water-quality monitor was calibrated daily according to procedures outlined in the manufacturer's operation manual.

Field measurements of the water-quality characteristics generally were recorded after each one-half well volume was purged, beginning with the first well volume. Purging was considered complete when field measurements were stable for three consecutive one-half well volumes. Generally, at least three well volumes were purged from the packed intervals (table 2). For packed intervals in which the hydraulic conductivity was relatively low, the water level in the drill-stem pipe open to those intervals was lowered to the pump-intake level (fig. 4) during pumping. For these intervals, less than three well volumes were purged, because it was necessary to repeatedly allow water

---

[3]Use of trade and brand names in this report is for identification only and does not constitute endorsement by the U.S. Geological Survey.

Table 2.--Purging and sampling summary for borehole G127GP

Test interval, in feet below land surface	Borehole volume, in gallons	Borehole volume purged, in gallons	Number of borehole volumes purged	Date borehole purged and sampled
41.0- 55.6	44.0	84	1.9	06-18-91
145.1-166.7	48.7	150	3.1	06-19-91
166.7-188.3	52.9	110	2.1	06-21-91
188.3-209.8	56.7	171	3.0	06-20-91
209.8-231.4	57.8	116	2.0	06-20-91
231.4-253.0	60.6	55	.9	06-20-91
253.4-273.8	63.7	230	3.6	06-08-91
273.8-301.0	72.5	220	3.0	06-06-91
[1]41.0-301.0	365	450	1.2	06-11-91
[2]41.0-301.0	330	30,000	90	06-12-91

[1]Ground water from borehole sampled within 30 minutes of the start of the aquifer test.

[2]Ground water from borehole sampled within 30 minutes of the end of the aquifer test.

levels to recover sufficiently for pumping. Stability of field measurements was still required in the intervals with low hydraulic conductivities, but stability was determined over fewer consecutive one-half well volumes. Only 0.9 well volume was purged in the interval 231.4 to 253.0 ft. This interval was assumed to have a very low hydraulic conductivity (test problems precluded accurate quantification of hydraulic conductivity in the interval) and required almost 7 hours to purge 55 gal of water.

Stabilized field measurements were recorded to aid characterization of ground-water chemistry in the test intervals. Ground water from all test intervals in borehole G127GP were analyzed for VOC's and selected inorganic constituents by USEPA contract labs. Alkalinity (as calcium carbonate) was determined in the field by use of a Hach titration test. Water samples from two depth intervals (253.0-273.8 ft and 273.8-301.0 ft) also were analyzed for VOC's by the USGS National Water Quality Laboratory. Sample collection and quality-assurance/quality-control (QA/QC) procedures--such as collection of sample duplicates, spikes, method blanks, and trip blanks--were included as part of the sampling protocol. The QA/QC procedures were done as described in the quality assurance project plan for the Parson's Casket Hardware site (Science Applications International Corporation, 1990b).

HYDROGEOLOGY OF THE GALENA-PLATTEVILLE AQUIFER

The hydrogeology of the Galena-Platteville aquifer is described in the following report section. The hydrogeologic framework of the aquifer was determined as a basis for evaluating the effects of municipal-well pumping on the aquifer, selecting and interpreting field tests to estimate the hydraulic properties of the aquifer, and characterizing the distribution of waste-related solutes in the aquifer.

Hydrogeologic Framework

Berg and others (1984, p. 10, 11) describe the Galena and Platteville Groups (fig. 3) in north-central Illinois as follows. The Galena Group is a medium- to coarse-crystalline, partly cherty dolomite. The underlying Platteville Group is a finely crystalline, dense, and partly argillaceous dolomite; its lower part is in places sandy and its upper part cherty.

The lithologic units that compose the Galena and Platteville Groups were deposited as virtually horizontal beds which range in thickness from a few inches to several feet. Individual beds can be difficult to recognize where there is no obvious change in composition or physical parting of the beds; however, the individual beds can be easily recognized in many places where the beds are separated by a thin film of clay on the bedding surfaces (Willman and Kolata, 1978, p. 12).

The dolomite of the Galena and Platteville Groups typically has considerable secondary permeability resulting from joints, fractures, bedding-plane partings, and solution openings. The principal orientations of vertical joints and fractures in the dolomite in north-central Illinois are about N. 60° W. and N. 30° E. (Foote, 1980). The network of secondary openings account for the usually dependable supply of moderate quantities of water to wells from the aquifer (Schumacher, 1990).

The lithology of the Galena-Platteville aquifer beneath the study site was determined by use of rock cores and drill cuttings. Rock cores from observation wells G125B, G115BD, and borehole G127GP (fig. 2) were used to describe the bedrock unit from its surface to a depth of 197.3 ft. Drill cuttings from borehole G127GP were used to describe the bedrock unit from 200.0 to 301.0 ft below land surface. The lithology also was determined by use of borehole-geophysical data, which included natural gamma, spontaneous-potential, and single-point resistance logs. Additional information on structures within the dolomite, such as fractures and bedding-plane-solution fissures, and the hydraulic significance of the structures was obtained by use of three-arm caliper, acoustic-televiewer, temperature, downhole-videocamera, and borehole ground-penetrating radar, borehole ground-water flow (heat-pulse flow meter) logging data and discrete-interval aquifer-test data. Figure 7 presents representative geophysical-log data from borehole G127GP (fig. 2). The log data from this and other boreholes at the site (G115BD, G125BD, and G126BD) are summarized in Appendixes 1-4.

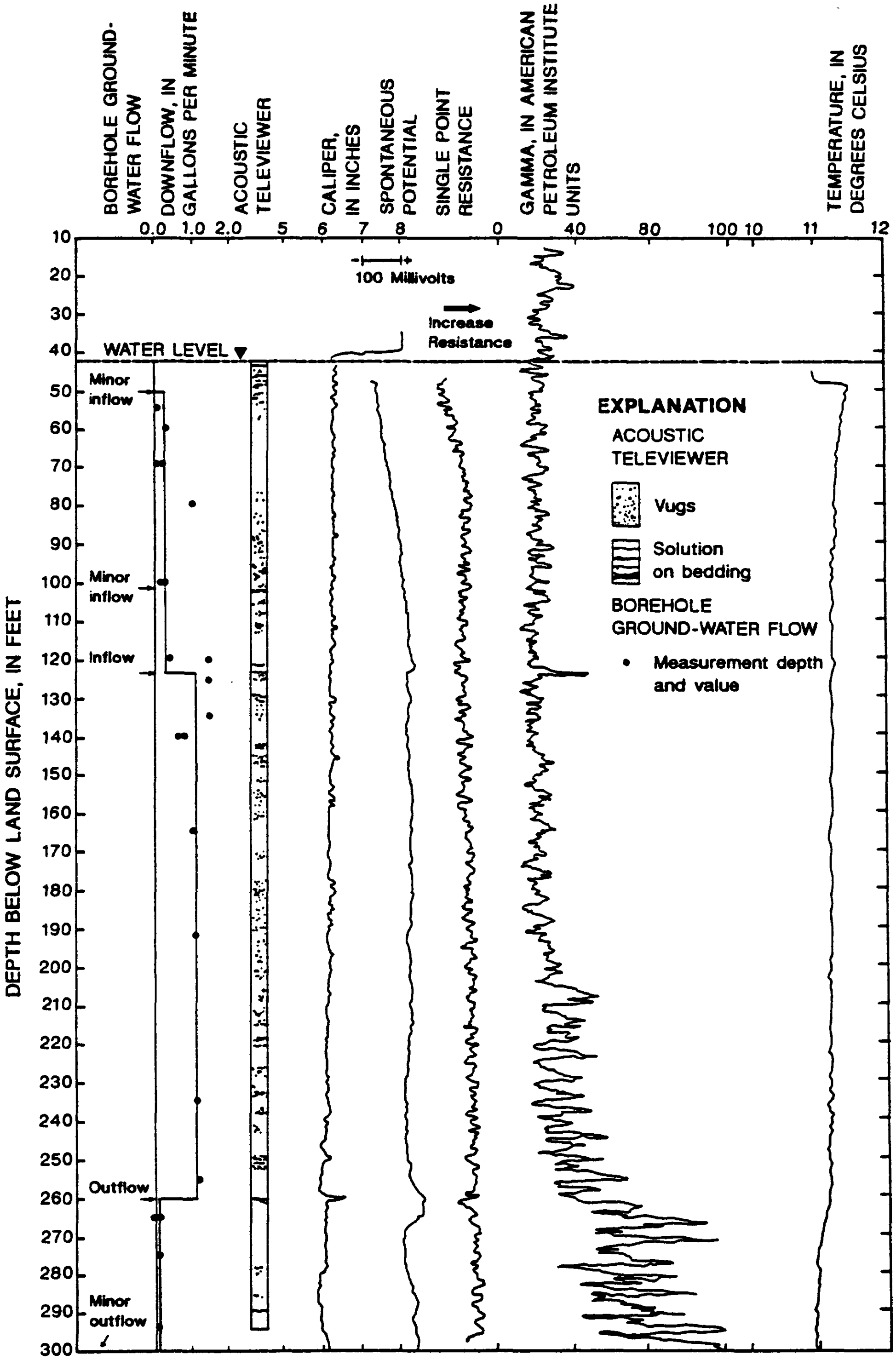


Figure 7.--Geophysical logs of borehole G127GP.

The surface of the Galena Group ranges in depth from about 25 to 40 ft below land surface. The Galena-Platteville dolomite can be subdivided into six geologic units on the basis of lithology. The description and approximate depth from land surface of each unit are as follows:

1. Dolomite, buff; fractured, granular as a result of weathering, uppermost 1.5 ft (at wells G115BD and G125BD) to 4 ft (at borehole G127GP) of bedrock;

2. Dolomite, light-buff-gray; vugs rare, solution along bedding plane rare; base of the weathered bedrock surface to 80 ft;

3. Dolomite, light-gray; vugs common, solution along bedding plane common; 80 to 160 ft;

4. Dolomite to calcitic dolomite, buff to light-gray; vugs rare to common, solution along bedding planes rare to common, chert very common near base of interval; 160 to 200 ft;

5. Dolomite to calcitic dolomite, buff to dark-gray; argillaceous, chert rare to common; 200 to 265 ft; and

6. Argillaceous dolomite, buff to medium-gray; dense; 265 to 301 ft.

Borehole ground-penetrating-radar data indicate that planar features, interpreted as bedding-plane fissures, in the Galena-Platteville aquifer have a dip of 0 to 7° NE. (Appendix 3). Cross-hole correlation of features in the borehole geophysical logs also indicate little or no dip in bedding. Therefore, for the purposes of this study, bedding in the Galena-Platteville dolomite is assumed to be horizontal.

Vesicles and vugs are scattered throughout the dolomite matrix at all depths. Results of discrete-interval hydraulic-conductivity tests (Mills, 1993a) indicate that the vesicles and vugs represent a varied, yet consistently smaller fraction of the aquifer permeability than do the thin intervals of bedding-plane solution, which are present throughout the dolomite bedrock. Inclined angular fractures that crosscut the bedding planes also seem to contribute to the aquifer permeability.

Two bedding-plane-solution fissures in the Galena-Platteville aquifer are probably important conduits for ground-water flow and contaminant migration. An upper fissure, at a depth of about 125 ft (uppermost fissure in fig. 8), is evident in the geophysical logs (fig. 7) of all the bedrock boreholes that penetrated to depths of 150 ft or greater. At this same depth, packer tests indicated an interval of relatively high hydraulic conductivity (Mills, 1993a), and heat-pulse-flowmeter analysis in borehole G127GP (fig. 7) indicated inflowing ground water to the borehole. A lower fissure, at a depth of about 260 ft (lowermost fissure shown in fig. 8), is noted in the geophysical logs of borehole G127GP (fig. 7). Elevated water pressures and highly fractured aquifer material were found at this depth during drilling. Also at this depth, flowmeter analysis indicated outflowing ground water from the borehole, and temperature logging indicated a distinct decrease in water temperature (fig. 7).

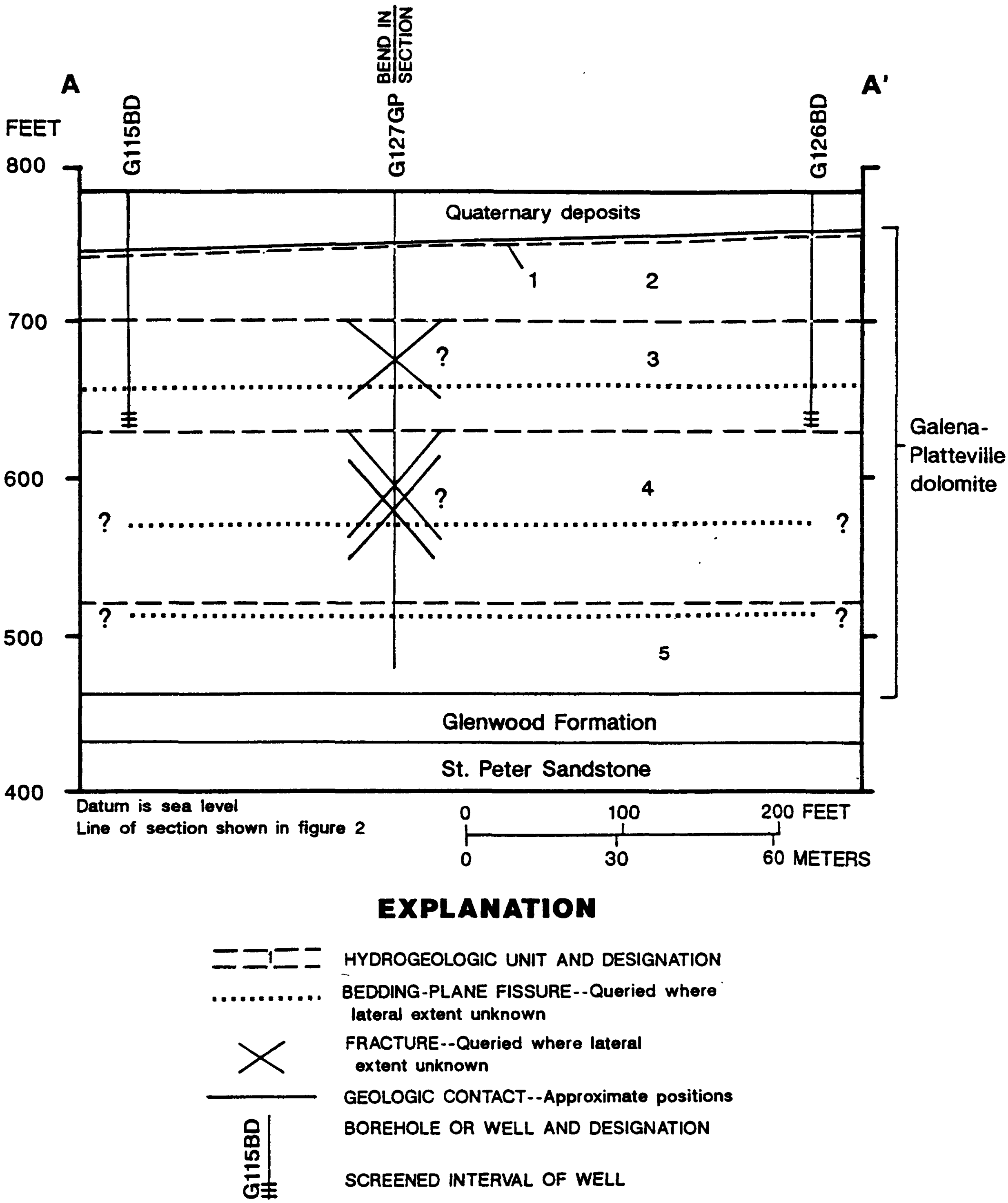


Figure 8.--Geologic section A-A' through the study site showing the primary hydrogeologic units, fissures, and fractures in the Galena-Platteville aquifer.

Three inclined features, interpreted as fractures, were identified in the dolomite at depths of about 107, 187, and 202 ft (fig. 8) by use of borehole ground-penetrating radar in borehole G127GP (Appendix 3). The radar data indicate that the fractures extend as far as 30 ft from the borehole. Examination of rock cores obtained from borehole G127GP indicates a 0.5- to 1-in. interval opened by fracturing and (or) dissolution at a depth of about 188 ft; this interval is assumed to be equivalent to the radar-identified fracture at the depth of 187 ft. No rock cores were obtained from the depths of 107 and 202 ft in borehole G127GP; thus, the presence of the radar-identified fracture at these depths could not be visually verified. Radar-identified fractures at the depths of 187 and 202 ft also were recognized during drilling. None of the three inclined fractures are readily apparent in the geophysical logs from the study site (fig. 7).

The inclined fractures, most notably the fractures at the depths of 107 and 202 ft, seem to be important hydraulic features. Inflowing water recorded in borehole G127GP at a depth of about 100 ft during flowmeter analysis (fig. 7) and elevated water pressures recorded at a depth of about 200 ft during drilling of borehole G127GP likely are associated with the presence of the two fractures. Elevated hydraulic conductivities were not identified in boreholes that were packer tested at the depth of the fractures; however, because the fractures are thin relative to the 10- to 20-ft-long packer-test intervals, it is assumed that the tests were insensitive to the hydraulic properties of the fractures. It is probable that the inclined fractures are moderately permeable conduits that connect the high conductivity horizontal fissures and that this connection enables more rapid vertical movement of ground water and contaminants than otherwise would be expected in the generally low conductivity dolomite matrix.

Several inconsistencies between the interpreted results of the acoustic-televiewer data and the ground-penetrating-radar data require examination. The acoustic-televiewer data from borehole G127GP indicate that the three features identified as inclined fractures by ground-penetrating radar are bedding-plane fissures. Rock-core data from well G115BD and well G127GP also seem to indicate that the features at 107 ft and 188 ft are laterally continuous bedding-plane fissures; however, because inclined fractures and joints are common in the Galena-Platteville dolomite throughout north-central Illinois (Foote, 1980), it seems unlikely that inclined fractures are not present in the dolomite within the study area. Additional investigation is necessary to resolve this issue.

The Galena-Platteville aquifer is unconfined, as indicated by the hydraulic properties of the dolomite and overlying glacial drift, by water levels in observation wells, and by the distributions of VOC's. Throughout most of the study area, glacial sand and gravel deposits with relatively high conductivities (Vanderpool and Yeskis, 1991) immediately overlie the dolomite bedrock. Water levels measured in wells vertically nested in the dolomite aquifer and the overlying glacial drift aquifer indicate that vertical hydraulic gradients between the two aquifers are downward and range from 0.02 to 0.03 ft/ft. Relatively low vertical gradients ranging from 0.07 to 0.12 ft/ft also exist between the top of the dolomite aquifer and about the midpoint of the aquifer (table 3).

Table 3.--Vertical hydraulic gradients within the Galena-Platteville aquifer

Observation wells	Aquifer	Screened interval, in feet below land surface	Date	Water-level altitude, in feet above sea level	Downward vertical hydraulic gradient, in foot per foot
G111S	Glacial drift	13.9- 24.4	04-29-91	766.35	0.03
G111D	Galena-Platteville	30.4- 35.4	04-29-91	765.91	
G115D	Glacial drift	32.8- 37.8	04-29-91	763.79	.02
G115B	Galena-Platteville	43.6- 48.6	04-29-91	763.63	
G115B	Galena-Platteville	43.6- 48.6	04-29-91	763.62	.12
G115BD	Galena-Platteville	140.6-150.6	04-29-91	751.78	
G111D	Galena-Platteville	30.4- 35.4	04-29-91	765.91	.07
G126BD	Galena-Platteville	141.0-151.3	04-29-91	757.56	
G125B	Galena-Platteville	31.2- 36.2	06-11-91	761.15	.08
G125BD	Galena-Platteville	137.4-147.7	06-11-91	751.92	

Flowmeter analysis of borehole G127GP (table 4) and water levels measured in boreholes G115BD, G125BD, and G126BD (Mills, 1993a) further indicate that low downward gradients exist throughout the dolomite aquifer. Gradients calculated by Mills (1993a) were generally less than about 0.05 ft/ft. Elevated gradients, as high as 0.37 ft/ft, were identified below a depth of about 125 ft at some test locations. The elevated gradients were determined to be associated with flow through the bedding-plane fissure at that depth and not with any specific confining units within the dolomite aquifer. Upward gradients that have been detected in the dolomite aquifer (table 4) are attributed to the transient effects of municipal-well pumping.

Although there is no apparent confining unit that isolates the glacial drift aquifer from the underlying dolomite aquifer, the relatively low conductivity dolomite strata that are present at a depth of about 40-80 ft (Mills, 1993a) may have some capacity for limiting vertical flow between the upper and lower parts of the dolomite aquifer. That capacity, however, seems to be small, as indicated by several factors, including (1) vertical gradients between the upper and lower parts of the dolomite aquifer that are only slightly higher than the gradients between the glacial drift and dolomite aquifers; (2) the distribution of VOC's throughout the vertical extent of the dolomite aquifer (as will be discussed in the report section "Water Quality of the Galena-Platteville Aquifer"); and (3) the documented existence of inclined fractures in the dolomite aquifer, which likely crosscut the strata of low hydraulic conductivity near the top of the aquifer and strata of high hydraulic conductivity in lower parts of the aquifer.

The six lithologic units identified in the Galena-Platteville aquifer can be partitioned into five hydrogeologic units (fig. 8) on the basis of the hydraulic-property data collected in the first (Mills, 1993a) and second phases of the USGS site investigation. The approximate range of horizontal hydraulic conductivity and depth of each hydrogeologic unit are as follows:

Table 4.--Borehole ground-water flow-logging data from borehole G127GP

[table summarizes data from F.L. Paillet, U.S. Geological Survey, written commun., 1991; gal/min, gallon per minute; <, less than]

Depth below land surface, in feet	Flow direction	Estimated ground-water flow rate, in gal/min
55	Down[1]	0.05
55	Up[1]	.07
60	Up[2]	.10
60	Down	.28
70	Up	.05
70	Down	.20
80	Down	1.00
100	Down	.30
100	Down	.15
120	Down	1.5
120	Down	.40
125	Down	1.5
135	Down	1.5
140	No flow	<.05
140	No flow	<.08
140	Down	.80
140	Down	.60
165	No flow	<.05
165	Down	1.0
192	No flow	<.05
192	Down	1.1
215	No flow	<.05
235	No flow	<.05
235	Down	1.1
255	No flow	<.05
255	Down	1.2
265	Down	.12
265	Down	.12
265	No flow	<.05
275	Down	.12
280	Down	.12
295	Down	.12

[1] Flow direction changes with time.

[2] Flow reverses from weak downflow to upflow, then stabilizes at given value.

Unit 1--1 to 200 ft/d, the weathered bedrock surface;
Unit 2--0.2 to 0.8 ft/d, base of the weathered bedrock surface to 80 ft;
Unit 3--0.2 to 1 ft/d, 80 to 160 ft;
Unit 4--0.04 to 0.2 ft/d, 160 to 260 ft; and
Unit 5--0.2 to 0.7 ft/d, 260 to 301 ft.

Specific analysis and discussion of hydraulic-conductivity data for depths below 150 ft are presented in the subsequent report section "Results of Aquifer Tests in Borehole G127GP."

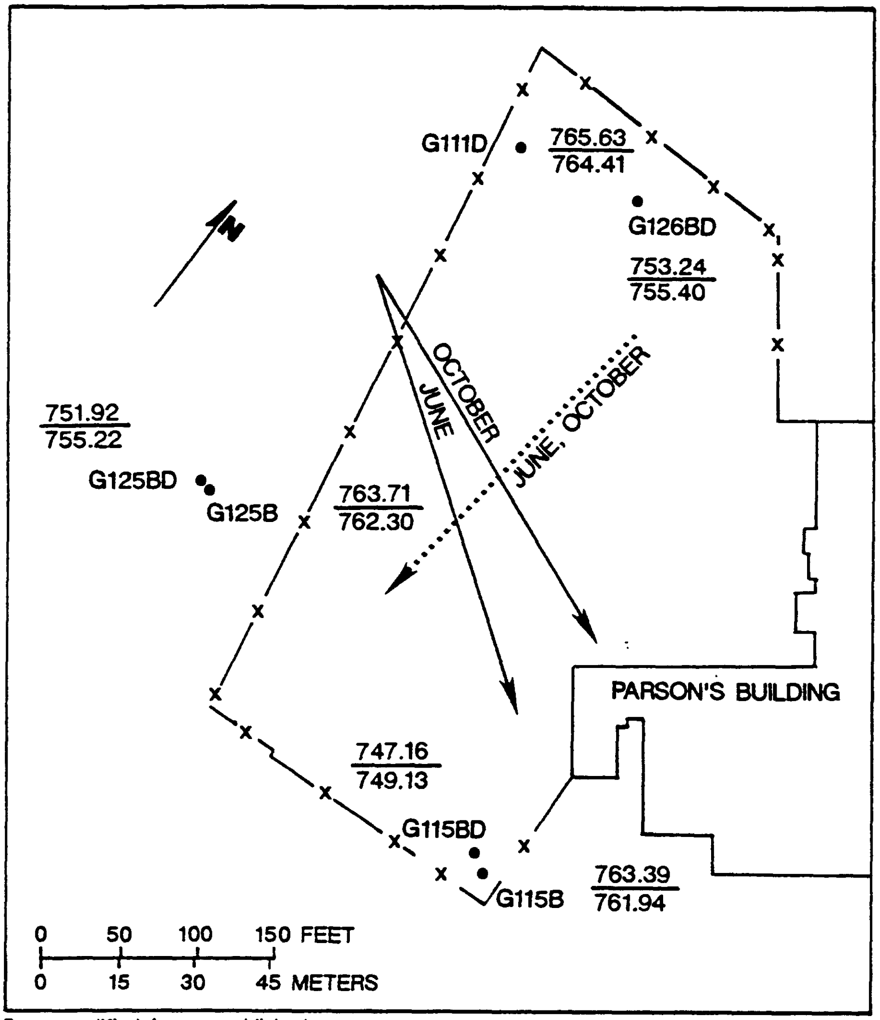
Effects of Municipal-Well Pumping

The effects of offsite pumping on ground-water flow in the Galena-Platteville aquifer beneath the Parson's Casket Hardware site were seen in many aspects of the ground-water investigation. It is assumed that Belvidere Municipal Wells No. 4 and No. 6 are the principal source of the offsite pumping interference because of (1) the absence of other pumped wells completed in the bedrock in the immediate vicinity of the site and (2) the apparent correlation between pumping of Wells No. 4 and No. 6 and water-level changes in observation wells at the Parson's Casket Hardware site.

Municipal-well pumping affected many of the aquifer tests. Discussion of the effects of the pumping of municipal wells on the aquifer tests is presented in the section "Hydraulic Properties." Additionally, changes in ground-water flow, which are attributed to municipal-well pumping, were detected during flowmeter analysis of borehole G127GP (table 4). During the 1- to 2-hour period in which measurements were made, reversals in flow direction and changes in flow rates were recorded at many of the test depths.

Water-level data collected in June and October 1991 from vertically nested observation wells open to the top and to the midpoint of the Galena-Platteville aquifer indicate that the shallow part of the aquifer responds differently to municipal-well pumping than does the deeper part. This conclusion is supported by observations regarding (1) directions and gradients of horizontal ground-water flow; (2) seasonal change in directions of ground-water flow; (3) seasonal change in ground-water levels; and (4) the magnitude of change in ground-water levels in apparent response to municipal-well pumping. Factors that may contribute to the differing response to municipal-well pumping in the shallow and deep parts of the aquifer are discussed in the report section "Results of Multiple-Well Aquifer Test."

Horizontal flow in the Galena-Platteville aquifer beneath the study site generally is southward to southeastward toward the Kishwaukee River (fig. 1). Flow near the top of the aquifer seems to be southward (fig. 9) at a gradient of less than 0.01 ft/ft. The direction of flow near the top of the Galena-Platteville aquifer approximates the direction of flow in the overlying glacial drift aquifer (Science Applications International Corporation, 1990a, fig. 1). From summer through fall, the flow direction near the top of the aquifer changes little, and water levels decline. In relation to the nearby municipal wells, shallow ground-water flow beneath the study site seems to be toward the general direction of Municipal Well No. 4 and away from Municipal Well No. 6 (fig. 1).



Base modified from unpublished map provided by Illinois Environmental Protection Agency

EXPLANATION

——x—— FENCE AND APPROXIMATE STUDY-AREA BOUNDARY

GROUND-WATER-FLOW DIRECTION

··········➤ Near top of the aquifer (data from wells G111D, G115B, G125B)

————➤ Near midpoint of the aquifer (data from wells G115BD, G125BD, G126BD)

G115BD ● OBSERVATION WELL AND DESIGNATION

747.16 / 749.13 WATER LEVELS IN CORRESPONDING OBSERVATION WELL--In feet above sea level. Top number is water level on June 11, 1991, and bottom number is water level on October 9, 1991

Figure 9.--Water-level altitudes and the approximate horizontal ground-water-flow directions in the Galena-Platteville aquifer, June 11 and October 9, 1991.

Horizontal flow near the midpoint of the Galena-Platteville aquifer seems to be southeastward at a gradient of about 0.02 ft/ft. From summer through fall, the flow direction changes northward by about 15°, and water levels rise. In relation to the nearby municipal wells, deep ground-water flow beneath the study site seems to be away from Municipal Wells No. 4 and No. 6.

The temporal shift in flow directions near the midpoint of the aquifer is attributed to a greater rise of water level in well G125BD than in wells G115BD and G126BD between the June and October water-level measurements (fig. 9). Of the three wells, G125BD is closest to the municipal wells, and apparently is most affected by municipal-well pumping. The proportionally greater rise in water level in well G125BD seemingly was in response to a significant reduction in pumping of Wells No. 4 and No. 6 during September and early October 1991.

The effect of municipal-well pumping on water levels in the site observation wells is indicated by hydrographs for wells G115B, G115BD, and for the 150-ft level for borehole G127GP (fig. 10). As indicated, the magnitude of water-level change in response to municipal-well pumping differed among the three locations. Water levels changed most in well G115BD (150.8 ft in depth) and least in well G115B (49.0 ft in depth). Water-level changes in borehole G127GP, open to shallow and deep intervals in the aquifer, were intermediate, as would be expected.

The daily pumping rates of Municipal Wells No. 4 and No. 6 also are shown in figure 10. On the basis of visual inspection of the hydrographs, there appears to be a correlation between the timing and magnitude of municipal-well pumping and water-level change in some of the observation wells at the study site. Aquifer heterogeneity almost certainly contributes to a complex relation between pumping of the municipal wells and aquifer response beneath the study site. Analysis of the relation between pumping of Wells No. 4 and No. 6 and aquifer response is further complicated by factors such as differences in proximity of the municipal wells to the site; municipal-well construction; pumping schedules and pumping volumes; and, possibly, pumping interference from other municipal wells in Belvidere or other unidentified high-capacity wells in the vicinity of the site.

Water levels in the site wells appear to respond more to pumping of Well No. 6 than to pumping of Well No. 4. Water levels in the site wells probably respond more to the pumping of Well No. 6, because Well No. 6 is about 0.25 mi closer to the study site than is Well No. 4. Well No. 6 may also be in more direct hydraulic connection with the site wells than Well No. 4. Well No. 6 has a shallower surface casing than does Well No. 4; thus, it is possible that the well bore of Well No. 6 is intersected by the fissure identified at the site at a depth of about 125 ft. Apparently, the closer proximity and the characteristics of construction of Well No. 6 account more for the municipal-well pumping effects on the aquifer beneath the site than does the greater pumping of Well No. 4.

The patterns of the hydrographs in figure 10 indicate a temporal correlation with a short time lag between adjustment of pumping rates at Well No. 6 and aquifer response beneath the study site. As a means of estimating the time lag between well pumping and aquifer response, the coefficient of correlation (r) between daily pumpage rates for Well No. 6 and water levels in site

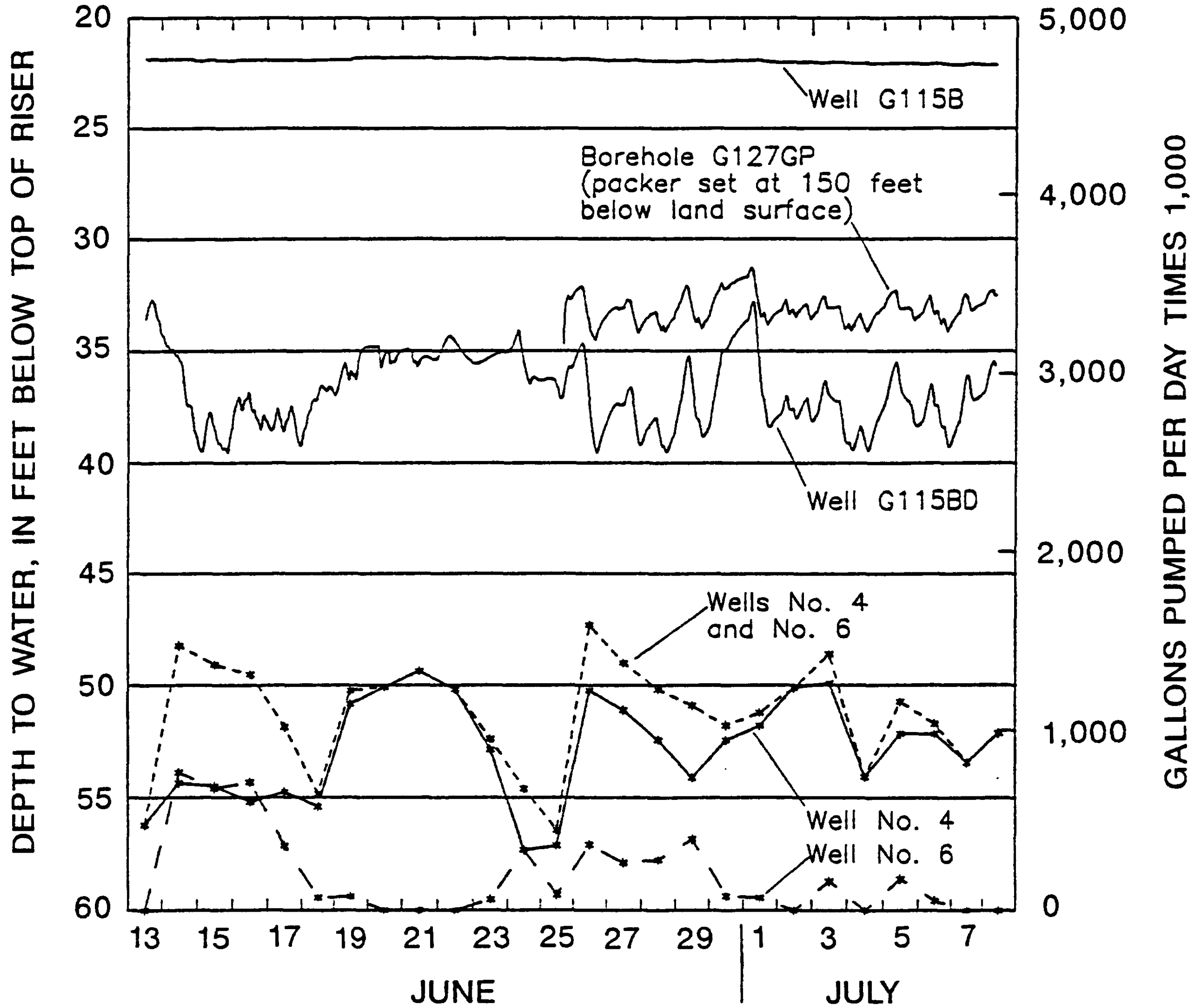


Figure 10.--Water levels in borehole G127GP and observation wells G115B and G115BD; and pumping from Belvidere Municipal Wells No. 4 and No. 6, June 13-July 8, 1991.

well G115BD (daily average) was determined. Shifting the water level of well G115BD 1 day forward in time produced the best correlation (r=0.517). This indicates that about 24 hours is required for pumping stresses on the aquifer from Well No. 6 to propagate to the study site. A more complex relation between pumping of Well No. 4 and aquifer response in site wells precluded lag-time analysis of Well No. 4.

The differing responses of water levels in the Galena-Platteville aquifer to municipal-well pumping also can be seen in the hydrographs for wells G111D and G126BD and for the 300-ft level of borehole G127GP. Depth to water for the well and borehole locations, as measured June 9-11, 1991, before the start of the multiple-well aquifer test is shown in figure 5. Water levels in well G111D, open to the top of the aquifer, showed little indication of a response to municipal-well pumping. Small, rapid changes in water level in the fully penetrating borehole G127GP during the first 20 hours of measurement were followed by a large water-level decline beyond the measurement range of the pressure transducer. Unlike water levels in borehole G127GP, water levels in well G126BD, open to the midpoint of the aquifer, did not change before the large decline.

The large decline in water level in well G126BD and borehole G127GP at about noon, June 10, 1991, is presumed to result from an increase in pumping rate at Well No. 6 from 0 gal on June 8 and 9 to 1,349,000 gal on June 10 in association with pumpage regulation for the multiple-well aquifer test. Pumpage regulation of Wells No. 4 and No. 6 began about 10 a.m. on June 10. This apparent response to regulation of pumping indicates a considerably shorter time lag than the previously estimated 24 hours for pumping stresses on the aquifer from Well No. 6 to propagate to the study site.

The rapid water-level changes in borehole G127GP before the large water-level decline on June 10 are presumed to result from the intermittent manner in which ground water is pumped at Municipal Well No. 4. Water from this well is first pumped into a 70,000-gal underground tank. When the tank is filled, the water is then pumped into the municipal water-distribution system. The well pump then refills the underground tank. Water from Well No. 6, as is the water from other municipal wells, is pumped directly into the municipal water-distribution system.

Effects of municipal-well pumping were more pronounced in borehole G127GP than in well G126BD, presumably because borehole G127GP is open to a larger part of the aquifer and is thus in greater hydraulic connection with the municipal wells than is well G126BD. Assuming that the hydraulically important fissures identified beneath the site are horizontally continuous for at least 0.5 mi, it is possible that borehole G127GP is hydraulically connected with Municipal Well No. 6 by the identified fissures at depths of 125 ft, 212 ft, and 260 ft and with Municipal Well No. 4 by the fissures at 212 ft and 260 ft. Under the same assumption, the only hydraulically important fissure connecting well G126BD with Well No. 6 would be the fissure at 125 ft; no hydraulically important fissures would connect well G126BD with Well No. 4. The absence of important fissures connecting well G126BD with Well No. 4 may also explain the absence of the rapid water-level changes that were recorded in borehole G127GP in apparent response to pumping of Well No. 4.

It is also possible that the effects of municipal-well pumping are more pronounced in borehole G127GP than in well G126BD because the bottom of borehole G127GP is closer to the underlying St. Peter Sandstone aquifer. The highly transmissive St. Peter Sandstone aquifer is extensively pumped and provides a large quantity of water to the Belvidere municipal wells. Stresses imposed on the Galena-Platteville aquifer by pumping in the St. Peter Sandstone aquifer would be expected to be greatest near the base of the Galena-Platteville aquifer.

The observation that ground-water flow beneath the Parson's Casket Hardware site is affected by pumping of Belvidere Municipal Wells No. 4 and No. 6, yet horizontal flow in the Galena-Platteville and glacial drift aquifers is oriented away from the two municipal wells may be explained as follows. The site may be near the horizontal extent of the cone of depression induced by pumping of the municipal wells; thus, although water in the aquifer responds to stresses induced by pumping of the municipal wells, natural gradients control the direction of horizontal ground-water flow. It also is possible that pumping of Wells No. 4 and No. 6 induces localized stresses on the aquifer that are superimposed on larger-scale stresses that result from pumping of other high-capacity wells downgradient from the study site. In this case, the horizontal ground-water-flow direction in the aquifer beneath the site would represent the cone of depression induced by pumping of the more distant downgradient wells.

Of the two explanations, the first seems most likely. Preliminary calculations indicate that the Parson's Casket Hardware site is near the horizontal limits of the cones of depression of Municipal Wells No. 4 and No. 6. Additionally, the nearest identified high-capacity well downgradient from the study site is an industrial well across the Kishwaukee River, about 0.5 mi south of the site. It seems unlikely that this well is significantly affecting ground-water flow beneath the study site.

In conclusion, it is apparent that offsite well pumping is affecting flow in the Galena-Platteville aquifer beneath the Parson's Casket Hardware site. The available data indicate that flow beneath the site is most likely affected by pumping of Belvidere Municipal Wells No. 4 and No. 6 and that pumping of Well No. 6 affects flow beneath the site more than does pumping of Well No. 4. Currently, many questions remain about specific aspects of the effects of offsite pumping including those that follow:

1. How substantially does pumping of Wells No. 4 and No. 6--and possibly other nearby high-capacity wells--affect natural ground-water flow gradients that, in part, control the distribution and rate of contaminant migration?

2. Are contaminants at the site currently migrating towards Wells No. 4 and No. 6 or towards other nearby wells?

3. If contaminants are migrating towards Wells No. 4 and No. 6 or towards other nearby wells, is the migration primarily horizontal (through the network of fractures and fissures in the Galena-Platteville aquifer) or vertical (through the Galena-Platteville aquifer and the underlying Glenwood Formation and into the more extensively pumped St. Peter Sandstone aquifer)?

4. Are the fractures and fissures in the Galena-Platteville aquifer capable of allowing upgradient migration of the contaminants, that, in some cases, have limited solubility in water and are more dense than water?

Additional aquifer testing, water-quality sampling, and ground-water-flow modeling would be needed to attempt to answer these questions.

Hydraulic Properties

Results of the single- and multiple-well aquifer tests are described in the following report sections. The tests indicate the distribution of hydraulic properties of the aquifer at various spatial scales. Quantification of the hydraulic properties horizontal hydraulic conductivity (K), transmissivity (T), and specific yield (S_y) is important for identification of potential pathways for waste-solute migration, estimation of rates of water and solute movement in the aquifer, and assessment of the feasibility of aquifer remediation by pumping from wells.

Results of Aquifer Tests in Borehole G127GP

The hydraulic conductivity of discrete vertical intervals of the Galena-Platteville aquifer in borehole G127GP was estimated by use of the slug-test method of Bouwer and Rice (1976) and the constant-discharge time-drawdown method of Cooper and Jacob (1946). The Bouwer and Rice (1976) method is appropriate for estimating K in partially and fully penetrating boreholes (and wells) in confined and unconfined aquifers. The value of K may be estimated by use of rising- and falling-head data provided that the equilibrium water level is above the tested interval open to the aquifer. A principal assumption of the Bouwer and Rice (1976) method is that the tested aquifer is homogeneous and isotropic. Although this condition is not fully met in the Galena-Platteville aquifer, its effect on the test results is considered minimal. It is reasonable to assume that the aquifer is homogeneous and isotropic within the small spatial domain analyzed by use of the slug tests. In the test intervals that included conductive fissures, the assumption of heterogeneity and isotropy is less valid. For those intervals, the test results are considered to be estimates representing the average K of the intervals.

Another assumption of the Bouwer and Rice (1976) method is that the tests are done when background water levels are at equilibrium. This assumption was violated because background water levels changed in the borehole during the tests in apparent response to pumping of the nearby municipal wells. The magnitude of the effect of municipal-well pumping on the slug-test results was variable, but the effect was evident for all the test intervals.

As with the Bouwer and Rice (1976) method, the constant-discharge test method of Cooper and Jacob (1946) also is appropriate for estimating K in partially and fully penetrating boreholes (and wells) in confined and unconfined aquifers. The controlling assumptions of the constant-discharge-test method of Cooper and Jacob (1946) include the following:

1. The aquifer is extensive and of uniform thickness and permeability.

2. Drawdown and time elapsed since start of pumping are sufficiently large and distance of the monitoring well from the pumping well is sufficiently small. (See Cooper and Jacob (1946) for a discussion of this assumption.)

3. The well is pumped at a steady rate.

4. The tests are done when background water levels are at equilibrium.

As with the slug tests, background water levels were not always at equilibrium during the constant-discharge tests, and it is likely that the aquifer was not truly homogeneous and isotropic in the vicinity of all test intervals. All other controlling assumptions of the test were met or approximated.

Horizontal hydraulic conductivities estimated on the basis of the slug-tests and constant-discharge tests are presented in table 5. Effects of municipal-well pumping accounted for large deviations of the field data from the theoretical straight-line plots of water level as a function of time, as indicated in figures 11-14. Thus, the results of the slug tests and the constant-discharge tests listed in table 5 are considered approximate. Results from the test intervals that were most affected by offsite well pumping were considered of little value in the estimation of K's and are omitted from table 5.

Hydraulic conductivities estimated by use of the Bouwer and Rice (1976) method ranged from $2.5x10^{-2}$ to $8.0x10^{-1}$ ft/d. Under ideal conditions, K's derived from falling-head and rising-head measurements are expected to agree. In most cases, the falling-head and rising-head K's for the tests done in borehole G127GP differed by at least a factor of 2. It is assumed that the K's for test intervals in which the falling- and rising-head K's most closely agree are the most reliable.

Deviations of data from the theoretical straight-line plot previously were noted in the analysis of K tests from the wells G115BD, G125BD, and G126BD (Mills, 1993a). The deviations in the previous tests were less pronounced, probably because the test intervals in wells G115BD, G125BD, and G126BD were shallower than the test intervals in borehole G127GP; thus, the tests were less affected by municipal-well pumping. Several explanations were presented for the deviations in the previous K tests (Mills, 1993a); however, none included interference from offsite pumping. Municipal-well pumping interference seems to have partly contributed to the deviations noted in the previous tests.

Hydraulic conductivities estimated by use of the method of Cooper and Jacob (1946) ranged from $3.5x10^{-2}$ to $5.8x10^{0}$ ft/d. As with falling- and rising-head slug-test estimates, K's derived from the pumping and the recovery phases of the constant-discharge tests generally differed by at least a factor of 2.

Table 5.--Estimated horizontal hydraulic conductivities and transmissivities of the Galena-Platteville aquifer, as determined from slug tests and constant-discharge aquifer tests in borehole G127GP

[ft/d, foot per day; ft^2/d, foot squared per day; ND, test not done: NQ, test data not reliably quantified; --, no data]

Test interval, in feet below land surface	Slug test (Bouwer and Rice, 1976) Hydraulic conductivity, in ft/d		Constant-discharge test (Cooper and Jacob, 1946) Hydraulic conductivity, in ft/d		Transmissivity, in ft^2/d	
	Falling head	Rising head	Pumping	Recovery	Pumping	Recovery
[1]41.0-301.0	ND	ND	$3.2x10^{-1}$	$1.4x10^{-1}$	90	40
	ND	ND	$8.8x10^{-1}$	$3.5x10^{0}$	250	1,000
62.4- 84.0	$3.4x10^{-2}$	$2.5x10^{-2}$	ND	ND	--	--
145.1-166.7	$8.0x10^{-1}$	$4.2x10^{-1}$	$1.8x10^{-1}$	$3.9x10^{-1}$	--	--
166.7-188.3	$2.1x10^{-1}$	$2.1x10^{-1}$	$8.8x10^{-2}$	$1.8x10^{-1}$	--	--
188.3-209.8	$1.1x10^{-1}$	$1.1x10^{-1}$	$3.5x10^{-2}$	$7.4x10^{-2}$	--	--
209.8-231.4	$3.6x10^{-2}$	$7.3x10^{-2}$	$3.8x10^{-2}$	NQ	--	--
231.4-253.0	NQ	NQ	NQ	$8.6x10^{-2}$	--	--
253.0-273.8	$1.3x10^{-1}$	NQ	$5.8x10^{0}$	NQ	--	--
273.8-301.0	$2.1x10^{-1}$	$6.9x10^{-1}$	$1.5x10^{-1}$	$1.7x10^{-1}$	--	--

[1]The first-listed values of transmissivity and hydraulic conductivity represent early-time data. The second-listed values represent late-time data.

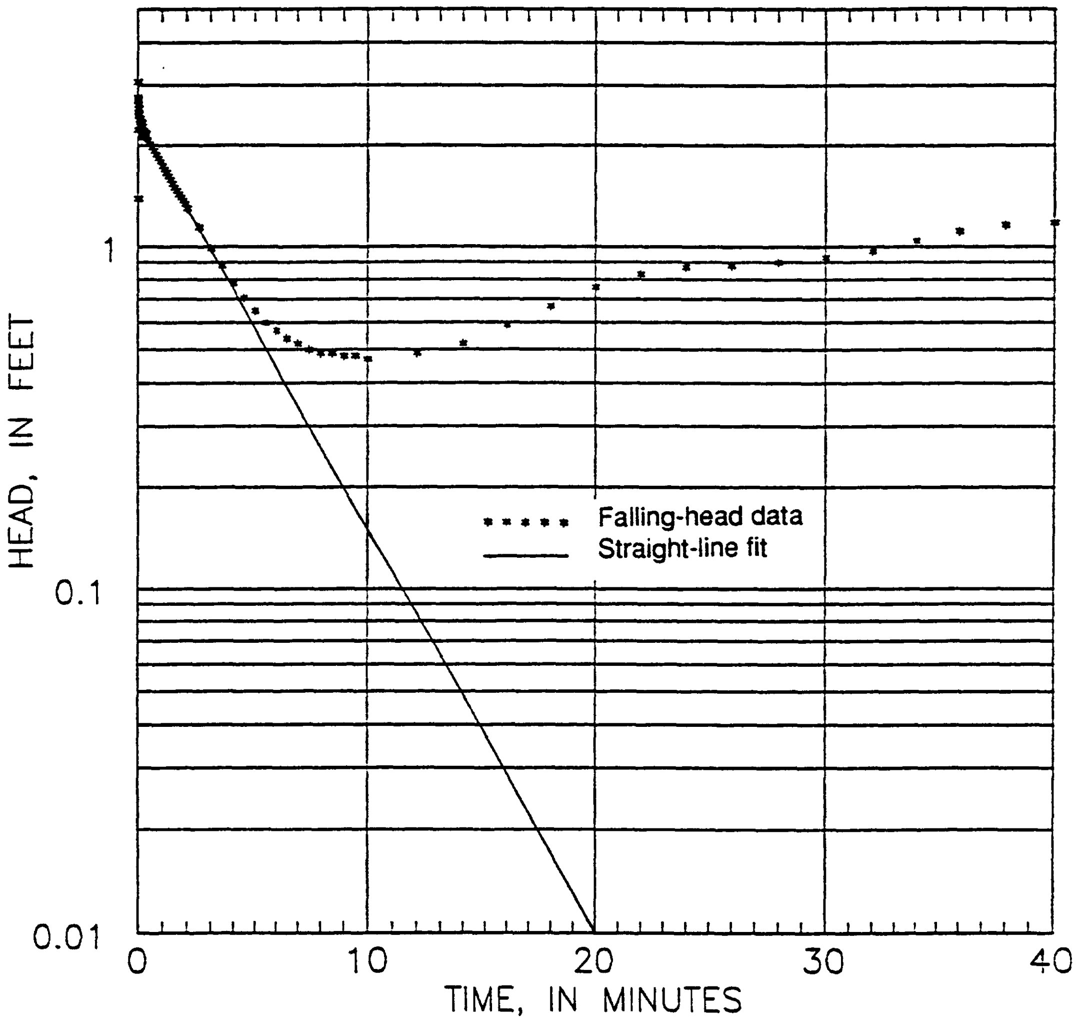


Figure 11.--Falling-head slug-test data and analysis, borehole G127GP, interval 273.8-301.0 feet below land surface.

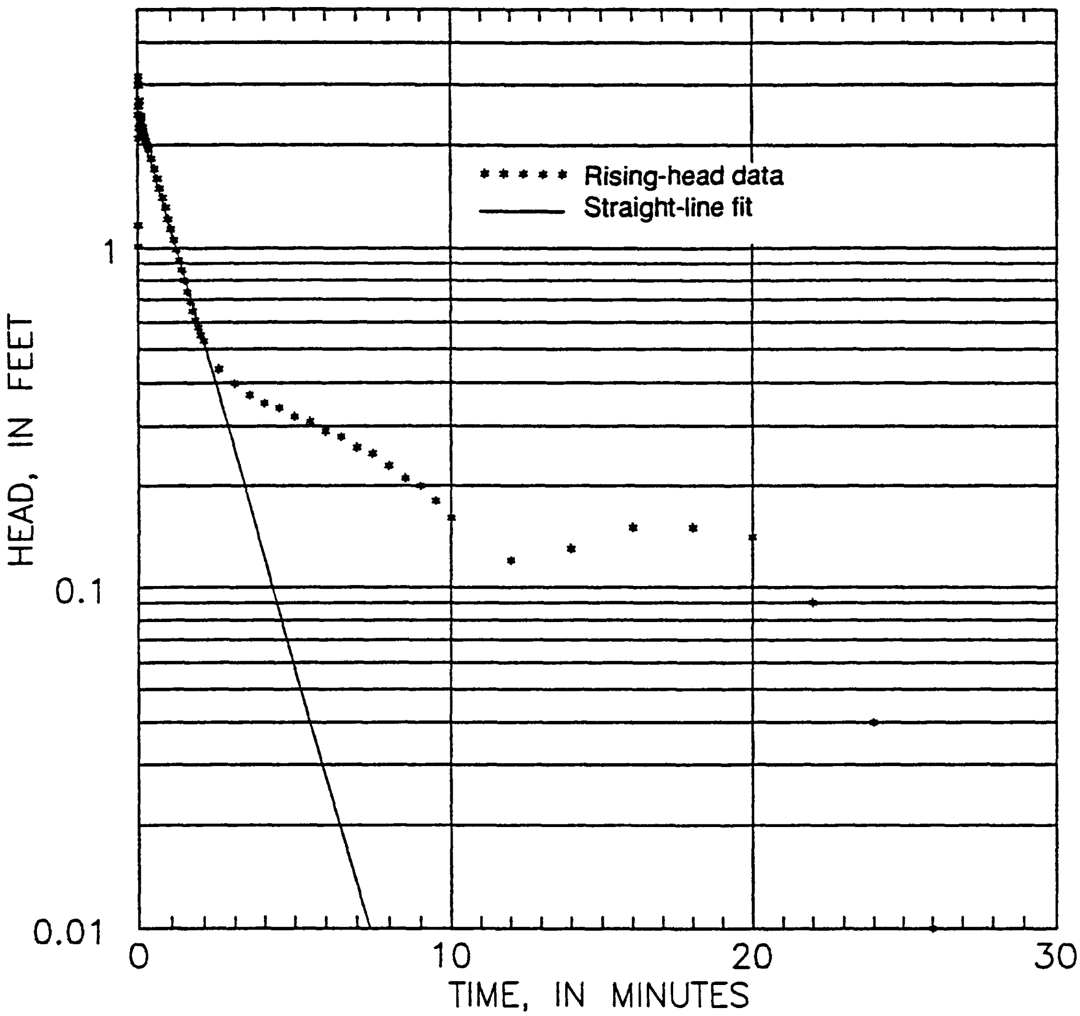


Figure 12.--Rising-head slug-test data and analysis, borehole G127GP, interval 273.8-301.0 feet below land surface.

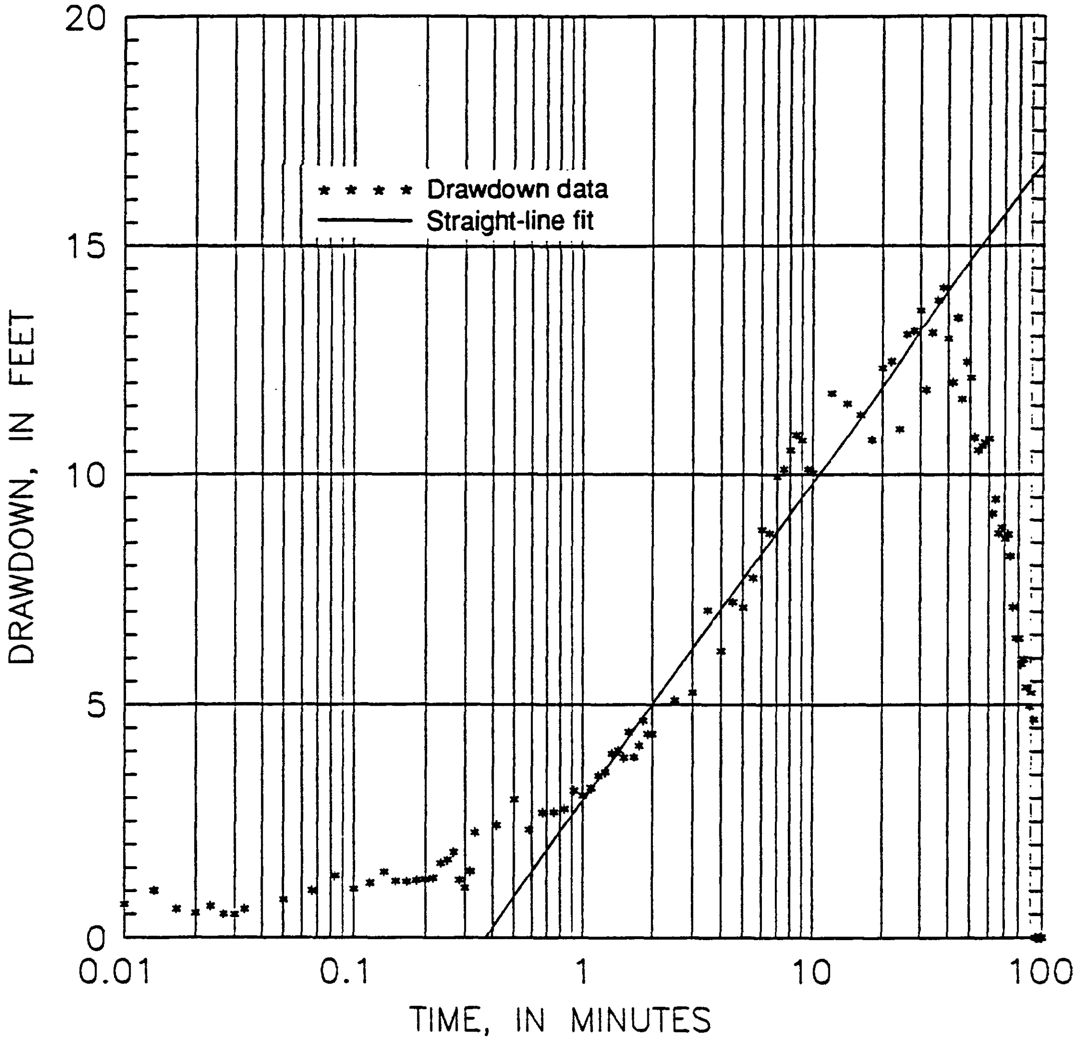


Figure 13.--Constant-discharge drawdown data and analysis, borehole G127GP, interval 273.8-301.0 feet below land surface.

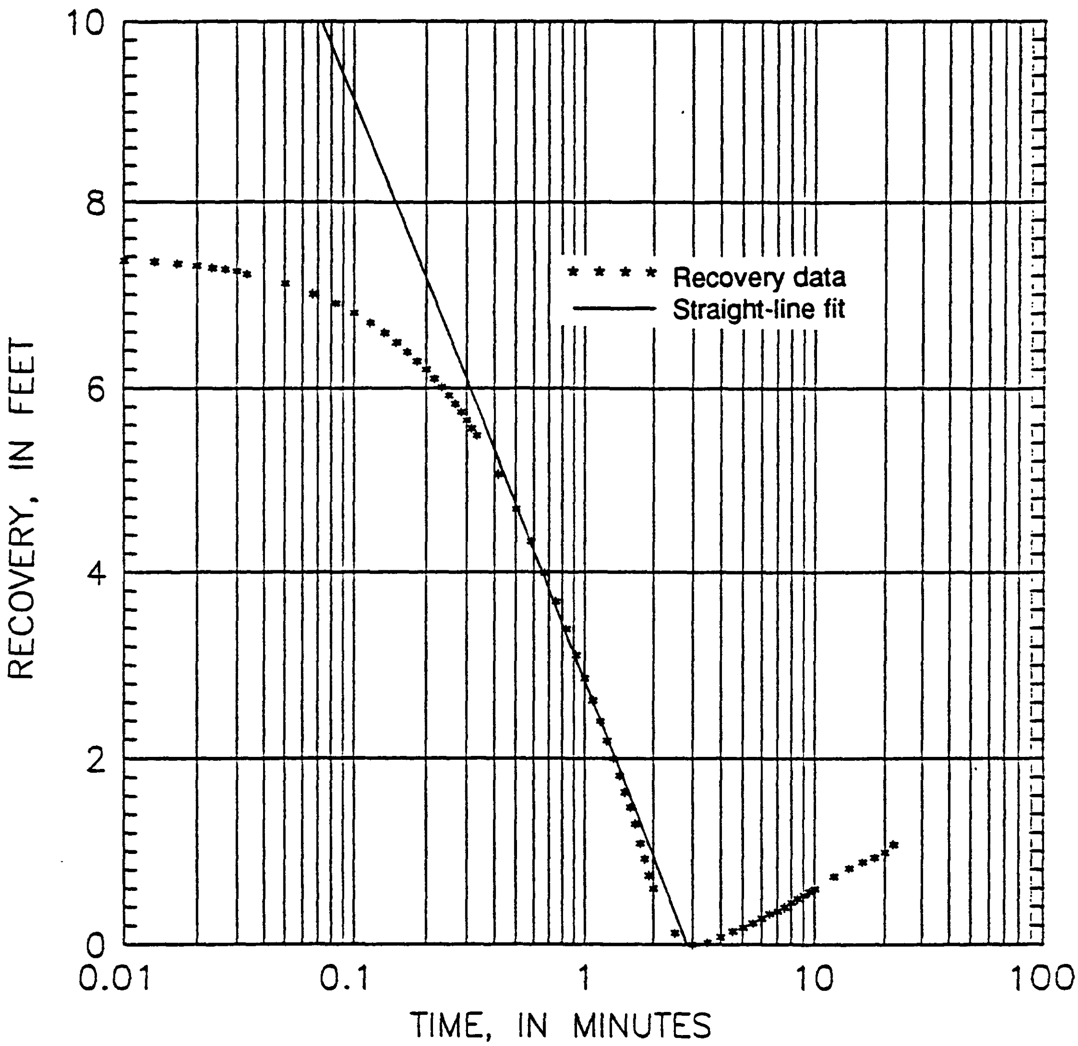


Figure 14.--Constant-discharge recovery data and analysis, borehole G127GP, interval 273.8-301.0 feet below land surface.

The K's estimated by use of the Cooper and Jacob (1946) method are considered to represent the K's of the aquifer more reliably than K's estimated by use of the Bouwer and Rice (1976) method for two reasons. First, the water-level changes induced by the constant-discharge aquifer tests were greater relative to water-level changes induced by offsite pumping than were the water-level changes induced by the slug tests. Water-level changes of 3 to 50 ft were induced by the constant-discharge tests. The slug tests induced a change in water level of only about 2.5 ft. Second, the K's derived by use of the Cooper and Jacob (1946) method generally agreed more closely with other hydraulic data than did K's derived by use of the Bouwer and Rice (1976) method. This fact was especially evident for the interval of 253.0 to 273.8 ft, in which a hydraulically important fissure is present. The Cooper and Jacob (1946) K's for this interval were, as expected, elevated relative to the K's of the other test intervals; the Bouwer and Rice (1976) K's were not.

Some caution is necessary in comparing and assessing the relative reliability of the results of the constant-discharge tests and the slug tests. Because the constant-discharge tests used at the site provide estimates of K for a larger volume of the aquifer than do the slug tests, the results of the two tests may not be readily comparable. The constant-discharge tests are more likely to have been affected by heterogeneities in the aquifer than are the slug tests.

A qualitative method for estimating relative K provides some additional insight into the vertical distribution of K in the aquifer penetrated by borehole G127GP. The qualitative information regarding K is useful because, as previously noted, K either could not be reliably quantified or was not tested in all depth intervals in borehole G127GP. The qualitative method for estimating relative K's is based on observed correlation between slug-test-determined K's for aquifer material at the study site and the rate at which drawdown occurred in the packed test intervals during pumping. Test intervals in which the water level was not drawn down to the pump-intake level when pumping at a constant rate of 1 gal/min were assumed to have the highest K; test intervals in which the water level was drawn down to the pump-intake level when pumping at a rate of 1 gal/min, but not when pumping at a rate less than 1 gal/min, were assumed to have an intermediate K; and test intervals in which the water level was drawn down to the pump-intake level when pumping at the minimum pump rate of about 0.2 gal/min were assumed to have the lowest K. Relative K's based on this relation for the test intervals in borehole G127GP are listed in table 6.

In conclusion, although the calculated K's for the individual depth intervals in borehole G127GP should, for the most part, be considered approximate, the results are considered a reliable indication of the hydraulic conductivity for the Galena-Platteville aquifer. The data indicate that, throughout most of the thickness of the aquifer below the weathered surface, K's vary over a small interval of about two orders of magnitude. The K's determined at borehole G127GP are within the range estimated for the upper 150 ft of the aquifer at wells G115BD, G125BD, and G126BD (Mills, 1993a) and for the entire aquifer in the study area, as determined by the multiple-well, constant-discharge aquifer test.

Table 6.--Relative horizontal hydraulic conductivities of the Galena-Platteville aquifer at borehole G127GP

Test interval, in feet below land surface	Relative horizontal hydraulic conductivity[1]
41.0- 55.6	Low
145.1-166.7	High
166.7-188.3	Medium
188.3-209.8	High
209.8-231.4	Medium
231.4-253.0	Low[2]
253.0-273.8	High
273.8-301.0	High

[1] High, water level not drawn down to pump-intake level when pumped at a constant rate of 1 gallon per minute; medium, water level drawn down to pump-intake level when pumped at a rate of 1 gallon per minute, not drawn down to pump-intake level when pumped at a lesser rate; low, water level drawn down to pump-intake level when pumped at the minimum rate of about 0.2 gallon per minute.

[2] Interval required 7 hours to pump 55 gallons of water.

Results of Multiple-Well Aquifer Test

Within the study area, the Galena-Platteville aquifer consists of two parts: porous dolomite and fissures. Although flow takes place in each part, each has different hydraulic properties. Additionally, the aquifer is immediately overlain by a glacial drift aquifer, which for the most part is unconfined. This conceptual model indicates that the Boulton and Streltsova-Adams (1978) double-porosity model for unconfined aquifers is best suited for the analysis and interpretation of the data obtained from the multiple-well, constant-discharge aquifer test at the Parson's Casket Hardware site.

The principal assumptions of the double-porosity model are the following:

1. The pumped well is fully penetrating.

2. The pumped well discharges at a constant rate, beginning at time equals zero.

3. The radius of the pumped well is infinitesimal.

4. Fractured aquifers consist of "blocks" and "fissures." Blocks of some width and permeability are overlain by horizontal fissures of some width and permeability.

5. Fissures and blocks are compressible.

6. Flow in the blocks is vertical.

7. Flow in the fissures is horizontal.

8. The pressure differential due to the different elastic properties of the blocks and fissures results in the water exchange between blocks and fissures (Boulton and Streltsova-Adams, 1978).

Conditions at the study site approximate the assumptions of the double-porosity model of Boulton and Streltsova-Adams (1978).

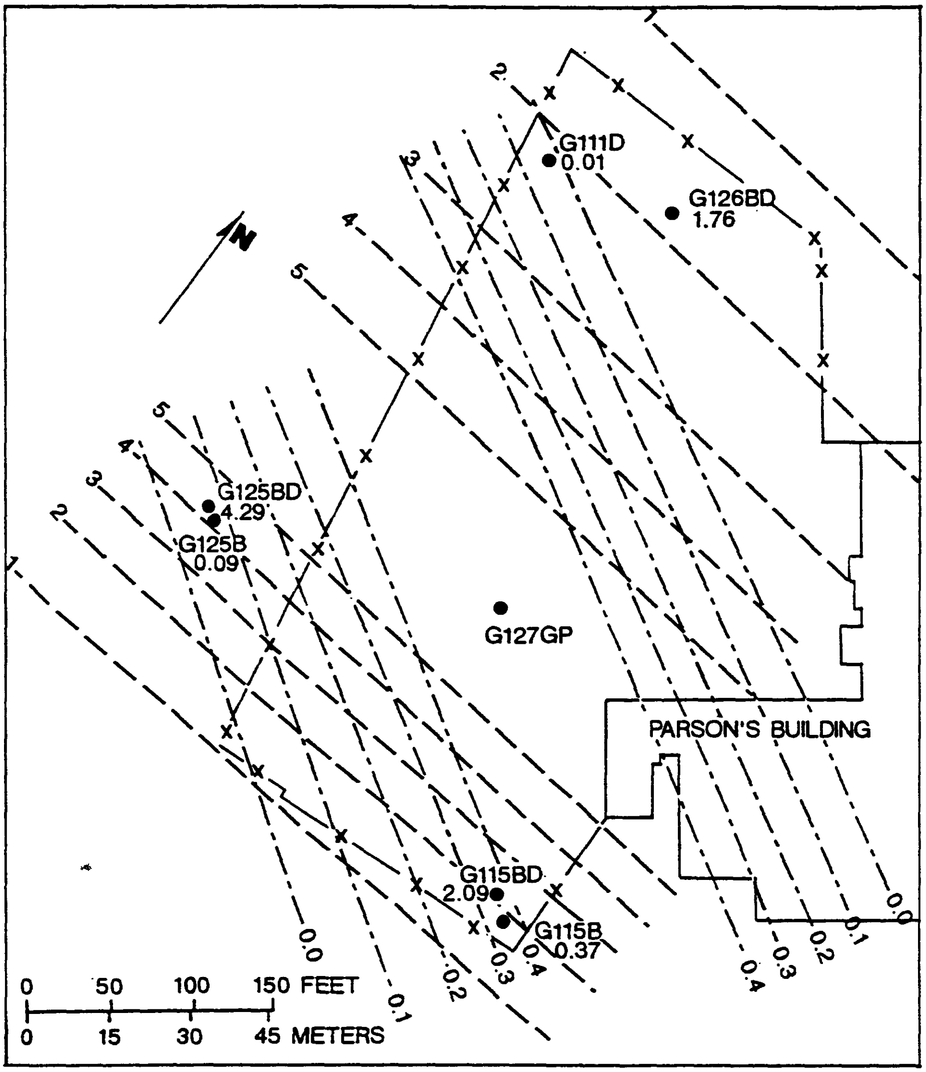
Drawdown data from the pumped well, borehole G127GP, was analyzed using the method of Cooper and Jacob (1946) as an additional means for estimating T and K. The specific assumptions and the suitability of the Cooper and Jacob (1946) test to conditions at the Parson's Casket Hardware site were discussed previously in this report.

The variable magnitude and response time of drawdown in the observation wells at the site are indicative of the heterogeneity and anisotropy of the Galena-Platteville aquifer (fig. 15). Especially notable in this regard is the observation that the maximum drawdown in the deep part of the aquifer occurred in the westernmost well (G125BD) and that the maximum drawdown in the shallow part of the aquifer occurred in the southeasternmost well (G115B).

The orientation of principal hydraulic connections within the aquifer presumably are represented by the orientation of the drawdown troughs (fig. 15). The drawdown troughs of the 150-ft-deep wells (G115BD, G125BD, and G126BD) and the wells screened near the top of the aquifer (G111D, G115B, and G125B) approximate the N. 60° W. orientation of one of the regional vertical fracture sets (Foote, 1980). Additionally, the orientation of the hydraulic connections within the aquifer may differ with depth, as the shallow-well drawdown trough is more closely aligned with the regional fracture set than is the deep-well trough. This pattern is consistent with previous hydrogeologic descriptions of the area because the density and aperture of vertical fractures in dolomite deposits in northern Illinois generally decrease with aquifer depth (Suter and others, 1959, p. 10).

Because drawdown data were available from only three observation wells at each depth interval, the orientation and shapes of the troughs depicted in figure 15 are approximate. Additionally, drawdown during the aquifer test may have been affected by more than the directional nature of hydraulic connections within the aquifer. Pumping of the nearby municipal wells could account for the asymmetric nature and orientation of the troughs, especially in the deep wells, because the deep wells are closer to the pump positions in the municipal wells where stresses on the aquifer are expected to be greatest and are presumably in greater hydraulic connection with the municipal wells than are the shallow wells. Most likely, the orientations of the drawdown troughs are affected by the orientation of hydraulic connections in the aquifer and by municipal-well pumping.

Time-drawdown and time-recovery data from the wells in the aquifer were plotted on a log-log scale and compared to type curves of the Boulton and Streltsova-Adams (1978) double-porosity model. The lack of drawdown in well



Base modified from unpublished map provided by Illinois Environmental Protection Agency

EXPLANATION

—x— FENCE AND APPROXIMATE STUDY-AREA BOUNDARY

— - — 0.2 APPROXIMATE LINE OF EQUAL DRAWDOWN, IN SHALLOW PART OF AQUIFER (ABOUT 40 FEET BELOW LAND SURFACE), IN FEET

2 — — — APPROXIMATE LINE OF EQUAL DRAWDOWN, IN DEEP PART OF AQUIFER (ABOUT 150 FEET BELOW LAND SURFACE), IN FEET

G115BD ● 2.09 BOREHOLE OR OBSERVATION WELL, DESIGNATION, AND DRAWDOWN, IN FEET

Figure 15.--Drawdown in observation wells in the Galena-Platteville aquifer after pumping of borehole G127GP at a constant rate of 28.6 gallons per minute for 960 minutes.

G111D and the small magnitude and erratic nature of drawdown in well G125B precluded the use of drawdown data from the two wells in the curve-matching analysis. Transmissivity and S_y were calculated on the basis of data at the match point common to the field-data curve and type curve (figs. 16-19). Calculated T's, K's, and S_y's for wells G115BD, G125BD, G126BD, G115B, and G125B are listed in table 7. The limited duration of the pumping phase and magnitude of stress induced by pumping discharge apparently were not sufficient enough to allow the full effects of double porosity to develop in the aquifer and thus to produce the typical double-porosity type curve shown in figure 16.

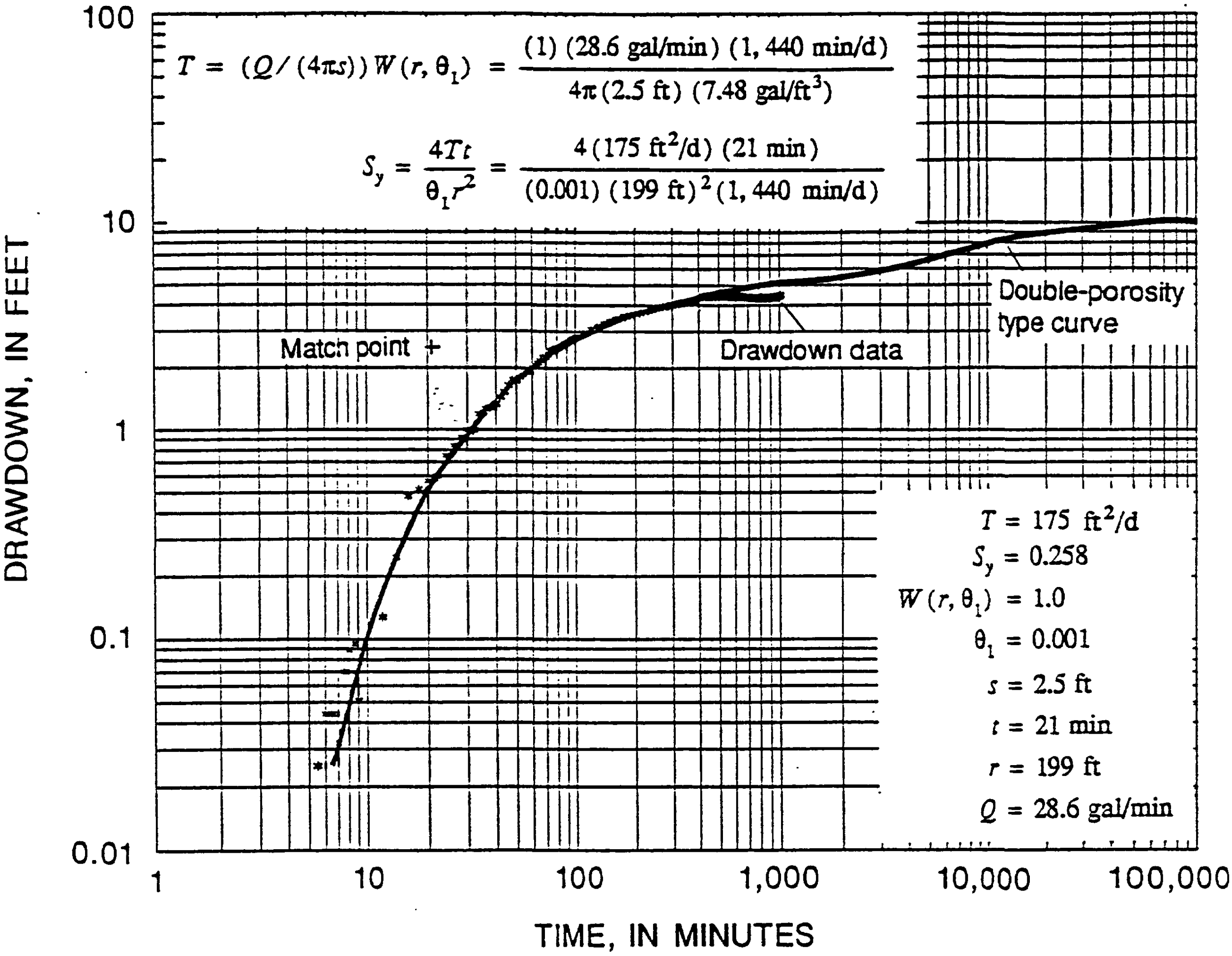
Some limitations in the analysis of the aquifer test are unavoidable because the aquifer is heterogeneous and anisotropic and because the observation wells only partly penetrate the aquifer. The T's obtained in the analysis with partially penetrating wells are expected to be lower than T's obtained with fully penetrating wells. Water levels in a partially penetrating well may not be indicative of the full hydraulic stress imposed on the aquifer by a fully penetrating pumped well. In fissured or fractured aquifers such as the Galena-Platteville aquifer, where partially penetrating wells may be remote from hydraulically important ground-water-flow conduits, aquifer T's may be particularly underestimated. Because of the heterogeneity and anisotropy of the aquifer, drawdown-data corrections could not be applied to counter the potential affect of the partially penetrating wells.

On the basis of the double-porosity model of Boulton and Streltsova-Adams (1978), estimated T's for the Galena-Platteville aquifer ranged from 160 to 7,300 ft^2/d (table 7). The T's determined on the basis of data from the shallow wells G115B and G125B were substantially greater than the T's determined on the basis of data from the deep wells (G115BD, G125BD, and G126BD). The percentage difference between the T's determined for the pumping and recovery phases of the aquifer test ranges from 11 (well G125BD) to 42 percent (G115B). In all cases, the recovery-derived T's are less than the pumping-derived T's.

The estimated K's (table 7) were calculated by dividing the determined T's by an approximate aquifer thickness of 285 ft. Assuming that the aquifer material is an equivalent porous media, then the estimated K's for the aquifer ranged from 5.6×10^{-1} to 3.0×10^{1} ft/d (table 7). The K's determined on the basis of shallow-well data were greater than the K's determined on the basis of deep-well data. The K's determined on the basis of the multiple-well aquifer test are similar to the K's determined on the basis of packer tests of discrete vertical intervals of the aquifer (Mills, 1993a).

Specific yields determined for the aquifer ranged from 0.156 to greater than 0.4 (table 7). Specific yields for unconfined aquifers usually range from about 0.1 to 0.3 (Lohman, 1979, p. 8). The calculated S_y's greater than 0.4, therefore, are considered unrealistically high and are not reported in table 7.

It seems most likely that the unrealistically high S_y's that were determined for the aquifer are attributable to municipal-well pumping interference during the aquifer test; however, it is also possible that a conceptual/analytic model other than Boulton and Streltsova-Adams (1978) double-porosity



ABBREVIATIONS

T = Transmissivity, in ft^2/d (feet squared per day)

S_y = Specific yield (dimensionless)

$W(r, \theta_1)$ = Double-porosity type curve well function

θ = A value defined as equal to $(4Tt)/(S_y r^2)$

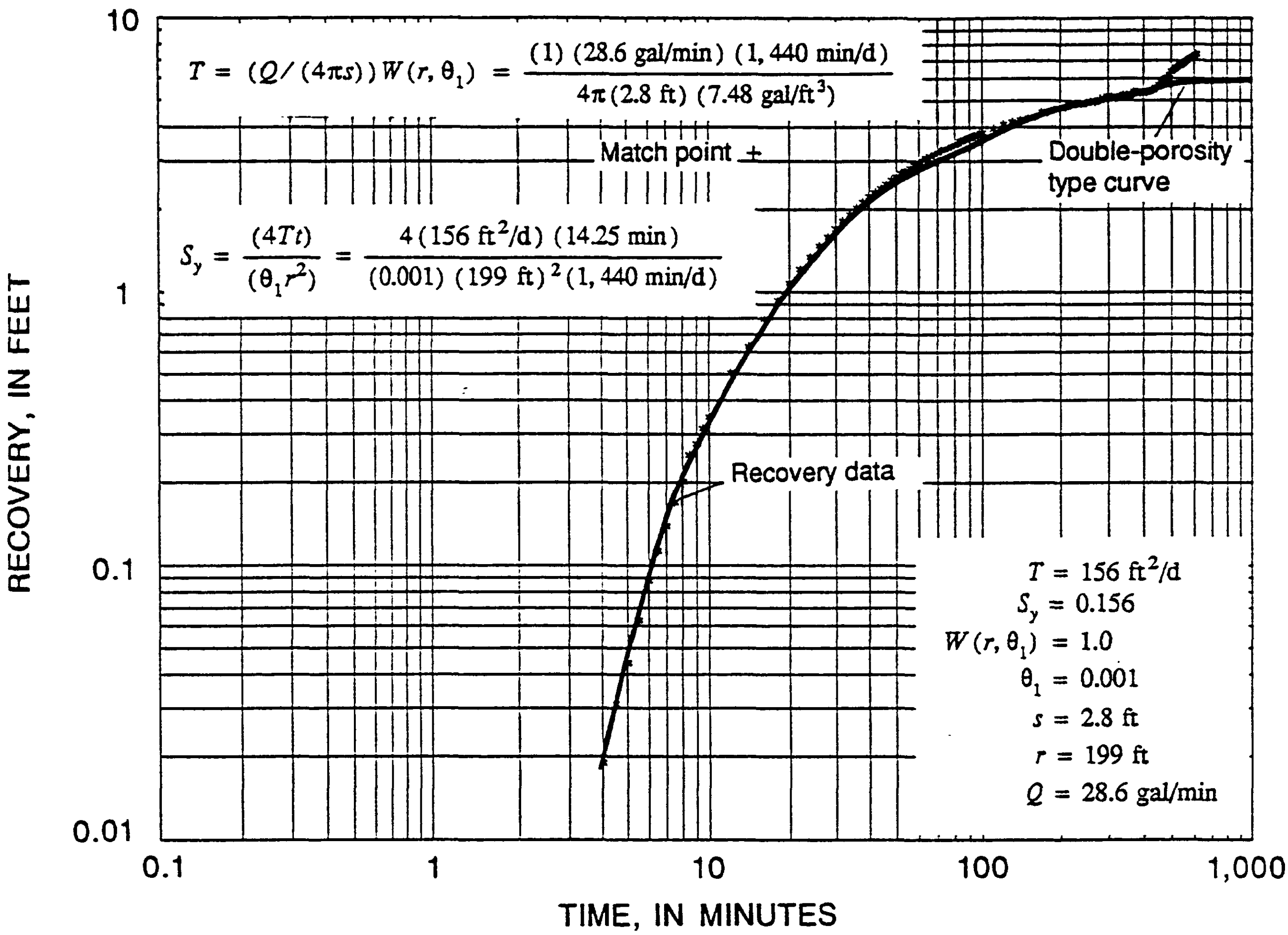
s = Drawdown, in ft (feet)

r = Radial distance from the pumped well, in ft (feet)

Q = Discharge, in gal/min (gallons per minute)

t = Time since the start of pumping, in min (minutes)

Figure 16.--Constant-discharge drawdown data and analysis, observation well G125BD matched with the Boulton and Streltsova-Adams (1978) double-porosity type curve.



ABBREVIATIONS

T = Transmissivity, in ft^2/d (feet squared per day)

S_y = Specific yield (dimensionless)

$W(r,\theta_1)$ = Double-porosity type curve well function

θ = A value defined as equal to (4Tt)/($S_y r^2$)

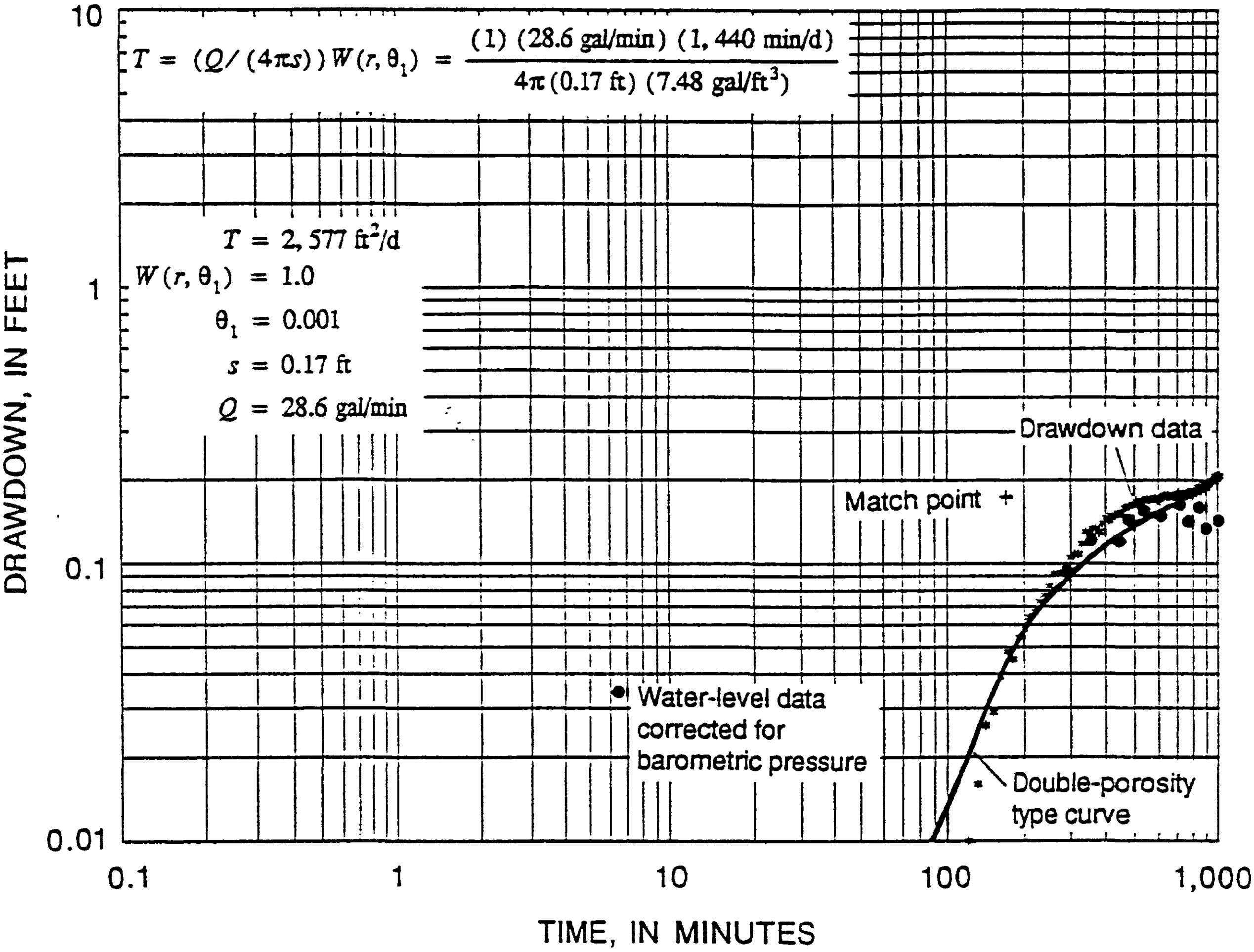
s = Drawdown, in ft (feet)

r = Radial distance from the pumped well, in ft (feet)

Q = Discharge, in gal/min (gallons per minute)

t = Time since the start of pumping, in min (minutes)

Figure 17.--Constant-discharge recovery data and analysis, observation well G125BD matched with the Boulton and Streltsova-Adams (1978) double-porosity type curve.



ABBREVIATIONS

T = Transmissivity, in ft^2/d (feet squared per day)

S_y = Specific yield (dimensionless)

$W(r, \theta_1)$ = Double-porosity type curve well function

θ = A value defined as equal to $(4Tt)/(S_y r^2)$

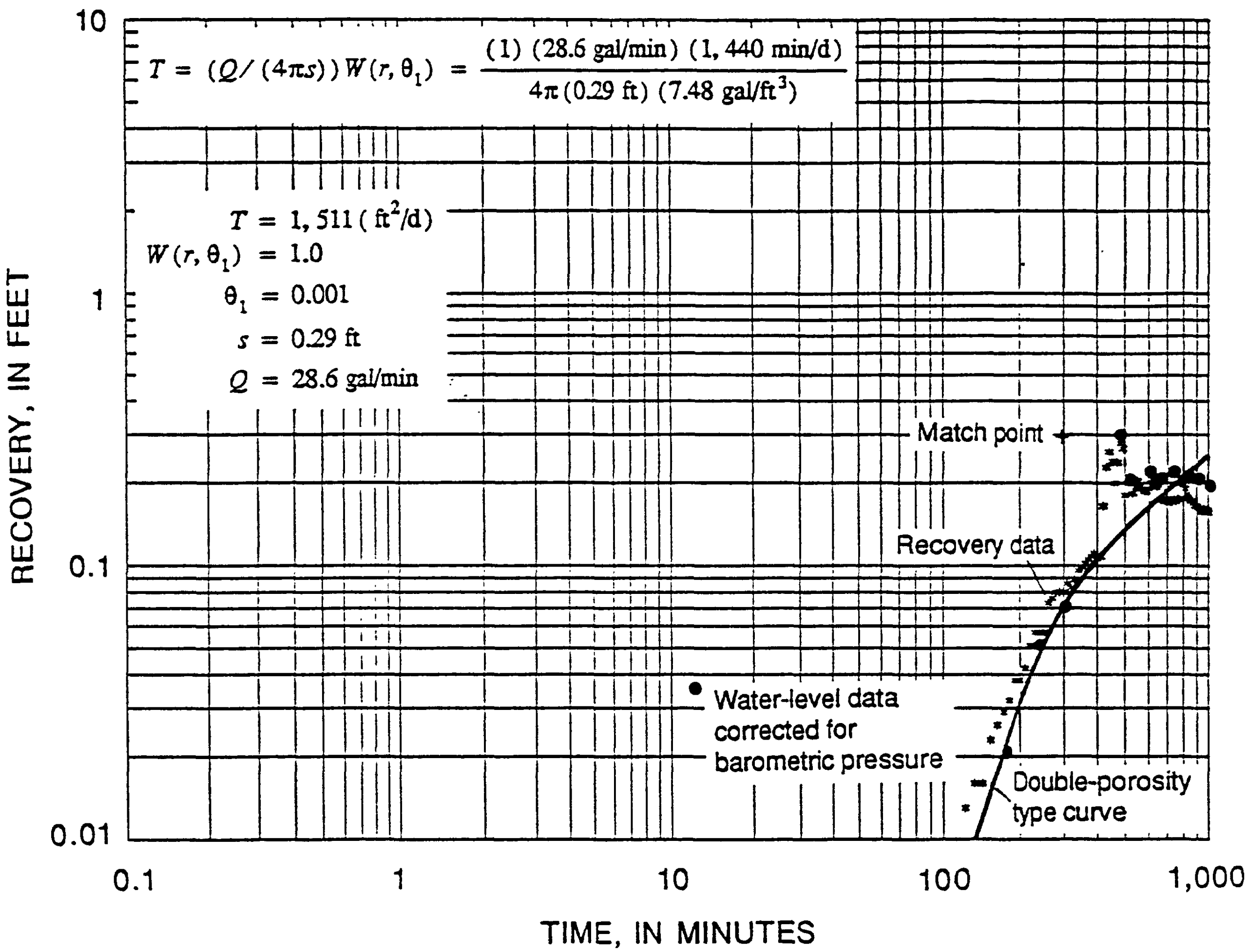
s = Drawdown, in ft (feet)

r = Radial distance from the pumped well, in ft (feet)

Q = Discharge, in gal/min (gallons per minute)

t = Time since the start of pumping, in min (minutes)

Figure 18.--Constant-discharge drawdown data and analysis, observation well G115B matched with the Boulton and Streltsova-Adams (1978) double-porosity type curve.



ABBREVIATIONS

T = Transmissivity, in ft^2/d (feet squared per day)

S_y = Specific yield (dimensionless)

$W(r, \theta_1)$ = Double-porosity type curve well function

θ = A value defined as equal to $(4Tt)/(S_y r^2)$

s = Drawdown, in ft (feet)

r = Radial distance from the pumped well, in ft (feet)

Q = Discharge, in gal/min (gallons per minute)

t = Time since the start of pumping, in min (minutes)

Figure 19.--Constant-discharge recovery data and analysis, observation well G115B matched with the Boulton and Streltsova-Adams (1978) double-porosity type curve.

Table 7.--Estimated transmissivities, horizontal hydraulic conductivities, and specific yields of the Galena-Platteville aquifer, as determined from the constant-discharge aquifer test, June 11-12, 1991

[ft^2/d, foot squared per day; ft/d, foot per day; --, data not reliably quantified]

Well name	Transmissivity, in ft^2/d		Hydraulic conductivity, in ft/d		Specific yield, dimensionless	
	Drawdown	Recovery	Drawdown	Recovery	Drawdown	Recovery
Double-porosity model (Boulton and Streltsova, 1978)						
G115BD	290	200	1.0×10^{0}	7.0×10^{-1}	--	--
G125BD	180	160	6.3×10^{-1}	5.6×10^{-1}	0.258	0.156
G126BD	320	260	1.1×10^{0}	9.1×10^{-1}	--	--
G115B	2,600	1,500	9.1×10^{0}	5.3×10^{0}	--	--
G125B	--	7,300	--	3.0×10^{1}	--	--
Double-yield model (Boulton, 1963)						
G115BD	270	180	9.5×10^{-1}	6.3×10^{-1}	9.4×10^{-4}	6.4×10^{-4}
G125BD	150	140	5.3×10^{-1}	4.9×10^{-1}	2.3×10^{-4}	1.4×10^{-4}
G126BD	290	230	1.0×10^{0}	8.1×10^{-1}	6.1×10^{-4}	4.1×10^{-4}
G115B	2,400	1,400	8.4×10^{0}	4.9×10^{0}	3.0×10^{-2}	3.3×10^{-2}
G125B	--	6,700	--	2.4×10^{1}	--	7.8×10^{-3}

model would be better suited for analysis of the aquifer-test data. Some field data indicate the Galena-Platteville aquifer may not be unconfined, as presumed. Differences in flow directions, response to municipal-well pumping, drawdown-trough orientations, and calculated T's, K's, and S_y's indicate that the shallow and deep parts of the aquifer may be different flow systems separated by the low-K strata underlying the weathered bedrock surface. Other data, however, indicate that this interpretation of the field data is probably erroneous and that the selection of Boulton and Streltsova-Adams (1978) double-porosity model is best suited for analysis of the aquifer test. The consistent downward hydraulic gradients, the widespread distribution of VOC's, and the presence of inclined fractures that crosscut the dolomite strata and connect hydraulically conductive horizontal fissures strongly indicate the unconfined block-and-fissure nature of the aquifer. The data that indicate the aquifer is semiconfined to confined may by explainable in the context of an unconfined aquifer if, as supported by the hydraulic and geophysical data, water in the aquifer is transmitted primarily through several hydraulically conductive fissures and fractures. Thus, hydraulic data from the deep wells that are closest to the primary water-bearing fissures indicate hydraulic characteristics of the aquifer that are somewhat different than the characteristics indicated by data from the shallow wells.

Conceptualization of the Galena-Platteville aquifer as a block-and-fissure double-porosity system and selection of the Boulton and Streltsova-Adams (1978) analytic model are additionally supported because application of most alternative conceptual/analytic models resulted in inadequate matching of type curves or very low values of storativity that generally are not expected for unconfined aquifers. The alternative models included the following: (1) Boulton's model (1963) of an unconfined aquifer with delayed yield; (2) Boulton and Streltsova's model (1978) in which the water table in an unconfined double-porosity aquifer remains constant during pumping; (3) Hantush's model (1959) for confined leaky aquifers; (4) Lohman's model (1979) for confined leaky aquifers with storage in the confining beds; and (5) Theis' model (1935) for confined, homogeneous, isotropic aquifers.

On the basis of similarities in the conceptualized aquifer systems and the analytic results, the delayed-yield model of Boulton (1963) seemingly is the best alternative conceptual/analytic model. A double-porosity aquifer system may in one way be considered a delayed-yield system, in that application of pumping stress in a double-porosity aquifer induces a delayed yield from storage as water is derived first from fissures and then from the aquifer matrix. Of the alternative models, the T estimates of the Boulton (1963) model were most similar to the T estimates of the Boulton and Streltsova-Adams (1978) model and generally were about 15 percent lower (table 7). It should be noted that, for all the alternative models in which field data and type-curve data could be matched, the estimated T's were within one order of magnitude of the T estimates of the Boulton and Streltsova-Adams (1978) model.

The S_y estimates of the Boulton (1963) model were substantially lower than the S_y estimates of the Boulton and Streltsova-Adams (1978) model, typically in the range associated with confined aquifer systems (table 7). The low S_y's, however, are not unexpected for unconfined aquifers with delayed yield. The low S_y's represent the apparent S_y of the aquifer during the early phase of the aquifer test before delayed yield begins to affect drawdown.

Although Boulton's delayed-yield model (1963) may seem better suited for analysis of the Galena-Platteville aquifer-test data than the Boulton and Streltsova-Adams' double-porosity model (1978) on the basis of the estimated S_y of the aquifer, closer evaluation of the aquifer system and the aquifer-test results indicate otherwise. As previously stated, available hydrogeologic and hydraulic information indicate that the aquifer system is most conceptually consistent with the double-porosity model. Furthermore, there was no field evidence of a delay in yield (that is, drawdown in the water-table wells), which is inconsistent with Boulton's delayed yield model (1963). However, the lack of drawdown in the water-table wells may have been a function of the length of the test. It is possible that drawdown may have occurred if pumping were continued for a longer time.

Another conceptual/analytic model that seemingly could account for the relatively small magnitude of drawdown in the shallow bedrock wells is Boulton and Streltsova's model (1978) in which the water table in a pumped unconfined double-porosity aquifer remains constant. Consistent with the assumptions of the model, there was no apparent decline of the water table during the aquifer test. Thus, the glacial drift aquifer seemed to function as an unlimited source of water to the shallow bedrock wells. This model, however, was rejected on the basis of inadequate matching of the field drawdown data and the theoretical type curve.

The effects of municipal-well pumpage are evident in several aspects of the aquifer-test results. First, before the start of the aquifer test and presumably during the test, water levels in the observation wells were gradually declining in response to municipal-well pumping (fig. 5). Second, recovery-determined T's were always less than drawdown-determined T's (table 7), a relation that can be expected if drawdown due to municipal-well pumping interference is occurring during an aquifer test (Rushton, 1985). Third, at about 420 minutes into the recovery phase of the aquifer test, water levels increased rapidly (figs. 17 and 19). The increase in water level represents, in part, the inverse expression of the reduction in drawdown also noted to occur at about 420 minutes into the drawdown phase (fig. 16). The reduction in drawdown apparently is induced by an undetermined source of recharge, such as delayed yield from the dolomite block or interception of a conductive fracture by the cone of depression. The increase in water level during the recovery phase, however, was greater than expected on the basis of the drawdown response, thus indicating that the termination of continuous pumping of Municipal Well No. 6 near that time also contributed to the rapid increase in water level. As previously indicated, quantifying and accounting for the interfering effects of municipal-well pumping in the analysis of the aquifer-test data proved impractical.

The estimated T's and K's for the aquifer based on data from the pumping well (borehole G127GP) are presented in table 5. The K's were determined by dividing T's by 285 ft, the approximate thickness of the aquifer.

Neither time-drawdown nor time-recovery data from the constant-discharge test plotted as a straight line on a semilog plot. The early-time data and the late-time data from the pumping and recovery phases of the test could be fitted to separate straight lines, thus allowing estimation of early-time and late-time T's and K's (figs. 20, 21).

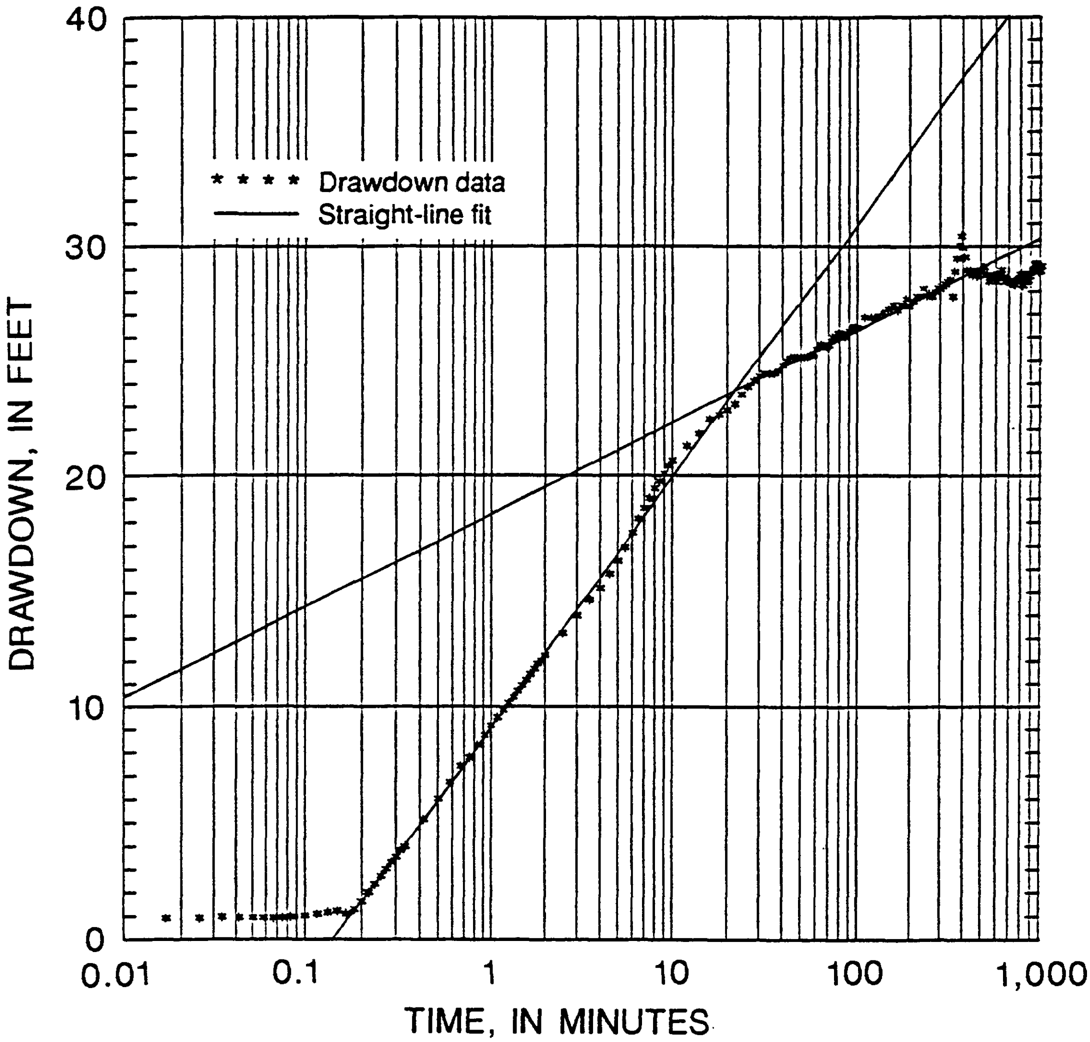


Figure 20.--Constant-discharge drawdown data and analysis, borehole G127GP.

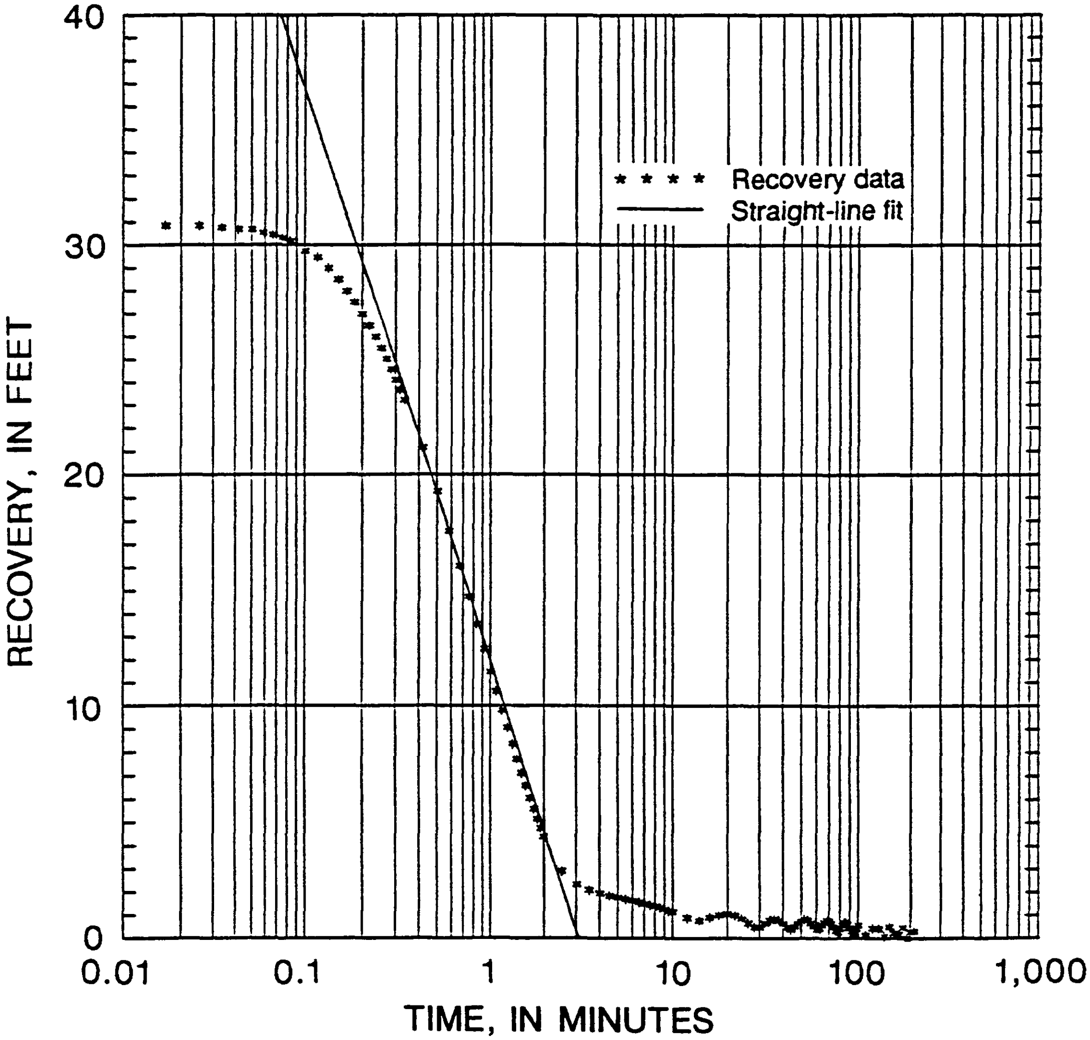


Figure 21.--Constant-discharge recovery data and analysis, borehole G127GP.

The reason for the early- and late-time trends in pumping and recovery data is not well understood. The early- and late-time trends were observed previously during slug tests and constant-discharge tests in which packers at discrete intervals were used in wells G115BD, G125BD, and G126BD (Mills, 1993a). Several explanations for the trends were proposed. One explanation was that pumping rates may not have been constant when the tests were done. This explanation was not totally satisfactory, however, because the trends also were observed in data from the recovery phases of the constant-discharge tests and from the slug tests, neither of which involved pumping. Furthermore, inconsistent pumping rates do not account for the time-water-level trends noted in the constant-discharge test data from borehole G127GP because discharge rates remained constant during the tests. On the basis of the present study, inconsistent pumping rates probably can be discounted for the previous tests. Interference by municipal-well pumping seems to be a primary cause for the early- and late-time water-level trends. The effects of aquifer heterogeneity and anisotropy as discussed by Mills (1993a) and, to a lesser extent, well loss during pumping (which was not accounted for in the analysis), probably also contribute to the observed trends.

Early-time T's and K's calculated from borehole G127GP data are within one order of magnitude for the pumping and recovery phases (table 5). There is less agreement between the late-time T's and K's for the pumping and recovery phases. Late-time T's and K's for the pumping and recovery phases were larger than the early-time T's and K's. The late-time-pumping T and K (250 ft^2/d and $8.8x10^{-1}$ ft/d, respectively) were most similar to the T's and K's of Boulton and Streltsova-Adams (1978) for the Galena-Platteville aquifer.

In conclusion, many factors contribute to uncertainty regarding the interpreted results of the multiple-well aquifer test. These factors include the hydrogeology of the Galena-Platteville aquifer and interference by municipal-well pumping.

The hydrogeology of the dolomite aquifer is obviously complex. The double-porosity aquifer has a vertically varying K and includes several notable horizontal hydraulic conduits. Near the top of the aquifer, high-K weathered deposits overlie a sequence of low-K strata that seem to be crosscut by vertical or inclined fractures. The Galena-Platteville aquifer is overlain by a glacial drift aquifer that may be locally semiconfining where interbedded silt and clay deposits are present. The Galena-Platteville aquifer is underlain by argillaceous dolomite and sandstone deposits that are assumed to be, but may not be, semiconfining. Flow in the Galena-Platteville aquifer is affected by pumping of nearby municipal wells and apparently was affected to an undetermined extent during the aquifer test.

Assessing the results of the multiple-well aquifer test in light of all the available hydrogeologic and hydraulic data, one concludes that, in general, the T's and K's determined from the aquifer test reliably represent the hydraulic properties of the Galena-Platteville aquifer. The T's and K's determined on the basis of data from the deep observation wells probably are more reliable indicators of the average hydraulic properties of the aquifer than the T's and K's determined on the basis of data from the shallow observation wells.

The S_y data are considered less reliable than the T and K data and should be viewed with caution. There are uncertainties regarding the extent to which S_y determinations were affected by municipal-well pumping during the aquifer test and regarding the choice of the conceptual/analytic model used to determine S_y's.

WATER QUALITY OF THE GALENA-PLATTEVILLE AQUIFER

Several indicators of water quality in the Galena-Platteville aquifer were evaluated. The indicators included measurement of pH, temperature, specific conductance, Eh, dissolved oxygen, and alkalinity in the field and laboratory determinations of selected inorganic constituents and VOC's. The results of the field and laboratory determinations are described in the following report sections. Water-quality in an aquifer can, in some ways, be related to former waste-disposal activities in the aquifer's recharge area.

Field Measurements

The field measurements of pH, temperature, specific conductance, and Eh for ground water from the Galena-Platteville aquifer for the test intervals in borehole G127GP are presented in table 8. Field water-quality measurements of water samples from wells G115BD, G125BD, and G126BD (Derral Van Winkle, Science Applications International Corporation, written commun., 1990), screened in the aquifer at a depth of about 150 ft, also are listed for comparison. The range of pH in borehole G127GP was 7.0 to 7.3, which is comparable to the range of measurements recorded in wells G115BD, G125BD, and G126BD and in the previously tested boreholes at these well locations (Mills, 1993a).

Ground-water temperatures in borehole G127GP ranged from 11.6 to 12.3°C (table 8). The effect of ambient air temperature, which was about 25°C when borehole G127GP was sampled in mid-June, most likely accounts for the high water temperature detected at the depth interval of 41.0-55.6 ft and for the low water temperatures recorded in wells G115BD, G125BD, and G126BD, which were sampled in mid-January. In-situ measurements of water temperature determined during geophysical logging gradually decreased from 11.45°C at a depth of 50 ft to 11.15°C at about 260 ft. Below 260 ft, water temperature decreased less gradually to 10.95°C at 300 ft (fig. 7). The rate of decline in water temperature generally decreased at depths from 50 to 260 ft in accordance to the Earth's natural thermal gradient. The change in the rate of temperature decline below 260 ft apparently represents the effect of ground-water flow through the previously described fissure at that depth in the aquifer.

Specific conductance of the ground water in borehole G127GP ranged from 580 to 940 µS/cm (table 8). The highest specific conductance was recorded in the shallowest test interval (41.0-55.6 ft). Water in this interval also had the highest concentration of VOC's (total VOC concentration was 2,444 ppb). Specific conductances were substantially lower in the deeper test intervals, as were the VOC concentrations. The specific conductances of ground water from all but the shallowest test interval in borehole G127GP were equivalent to the lowest specific conductances recorded in boreholes G115BD, G125BD, and

Table 8.--Field measurements of water-quality characteristics of ground water from borehole G127GP and observation wells G115BD, G125BD, and G126BD

[--, no data]

Test interval, in feet below land surface	Date	Water-quality characteristic: pH, in standard unit	Temperature, in degrees Celsius	Specific conductance, in microsiemens per centimeter at 25 degrees Celsius	Eh, in millivolts	Remarks
				Borehole G127GP		
41.0- 55.6	06-18-90	7.0	12.3	940	52	Discharge water cloudy at one borehole volume, clear at one and one half borehole volumes
145.1-166.7	06-19-91	7.1	11.9	650	2	
166.7-188.3	06-21-91	7.2	11.6	610	56	
188.3-209.8	06-20-91	7.1	11.7	580	19	Small air bubbles in discharge water
209.8-231.4	06-20-91	7.1	11.8	670	74	Air bubbles in discharge water; fine grains of pyrite in water
231.4-253.0	[1]06-20-91	7.3	11.9	650	-32	
253.0-273.8	06-08-91	7.1	11.9	580	-34	Air bubbles in discharge water; fine grains of pyrite in water
273.8-301.0	06-06-91	7.2	11.6	660	-52	Air bubbles in discharge water
				Well G115BD[2]		
140.6-150.6	01-16-91	7.4	10.1	1,630	--	
				Well G125BD[2]		
137.4-147.7	01-16-91	7.2	10.6	1,700	--	
				Well G126BD[2]		
141.0-151.3	01-14-91	7.6	9.3	740	--	

[1] Purged 0.9 borehole volume.
[2] Data obtained from Derral Van Winkle, Science Applications International Corporation, written commun., 1990.

G126BD (Mills, 1993a). The low specific conductances for boreholes G125BD, G115BD, and G126BD also were associated with relatively low VOC concentrations. This correlation between specific conductances and VOC concentrations in ground water from the study site has been noted previously (Mills, 1993a), and it has been suggested that the relation between the values indicates that the distribution of inorganic-waste solutes through the aquifer is somewhat similar to the distribution of VOC's.

Values of Eh ranged from -52 to 74 mv (table 8). The Eh data indicate that ground water in the aquifer changes from an oxidizing to a progressively more reducing environment below a depth of about 150 ft. The Eh's were notably lower in ground water sampled from borehole G127GP than from ground water sampled from the other bedrock boreholes at the site. Eh's at equivalent depths elsewhere on site ranged from 28 to 180 mv and averaged 100 mv (Mills, 1993a).

Inorganic Constituents

The concentrations of dissolved inorganic constituents in ground water from the Galena-Platteville aquifer for test intervals in borehole G127GP are listed in tables 9 and 10. Inorganic-constituent concentrations from wells G115BD, G125BD, and G126BD (Shirley Baer, Illinois Environmental Protection Agency, written commun., 1991), screened in the aquifer at a depth of about 150 ft, also are included for comparison.

Calcium and magnesium concentrations (72,200-103,000 ppb and 31,100-42,700 ppb, respectively) were the highest in water sampled from the aquifer. High concentrations of calcium and magnesium are to be expected in water from dolomite aquifers (Hem, 1985, p. 89-100).

Relatively high concentrations of sodium (5,630-36,700 ppb) also were recorded in all test intervals in the aquifer. The highest concentration of sodium was associated with the highest concentration of chloride; both were found in the shallowest test interval (41.0-55.6 ft). Possible sources of the elevated concentrations of sodium and chloride include application of road salt in the Belvidere area and disposal of industrial wastes at the Parson's Casket Hardware site. Sodium concentrations in well G116S, screened in the glacial drift aquifer, have been determined to be as high as 228,000 ppb (Shirley Baer, Illinois Environmental Protection Agency, written commun., 1991). Well G116S is near the former waste-disposal pond and within about 80 ft of borehole G127GP (fig. 2).

Iron concentrations in ground water from all test intervals, and most notably from the depth interval 145.1 to 166.7 ft (1,020 ppb), generally were higher than concentrations expected in natural waters (Hem, 1985, p. 83) including water of the Galena-Platteville aquifer. Similarly, high iron concentrations were detected at only one other ground-water sampling location at the study site, well G116S (maximum of 11,900 ppb) (Shirley Baer, Illinois Environmental Protection Agency, written commun., 1991). A review of ground-water data for selected wells screened in the Galena-Platteville aquifer indicate iron concentrations in the aquifer generally are less than 100 ppb.

Table 9.--Inorganic-constituent (cation) concentrations in ground water from borehole G127GP and observation wells G115BD, G125BD, and G126BD

[All concentrations in part per billion (ppb);
--, concentration below instrument reporting limits]

Test interval, in feet below land surface	SMO number[1]	Calcium	Iron	Magnesium	Manganese	Sodium	Zinc	Aluminum
				Borehole G127GP				
41.0- 55.6	MEPC44	103,000	258	42,700	83.8	36,700	219	101
145.1-166.7	MENM01	83,200	1,020	36,300	13.6	8,230	132	111
166.7-188.3	MEPC50	77,700	527	32,900	14.7	7,230	97.4	85.1
188.3-209.8	MEPC48	72,200	261	31,100	15.4	5,630	134	80.8
209.8-231.4	MEPC47	85,200	334	35,700	17.5	12,000	340	84.1
231.4-253.0	[2]MEPC46	73,900	325	31,500	26.2	8,010	272	79.9
253.0-273.8	MEPC45	86,600	283	36,400	35.5	13,000	59.7	61.4
273.8-301.0	MEPC39	86,800	647	37,900	23.7	8,990	38.7	45.3
				Well G115BD[3]				
140.6-150.6	MEMT16	135,000	18.1	51,400	19.9	29,000	[5]21.9	--
				Well G125BD[3,4]				
137.4-147.7	MEMT34	136,000	15	50,000	70.8	38,500	[5]25.5	33.9
				Well G126BD[3]				
141.0-151.3	MEMT36	[5]110,000	--	41,900	36.6	11,700	20	60

Table 9.--Inorganic-constituent (cation) concentrations in ground water from borehole G127GP and observation wells G115BD, G125BD, and G126BD--Continued

Test interval, in feet below land surface	SMO number	Antimony	Arsenic	Barium	Chromium	Cobalt	Nickel	Potassium	Selenium
				Borehole G127GP					
41.0- 55.6	MEPC44	--	--	153	--	--	16.8	4,160	[6]3.6
145.1-166.7	MENM01	--	--	95.7	--	--	--	1,560	--
166.7-188.3	MEPC50	--	--	96.3	--	--	--	2,050	--
188.3-209.8	MEPC48	--	--	78.7	--	--	--	1,460	--
209.8-231.4	MEPC47	--	--	126	--	--	--	1,800	--
231.4-253.0	MEPC46	--	--	108	--	--	--	1,610	--
253.0-273.8	MEPC45	[6]64.5	2.2	99.9	2.4	3.7	[6]12.6	2,020	--
273.8-301.0	MEPC39	[6]52.0	[6]6.6	178	8.0	--	--	1,780	--
				Well G115BD					
140.6-150.6	MEMT16	--	--	104	--	--	23.7	3,240	--
				Well G125BD					
137.4-147.7	MEMT34	--	--	92.3	--	--	65.9	2,970	--
				Well G126BD					
141.0-151.3	MEMT36	--	[6]3	72.8	--	--	--	3,190	--

[1] U.S. Environmental Protection Agency Sample Management Office (SMO) sample identification number.

[2] Purged 0.9 borehole volume.

[3] Data collected January 14-16, 1991 (Shirley Baer, Illinois Environmental Protection Agency, written commun., 1991).

[4] Also detected copper, 13.3 ppb; and cyanide, 3.1 ppb.

[5] Concentration is estimated.

[6] Concentration is estimated because of contamination or interference.

Table 10.--Inorganic-constituent (anion) concentrations in ground water from borehole G127GP

[All concentrations in part per million;
--, concentration below instrument reporting limits]

Test interval, in feet below land surface	SMO number[1]	Nitrite-Nitrate	Sulfate[2]	Fluoride[3]	Chloride	Akalinity, as calcium carbonate[4]
			Borehole G127GP			
41.0- 55.6	6361E-04	0.69	83.4	0.19	18.6	410
145.1-166.7	6361E-05	--	54.1	.35	7.09	310
166.7-188.3	6361E-10	--	38.1	.23	3.76	310
188.3-209.8	6361E-08	--	26.5	.29	2.62	300
209.8-231.4	6361E-07	--	61.8	.21	7.20	320
231.4-253.0	[5]6361E-06	--	38.8	.25	4.87	300
253.0-273.8	6361E-02	--	41.7	1.8	5.81	320
273.8-301.0	6361E-01	--	48.7	.19	6.31	340

[1] U.S. Environmental Protection Agency Sample Management Office (SMO) sample identification number.

[2] Concentrations are estimated because of potential high analytical bias.

[3] Concentration for SMO 6361E-02 is estimated because of low analytic bias, other concentrations are estimated because of low analytic bias and contamination.

[4] Alkalinity was determined in the field.

[5] Purged 0.9 borehole volume.

Zinc concentrations in ground water from all test intervals above the depth of 253 ft also were higher than concentrations generally expected in natural waters (Hem, 1985, p. 142). Zinc concentrations in ground water from borehole G127GP were higher than zinc concentrations in water sampled from all other site locations (Shirley Baer, Illinois Environmental Protection Agency, written commun., 1991) (fig. 2). The highest zinc concentration (6,310 milligrams per kilogram) at the site was detected in a soil sample collected within 2 ft of land surface.

Because of the proximity of borehole G127GP and well G116S to the former waste-disposal pond (fig. 2), it is probable that the high iron and zinc concentrations at these sampling locations are attributable to the disposal of iron- and zinc-rich metallurgical wastes in the pond. Industrial metallurgy was one of the primary industrial activities at the Parson's Casket Hardware site (Illinois Environmental Protection Agency, 1989).

Other sources for the high iron and zinc concentrations in borehole G127GP could include the black-steel surface casing (all other wells at the site consist of PVC or stainless-steel materials) and (or) the galvanized-steel tubing used in both the packer-sampling assembly and the temporary packer that was installed in the borehole for 2 weeks between field-sampling trips. These sources, however, are considered unlikely for the following reasons:

(1) The borehole was extensively developed before ground-water was sampled.

(2) Leaching of metals from the packer assembly during sampling would be minimal given the short exposure time of the packer assembly to the sampled ground water.

(3) High concentrations of iron and zinc also were detected at wells G116S and G116D, which were constructed and sampled differently than borehole G127GP.

Relatively high fluoride concentrations of 1.8 ppb in ground water from the test interval 253.0-273.8 ft below land surface are assumed to be related to the natural geochemistry of the aquifer. Lithologic logs of the Platteville and Galena Groups indicate the presence of several thin beds of bentonitic clay (Willman and Kolata, 1978, p. 15). Bentonitic clay is a natural source of fluoride in ground water (Hem, 1985, p. 120). The beds of bentonite seem to be a contributing source for the clay that infills the fractures and fissures detected in the Galena-Platteville dolomite, as indicated by the natural-gamma data (fig. 7), especially for the fissure detected at the depth of 260 ft.

Relatively high concentrations of nitrite-nitrate (0.69 ppm) in ground water from the test interval 41.0-55.6 ft are attributed to fertilization of corn and soybean fields in the Belvidere area. The nearest fields are about 0.5 mi north of the site.

The apparent absence of the inorganic constituents antimony, arsenic, chromium, cobalt, and nickel in the test intervals above the depth of 253 ft are attributed to different detection limits used in the analysis of water samples from the test intervals above and below the depth of 253 ft. Higher detection limits were used in analysis of samples collected above 253 ft than below 253 ft.

Volatile Organic Compounds

Volatile organic compounds are present throughout the vertical extent of the Galena-Platteville aquifer beneath the site, as indicated by the data from borehole G127GP (table 11). The concentrations of VOC's were significantly higher near the top of the aquifer than at lower depths in the aquifer. In the shallowest test interval (41.0-55.6 ft below land surface), VOC concentrations ranged from 33 ppb (estimated, below USEPA contract required quantification limit) for 1,2-dichloroethylene (total) to 1,300 ppb for trichloroethylene (TCE). Relatively high concentrations of 1,1,1-trichloroethane (1,1,1-TCA) (900 ppb) and methylene chloride (130 ppb) also were detected in the shallow test interval. In the deeper test intervals (145.1-301.0 ft below land surface), VOC concentrations ranged from 0.7 ppb (estimated) for 1,1-dichloroethylene to 21 ppb for TCE. Similar compounds were detected in the shallower and deeper test intervals. The compounds detected in ground water from borehole G127GP were similar to the compounds detected in ground water from other wells within and adjacent to the study site (Mills, 1993a).

Although the concentration of methylene chloride detected in the water sample from borehole G127GP was higher than concentrations detected in water samples from other wells and boreholes at the site, it is suspected that this constituent is a laboratory contaminant. Methylene chloride has been detected randomly at concentrations up to 85 ppb in ground-water and quality-assurance samples from the site (Shirley Baer, Illinois Environmental Protection Agency, written commun., 1991). Toluene detected in water samples from borehole G127GP also is suspected of being a laboratory contaminant.

Within the test intervals below the depth of about 145 ft, VOC concentrations seemed to be somewhat stratified. No VOC's were detected in the interval 209.8 to 231.4 ft. Concentrations in ground water from above that interval were slightly lower than concentrations in ground water from below that interval. Similar stratification of VOC's in the aquifer at the study site has been noted previously and attributed, in part, to the effect of aquifer heterogeneity and anisotropy on ground water and contaminant movement (Mills, 1993a).

Because no water samples were collected from the depth interval from 55.6 to 145.1 ft in borehole G127GP, it is not certain which factors may account for the distinct reduction in VOC concentrations between the depths of 55.6 and 145.1 ft. Although VOC concentrations tended to increase progressively with depth in other bedrock boreholes sampled at the site (Mills, 1993a), VOC concentrations in borehole G127GP did not progressively increase with depth in the borehole from the depth interval 145.1 to 301.0 ft.

The distinct decrease in VOC concentrations with depth noted in borehole G127GP has several possible explanations. First, VOC concentrations may decrease distinctly below the depth of about 150 ft at all locations at the site. Borehole G127GP is the only location at the site where water samples

Table 11.--Volatile organic compound concentrations in ground water from borehole G127GP and observation wells G115BD, G125BD, and G126BD

[All concentrations in part per billion (ppb); 1,1-DCA, 1,1-dichloroethane; 1,1,1-TCA, 1,1,1-trichlorethane; 1,1-DCE, 1,1-dichloroethylene; 1,2-DCE, 1,2-dichloroethylene (total); TCE, trichloroethylene; PCE, tetrachloroethylene; --, concentration below instrument reporting limit; NA, not applicable; na, not analyzed for]

Test interval, in feet below surface	SMO number[1]	1,1-DCA	1,1,1-TCA	1,1-DCE	1,2-DCE	TCE	PCE	Toluene	Methylene chloride	Carbon disulfide
					Borehole G127GP					
41.0- 55.6	EPJ10	[2]42	900	[2]39	[2]33	1,300	--	--	130	--
145.1-166.7	[3]EPJ13	--	[2]2	--	--	5	--	--	--	--
166.7-188.3	EPJ22	--	5	--	--	9	--	--	--	--
188.3-209.8	EPJ18	[2]2	5	--	--	14	--	--	--	--
209.8-231.4	EPJ17	--	--	--	--	--	--	--	--	--
231.4-253.0	[4]EPJ15	--	14	--	--	20	--	--	--	--
253.0-273.8	[5]EPJ03	[2]0.8	9	--	[2]0.8	14	--	--	--	--
	[6]NA	--	14	--	--	20.0	--	7.4	--	na
273.8-301.0	EPJ01	--	[2]4	--	[2]2	21	--	--	--	[2]0.6
	[6]NA	--	9.1	--	--	26.0	--	6.3	--	na
41.0-301.0	[7]EPJ06	[2]1	15	[2]0.7	[2]0.8	21	--	--	--	--
	EPJ09	--	[2]3	--	[2]0.6	6	--	--	--	--
					Well G115BD[8]					
140.6-150.6	EMR16	[2]4	130	--	[2]11	310	63	--	--	[2]3
					Well G125BD[8]					
137.4-147.7	EMR34	--	[2]280	--	[2]35	[2]600	[2]88	--	26	--
					Well G126BD[8]					
141.0-153.3	EMR36	--	10	--	--	11	--	--	--	--

1 U.S. Environmental Protection Agency Sample Management Office (SMO) sample indentification number.
2 Concentration is estimated (below USEPA contract required quantification limit).
3 Chloromethane also was detected, 2 ppb (estimated).
4 Purged 0.9 borehole volume.
5 Acetone also was detected, 6 ppb (estimated).
6 Analyzed by U.S. Geological Survey, National Water Quality Laboratory, Arvada, Colo.
7 First concentration represents sample collected at the start of an aquifer test (about 450 gallons pumped); second concentration represents sample collected at the end of an aquifer test (about 30,000 gallons pumped). Toluene also was detected in the first sample, 0.5 ppb (estimated).

8 Data collected January 14-16, 1991 (Shirley Baer, Illinois Environmental Protection Agency, written commun., 1991).

have been obtained for analysis below the depth of 150 ft. A small decrease in VOC concentrations was detected below a depth of about 125 ft in the 150-ft-deep wells G115BD, G125BD, and G126BD (in water samples collected during packer sampling of the initial boreholes). The decrease has been attributed to the probable affect of the hydraulically conductive fissure at the depth of 125 ft (Mills, 1993a). It was surmised that movement of the VOC's is predominantly through the horizontal fissure with lesser downward movement through the beds underlying the fissure.

Second, the distinct decrease in VOC concentrations with depth in borehole G127GP may be unique to that borehole location, due in part to localized hydrogeologic features. The hydrogeologic features could include the near-surface inclined fractures that were detected in the vicinity of the borehole by the borehole ground-penetrating radar (fig. 8, Appendix 3).

Third, it is possible that the VOC data do not accurately represent true contaminant distribution in the vicinity of borehole G127GP. During sampling of intervals below a depth of 188.3 ft, small gas bubbles were observed in the pump-discharge water. The presence of the bubbles could not be directly attributed to either equipment failure or natural causes (degassing, for example). Whatever the cause, the possibility exists that VOC's in the water phase below the depth of 188.3 ft were being lost to the gaseous phase by volatilization. If so, the VOC concentrations presented in table 11 for the depth intervals below 188.3 ft should be considered minimum expected concentrations, the actual concentrations in the ground water being higher than reported concentrations.

Water-quality data that could help clarify whether volatilization of VOC's was occurring during sampling is inconclusive. Low specific conductances in the deep test intervals indicate that the low VOC concentrations determined for these intervals were valid. Zinc concentrations, however, indicate that contaminants from the waste-disposal operations at the site may have migrated as deeply as 253 ft into the aquifer. The presence of substantial zinc concentrations at depth indicates that actual VOC concentrations could possibly be higher than the determined concentrations. This interpretation requires the assumption of similar disposal histories and solute-transport properties for zinc and VOC's.

Water samples collected from the fully penetrating well during the multiple-well aquifer test are presented in table 11. Near the beginning of the aquifer test, after 450 gal of water had been pumped, concentrations of TCE and 1,1,1-TCA were 21 and 15 ppb, respectively. Near the conclusion of the aquifer test, after 30,000 gal had been pumped, concentrations of TCE and 1,1,1-TCA were 6 and 3 (estimated) ppb, respectively. The reduction in VOC concentrations during pumping indicates that contaminated water from the dolomite aquifer was mixing with uncontaminated water from parts of the dolomite aquifer or adjacent aquifers.

SUMMARY AND CONCLUSIONS

The U.S. Geological Survey, in cooperation with the U.S. Environmental Protection Agency, investigated contaminant migration in the Galena-Platteville aquifer at the Parson's Casket Hardware site in Belvidere, Ill. This report presents the results of the second phase of a hydrogeologic investigation by the USGS, which lasted from March through October 1991.

Rock cores from well drilling, borehole-geophysical techniques, and single- and multiple-well aquifer tests were used to evaluate the hydrogeology of the Galena-Platteville aquifer. Single-well aquifer tests included slug tests and constant-discharge tests in discrete intervals in a borehole that fully penetrates the aquifer. Water-level data and municipal-well-pumpage data were used to evaluate the effect of pumping of nearby municipal wells on ground-water flow beneath the study site. Ground-water samples were collected and analyzed to evaluate contaminant migration in the aquifer. Values of pH, temperature, specific conductance, Eh, and dissolved oxygen were measured in the field, and inorganic-constituent and volatile-organic-compound concentrations were determined in the laboratory for samples collected at discrete depth intervals in the aquifer.

The surficial deposits at the study site are 25- to 40-ft-thick glacial drift deposits of Quaternary age. These deposits compose a generally unconfined glacial drift aquifer. The uppermost bedrock geologic units beneath the study site are the Galena and Platteville Groups of Ordovician age. These dolomite units, present from about 40 to 320 ft below land surface, compose the unconfined Galena-Platteville aquifer. The bedrock aquifer is partitioned into five hydrogeologic units. The approximate depth and range of horizontal hydraulic conductivity of each unit are as follows:

Unit 1--a weathered bedrock surface that can be several feet thick, horizontal K ranges from 1 to 200 ft/d;
Unit 2--40 to 80 ft, 0.02 to 0.8 ft/d;
Unit 3--80 to 160 ft, 0.02 to 1 ft/d;
Unit 4--160 to 260 ft, 0.04 to 0.2 ft/d; and
Unit 5--260 to 301 ft, 0.2 to 0.7 ft/d.

Vertical hydraulic gradients in the aquifer typically are downward. Horizontal flow in the aquifer generally is southward to southeastward from the site toward the Kishwaukee River.

Three notable bedding-plane solution fissures and three fractures that crosscut the bedding planes are identified within the dolomite bedrock. Bedding-plane fissures at depths of about 125 and 260 ft seem to be the most important conduits for horizontal flow in the aquifer. The K's in the 10- to 20-ft-long slug-test intervals in which the two fissures are present are about 1 to 10 ft/d and 0.1 to 1 ft/d, respectively. The angular fractures are assumed to function as conduits that connect high-conductivity horizontal fissures, thus allowing more rapid vertical movement of ground water and contaminants than would be expected in the generally low-conductivity dolomite matrix.

Flow in the Galena-Platteville aquifer beneath the study site is affected by pumping of Belvidere Municipal Wells No. 4 and No. 6. The relation between pumping of the municipal wells and aquifer response beneath the study site is complex; complicating factors include differences in municipal-well construction, pumping schedules, pumping volumes, and proximity of the municipal wells to the site.

Water levels in wells screened near the vertical midpoint of the aquifer are affected by municipal-well pumping substantially more than are water levels in wells screened near the top of the aquifer. Horizontal-flow directions near the top of the aquifer are southward, similar to flow directions in the overlying glacial drift aquifer, and they change little by season. Flow directions near the midpoint of the aquifer are southeastward and shift seasonally. The shift in flow direction in the deeper part of the aquifer is attributed to a relatively large seasonal rise in water level in the well nearest the municipal wells.

The results of a multiple-well, constant-discharge aquifer test confirm the heterogeneous and anisotropic properties of the aquifer. The orientation of drawdown troughs representing the shallow and deep parts of the aquifer approximated the regional fracture orientation of N. 60° W. There was little to no drawdown in wells open near the top of the dolomite aquifer, and the drawdown trough for wells near the top of the aquifer was oriented slightly different than the drawdown trough for wells near the midpoint of the aquifer. The difference in hydraulic characteristics between the shallow and deep parts of the dolomite aquifer are attributed, in part, to the presence of the hydraulically conductive fissures in the deep part of the aquifer and the effects of the hydraulically conductive weathered-bedrock surface and the overlying glacial drift.

Estimated transmissivities (T's) of the aquifer, as determined from data from the deep wells, range from 160 to 320 ft^2/d. Estimated T's of the aquifer, as determined from data from the shallow wells, range from 1,500 to 7,300 ft^2/d. The average T of the aquifer is presumed to be best represented by the T's determined from data from the deep wells. Specific yields range from 0.156 to greater than 0.4. The unrealistically high specific yields of greater than about 0.4 are attributed for the most part to interference from municipal-well pumping during the aquifer test.

The highest specific conductances (940 µS/cm) and the highest concentrations of sodium (36.7 ppm), chloride (18.6 ppm), and nitrite-nitrate (0.69 ppm) in the aquifer were within the shallowest test interval (41.1-56.6 ft below land surface). There was a possible correlation between specific conductances and VOC concentrations. Iron and zinc concentrations from most of the test intervals were higher than concentrations expected in natural waters. Iron concentrations ranged from 258 to 1,020 ppb. Zinc concentrations ranged from 97 to 340 ppb above the depth of 253 ft and from 39 to 60 ppb below 253 ft. The elevated concentrations of iron and zinc may be related to the placement of metallurgical wastes in a former disposal pond at the site.

Volatile organic compounds (VOC's) were detected throughout the vertical extent of the Galena-Platteville aquifer beneath the site. Concentrations of VOC's were highest near the top of the aquifer (41.1-56.6 ft). The predominant compounds were TCE (1,300 ppb) and 1,1,1-TCA (900 ppb). Concentrations of VOC's were lowest (TCE, 5-20 ppb; 1,1,1-TCA, 4-8 ppb) in the deep sample intervals in the aquifer (about 145-301 ft). Water samples were collected from the fully penetrating pumped well near the beginning and end of the aquifer test. Concentrations of TCE and 1,1,1-TCA were 21 and 15 ppb, respectively, after 450 gal of water were pumped; and 6 and 3 (estimated) ppb, respectively, after 30,000 gal were pumped. The vertical distribution of VOC's in the aquifer indicated that the fissure and fracture network in the aquifer may affect their distribution.

REFERENCES CITED

Berg, R.C., Kempton, J.P., and Stecyk, A.N., 1984, Geology for planning in Boone and Winnebago Counties: Illinois State Geological Survey Circular 531, 69 p.

Boulton, N.S., 1963, Analysis of data from non-equilibrium pumping tests allowing for delayed yield from storage: Proceedings of the Institute of Civil Engineers, v. 26, p. 469-482.

Boulton, N.S., and Streltsova, T.D., 1978, Unsteady flow to a pumped well in a fissured aquifer with a free surface level maintained constant: Water Resources Research, v. 14, no. 3, p. 527-532.

Boulton, N.S., and Streltsova-Adams, T.D., 1978, Unsteady flow to a pumped well in an unconfined fissured aquifer: Journal of Hydrology, v. 37, p. 349-363.

Bouwer, Herman, and Rice, R.C., 1976, A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells: Water Resources Research, v. 12, no. 3, p. 423-428.

Compton, R.R., 1962, Manual of field geology: New York, John Wiley and Sons, 378 p.

Cooper, H.H., Jr., and Jacob, C.E., 1946, A generalized graphical method for evaluating formation constants and summarizing well-field history: American Geophysical Union Transactions, v. 27, p. 526-534.

Folk, R.L., 1974, Petrology of sedimentary rocks: Austin, Tex., Hemphill, 182 p.

Foote, G.R., 1980, Fracture analysis in northeastern Illinois and northwestern Indiana: Urbana, Ill., University of Illinois, unpublished Master's thesis, 193 p.

Freeze, R.A., and Cherry, J.A, 1979, Groundwater: Englewood Cliffs, N.J., Prentice-Hall, 604 p.

Hantush, M.S., 1959, Nonsteady flow to flowing wells in leaky aquifers: Journal of Geophysical Research, v. 64, p. 1043-1052.

Hem, J.D., 1985, Study and interpretation of the chemical characteristics of natural water (3d ed.): U.S. Geological Survey Water-Supply Paper 2254, 263 p.

Illinois Environmental Protection Agency, 1989, Remedial investigation feasibility study, site investigations work plan, Parson's Casket Hardware site, Belvidere, Illinois: Springfield, Ill. [unnumbered pages].

Kay, R.T., Olson, D.N., and Ryan, B.J., 1989, Hydrogeology and results of aquifer tests in the vicinity of a hazardous-waste disposal site near Byron, Illinois: U.S. Geological Survey Water-Resources Investigations Report 89-4081, 56 p.

Lohman, S.W., 1979, Ground-water hydraulics: U.S. Geological Survey Professional Paper 708, 70 p.

Mills, P.C., 1993a, Vertical distribution of hydraulic characteristics and water quality in three boreholes in the Galena-Platteville aquifer at the Parson's Casket Hardware Superfund site, Belvidere, Illinois, 1990: U.S. Geological Survey Open-File Report 93-402, 36 p.

----- 1993b, Hydrogeology and water quality of the Galena-Platteville aquifer at the Parson's Casket Hardware Superfund site, Belvidere, Illinois, 1991-92: U.S. Geological Survey Open-File Report 93-404, 29 p.

Niva, Borje, 1991, Results from borehole radar tests at Parsons Casket Superfund site: Mala, Sweden, Abem AB, 16 p.

Rushton, K.R., 1985, Interference due to neighboring wells during pumping tests: Ground Water, v. 23, no. 3, p. 361-366.

Schumacher, D.A., 1990, The hydrogeology of the Galena-Platteville dolomite in De Kalb and Kane Counties, northeastern Illinois: De Kalb, Ill., Northern Illinois University, unpublished Master's thesis, 173 p.

Science Applications International Corporation, 1990a, Remedial investigation/feasibility study, Phase 2 site investigations work plan, Parson's Casket Hardware site, Belvidere, Illinois: Illinois Environmental Protection Agency, 24 p.

Science Applications International Corporation, 1990b, Quality assurance project plan, remedial investigation/feasibility study, phase 2, Parson's Casket Hardware site, Belvidere, Illinois: Illinois Environmental Protection Agency [variously paged].

Suter, Max; Bergstrom, R.E.; Smith, H.F.; Emrich, G.H.; Walton, W.C.; and Larson, T.E., 1959, Summary.--preliminary report on ground-water resources of the Chicago region, Illinois: Illinois State Water Survey Cooperative Groundwater Report 1-5, 18 p.

Theis, C.V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: Transactions of the American Geophysical Union, v. 16, p. 519-524.

Vanderpool, Luanne, and Yeskis, Douglas, 1991, Parson's Casket, Belvidere, Illinois, hydrogeologic testing: U.S. Environmental Protection Agency, Region 5 Technical Support Unit Report, 7 p. with appendixes.

Voelker, D.C., Oberg, D.J., and Grober, M.J., 1988, Water-quality data from the observation-well network in Illinois, 1985-87: U.S. Geological Survey Open-File Report 87-538, 725 p.

Willman, H.B.; Atherton, Elwood; Buschbach, T.C.; Collinson, Charles; Frye, J.C.; Hopkins, M.E.; Lineback, J.A.; and Simon, J.A., 1975, Handbook of Illinois stratigraphy: Illinois State Geological Survey Bulletin 95, 261 p.

Willman, H.B., and Kolata, D.R., 1978, The Platteville and Galena Groups in northern Illinois: Illinois Geological Survey Circular 502, 75 p.

Woller, D.M., and Sanderson, E.W., 1974, Public groundwater supplies in Boone County: Illinois State Water Survey Bulletin 60-6, 12 p.

APPENDIXES 1-4

APPENDIX 1.--Core and cuttings log interpretations for well G115BD and borehole G127GP

Cores from well G115BD were collected continuously from 41.6 to 150.5 ft below land surface; the 1.75-in.-diameter cores were collected by the Illinois Environmental Protection Agency. Cores from borehole G127GP were collected continuously from 150.0 to 198.5 ft below land surface; the cores were 4.9 in. in diameter. Cuttings from borehole G127GP were collected after each 5 ft of drilling from 150.0 to 301.0 ft below land surface.

[Crystalline sizes follow the convention of Folk (1974, p. 167)]

Depth below land surface, in feet	Core or cutting description
	Well G115BD
41.6- 47.6	Dolomite, light-buff-gray; dense; bedding-plane partings common, beds commonly 1 in. thick, up to 6 in. thick; crystalline; vesicular with few small vugs (less than 0.5-in. diameter); rare fossils; iron-oxide banding and stains common
47.6- 66.6	Dolomite, light-buff-gray; dense; beds 1-6 in. thick, minor solution along bedding-plane surfaces; crystalline; very few small vugs (less than 0.5-in. diameter); rare fossils; iron-oxide banding and stains common
66.6- 81.6	Dolomite, light-buff-gray to light gray; dense; beds 1-6 in. thick, more solution along bedding planes than above interval with minor brown clay on bedding-plane surfaces; crystalline; vesicular with few small vugs (less than 0.5-in. diameter), rare pyritic infilling of vugs
81.6-150.5	Dolomite, light gray; dense; beds generally 1-8 in. thick; bedding fractured at 104-105 ft below land surface; solution along bedding planes common with minor brown clay on bedding-plane surfaces, solution quite evident at 123 ft below land surface (0.5-1 in. solution); stylolites; finely to medium crystalline; vesicular with vugs common to very common, few large vugs up to 2-in. diameter; fossil molds rare; chert nodules rare (1-1.5 in. diameter)

Depth below land surface, in feet	Core or cutting description
	Borehole G127GP
150.0-162.5	Dolomite, buff to light-gray; dense; beds generally 1-9 in. thick; solution along bedding planes common; stylolitic with brown clay partings; finely to medium crystalline; vesicular with vugs (up to 2-in. diameter) common; vug surfaces coarsely crystalline; bioturbated with worm borings; rare fossils (crinoids, brachiopod fragments)
162.5-173.0	Dolomite, buff to light-gray; dense; beds generally 4-18 in. thick; solution along bedding planes rare; stylolitic with brown clay partings; finely to medium crystalline; vesicular with vugs (up to 1-in. diameter) rare
173.0-188.3	Dolomite, buff to light-gray; dense; beds generally 1-6 in. thick; solution along bedding planes common; stylolitic with red to brown clay partings; finely to medium crystalline; vesicular with vugs (up to 2-in. diameter) common; vug surfaces coarsely crystalline with fine grained pyrite infilling some vugs; bioturbated with worm borings; rare fossil casts and molds (gastropods, brachiopods); chert nodules rounded and flattened, light gray with some dark gray laminations; some nodules up to 6 in. thick; highly fractured chert layer at 185 ft below land surface
188.3-198.5	Calcitic dolomite, buff to light-gray; some buff mottling, uppermost 0.3 ft light gray with medium-gray banding; dense; beds generally 3-10 in. thick; solution along bedding planes rare to common; stylolitic with red to brown clay partings; finely to medium crystalline; vesicular with small vugs rare to common; few vugs infilled with fine-grained pyrite; bioturbated with rare fossils (ribbon bryozoans on bedding-plane surfaces, casts and molds of gastropods and brachiopods)
200.0-215.0	Dolomite, buff to light-gray; rare white chert
215.0-220.0	Dolomite, buff; rare gray chert
220.0-225.0	Dolomite, light-gray to buff; common white chert

Depth below land surface, in feet	Core or cutting description
	Borehole G127GP--Continued
225.0-240.0	Dolomite, buff; rare to common light-gray chert
240.0-245.0	Dolomite, light-gray to buff
245.0-258.0	Calcitic dolomite, buff, medium-gray (mottled); rare to common thin shards of red, brown shale; fractured at about 248 ft below land surface
258.0-264.0	Calcitic dolomite, medium-gray, dark-gray, buff (mottled); strongly fractured
264.0-270.0	Dolomite, buff to light- or dark-gray; argillaceous
270.0-301.0	Dolomite, medium-buff to medium-gray; rare to common thin shards of brown or dark-brown shale

APPENDIX 2.--Geophysical log interpretations for wells G115BD, G125BD, G126BD, and borehole G127GP

Depth below land surface, in feet	Geophysical log interpretations
	Well G115BD
	3-arm caliper
37.5- 38.6	Cavity, borehole diameter increases by as much as 2 in.; possible washout zone at the base of the surface casing
38.6- 43.6	Somewhat irregular surface; borehole has closely spaced increases in hole diameter; diameter increases by as much as 0.3 in. at 41.1-43.6 ft below land surface
43.6- 68.6	Generally smooth surface; infrequent small increases in borehole diameter
68.6- 81.1	Smooth surface
81.1- 96.1	Somewhat irregular surface; very small, closely spaced increases in borehole diameter
	Natural gamma
37.5- 96.1	Very low levels of radiation consistent with carbonate rocks with small amounts of clay; small increases in radiation detected at about 67.5, 80, and 95 ft below land surface
	Spontaneous potential (SP)
37.5- 47.1	Low SP, increasing with depth; corresponding possibly to the change in borehole diameter from the cased section of the borehole to the washout(?) interval immediately below the surface casing and to a change in lithology (weathered to unweathered bedrock?)
47.1- 78.6	SP higher relative to interval 37.5-47.1 ft below land surface; SP generally constant with depth; indicates change in lithology (extent of dolomitization?)

Depth below land surface, in feet	Geophysical log interpretations
	Well G115BD--Continued
	Spontaneous potential (SP)--Continued
78.6- 96.6	SP decreases slightly relative to interval 47.1-78.6 ft below land surface; generally constant with depth; indicates change in lithology (extent of dolomitization?)
	Single-point resistance
37.5- 47.1	Pronounced resistance increase and decrease; corresponding in part to the change in borehole diameter from the cased section to the washout(?) interval immediately below the surface casing and to a change in lithology (weathered to unweathered bedrock?)
47.1- 96.6	Resistance generally constant to slightly decreasing over the length of the interval; lithology may differ slightly from interval 37.5-47.1 ft below land surface (extent of weathering, dolomitization, and (or) degree of porosity?)
	Well G125BD
	3-arm caliper
31.1- 41.1	Somewhat irregular surface; thin, closely spaced increases in hole diameter; indication of two thin intervals of bedding-plane solution at 33.6 and 35.6 ft below land surface, apparent apertures 0.5 ft and horizontal extents 0.25 and 0.15 in., respectively
41.1- 84.1	Generally smooth borehole wall
84.1-148.6	Generally smooth surface; periodic small increases in borehole diameter (small bedding-plane solution features?)

Depth below land surface, in feet	Geophysical log interpretations
	Well G125BD--Continued
	Natural gamma
31.1-148.4	Low levels of radiation consistent with carbonate rocks with limited clay; prominent increase in radiation detected at about 120.8 ft below land surface
	Spontaneous potential (SP)
31.1- 43.6	Low SP, increasing with depth; corresponds in part to the change in borehole diameter from the cased to uncased sections of the borehole and to a change in lithology (weathered to unweathered bedrock?)
43.6- 78.6	SP increased relative to interval 31.1-43.6 ft below land surface; indicates change in lithology (extent of weathering and (or) dolomitization?)
78.6-146.6	SP increased relative to interval 43.6-78.6 ft below land surface; indicates change in lithology (extent of dolomitization?); pronounced increase in SP (permeability) at about 119.8 ft below land surface
	Single-point resistance
31.1- 46.6	Low resistance, low amplitude and short wave length of oscillations relative to interval 46.6-78.6 ft below land surface; indicates in part the change in borehole diameter from the cased to uncased sections of the borehole, and a change in lithology (extent of weathering?)
46.6- 78.6	Increase in resistance relative to interval 31.1-46.6 ft below land surface; increase in amplitude and wave length of oscillations relative to intervals 31.1-46.6 and 78.6-147.6 ft below land surface; indicates change in lithology (extent of weathering, dolomitization, and (or) degree of porosity?)

Depth below land surface, in feet	Geophysical log interpretations
	Well G125BD--Continued
	Single-point resistance--Continued
78.6-147.6	Resistance generally equivalent to interval 46.6-78.6 ft below land surface, decrease in amplitude and wave length of oscillations; indicates change in lithology (extent of dolomitization or degree of porosity?); slight decrease resistance at about 115.6 ft below land surface that may correlate with peaks on natural-gamma and SP logs
	Well G126BD
	3-arm caliper
29.5- 31.0	Cavity; borehole diameter increases by as much as 3 in.; possible washout interval below base of surface casing
31.0- 81.0	Very smooth surface; possible very small bedding-plane solution features at about 33.8 and 35.8 ft below land surface
81.0-150.6	Generally smooth borehole wall; periodic small increases in borehole diameter; notable increases representing possible bedding-plane solution at about 108.6 to 109.6 ft below land surface (apparent borehole diameter increase is about 0.3 in.), 110.6 ft below land surface (apparent borehole diameter increase is about 0.5 in.), and 122.0 ft below land surface (apparent borehole diameter increase is about 0.3 ft)
	Natural gamma
29.5-150.4	Low levels of radiation consistent with carbonate rocks with small amounts of clay; substantial increase in radiation detected at about 122.6 ft below land surface

Depth below land surface, in feet	Geophysical log interpretations
	Well G126BD--Continued
	Spontaneous potential (SP)
31.1- 48.6	Low SP, increasing with depth; corresponds in part to the change in borehole diameter from the cased to uncased sections of the borehole, and to a change of lithology (extent of weathering?)
48.6- 78.6	SP increased relative to interval 31.1-48.6 ft below land surface; indicates change in lithology (extent of weathering and (or) dolomitization?)
78.6-150.4	SP increased relative to interval 48.6-78.6 ft below land surface; indicates change in lithology (extent of dolomitization?); gradual increase in SP below about 105 ft below land surface, peak increase at about 110 ft below land surface; sharp increase in SP at about 121.8 ft below land surface, indicates interval of increased permeability (bedding-plane solution?)
	Single-point resistance
31.1- 81.0	Resistance slightly lower, increased amplitude and wave length of oscillations relative to interval 81.0-150.6 ft below land surface; indicates change in lithology (extent of dolomitization or degree of porosity?)
81.0-150.6	Resistance slightly higher, decreased amplitude and wave length of oscillations relative to interval 31.0-150.6 ft below land surface; indicates change in lithology (extent of dolomitization or degree of porosity); small decreases in resistance at about 111.6 and 122.8 ft below land surface, correlate with natural-gamma and SP increases
	Borehole G127GP
	3-arm caliper
41.2- 54.2	Somewhat irregular surface; borehole has closely spaced increases in diameter, apparent increase of 0.2 in.

Depth below land surface, in feet	Geophysical log interpretations
	Borehole G127GP--Continued
	3-arm caliper--Continued
54.2- 81.0	Generally smooth surface; few increases in borehole diameter, most notable 0.1-0.2 in. at about 67 ft below land surface
81.0-160.0	Irregular surface with closely spaced increases in borehole diameter about 0.1-0.2 in.; most notable increases (by as much as 0.5 in.) at about 111, 130, 145, and 156 ft below land surface (indicating bedding-plane solution?)
160.0-177.0	Smooth surface
177.0-190.0	Irregular surface with closely spaced increases in borehole diameter about 0.1-0.2 in.; most notable increase (by as much as 0.4 in.) at about 180 ft below land surface (indicating bedding-plane solution?)
190.0-229.0	Generally smooth surface with small, infrequent increases in borehole diameter; gradual reduction in borehole diameter by about 0.1 in. starting about 209 ft below land surface
229.0-300.0	Irregular surface with more widely spaced increases and decreases in borehole diameter; borehole diameter continues to decrease by as much as about 0.6 in.; bedding-plane solution(?) at about 248 ft below land surface, aperture about 0.5 ft and apparent horizontal extent about 0.15 in. (borehole diameter increases about 0.3 in.); extensive bedding-plane solution at about 259 ft below land surface, aperture about 1 ft and apparent horizontal extent about 0.4 in.
	Natural gamma
41.2-140.0	Low levels of radiation consistent with carbonate rocks with small amounts of clay; increase in radiation detected at about 121 ft below land surface

Depth below land surface, in feet	Geophysical log interpretations
	Borehole G127GP--Continued
	Natural gamma--Continued
140.0-200.0	Low levels of radiation; radiation greater than in interval 41.2-140.0 ft below land surface, indicating increased clay or other gamma-emitting constituents
200.0-260.0	Low levels of radiation; radiation greater than in interval 140.0-200.0 ft below land surface, indicating increased clay or other gamma-emitting constituents
260.0-300.0	Low to medium levels of radiation (maximum of about 4.5 times background); radiation greater than in interval 200.0-260.0 ft below land surface, indicating increased clay or other gamma-emitting constituents
	Spontaneous potential (SP)
45.2-121.0	Low SP, increasing with depth
121.0-301.0	SP slightly increased relative to interval 45.2-121.0 ft below land surface; indicates change in lithology (extent of dolomitization?); SP increase (small peak) at about 121.0 ft below land surface; SP increase from about 254.0-265.0 ft below land surface, peak(s) at about 260.0 ft below land surface, indicates possible change in lithology, bedding-plane solution or fluid movement into or out of the formation
	Single-point resistance
47.0- 78.0	Increase in resistance with depth; indicates change in lithology (extent of dolomitization or degree of porosity?) relative to interval 78.0 to 159.0 ft below land surface

Depth below land surface, in feet	Geophysical log interpretations
	Borehole G127GP--Continued
	Single-point resistance--Continued
78.0-159.0	Increase in resistance relative to interval 47.0-78.0 ft below land surface; indicates change in lithology (extent of dolomitization or degree of porosity?)
159.0-301.0	Slight increase in resistance relative to interval 78.0-159.0 ft below land surface; indicates change in lithology (extent of dolomitization or degree of porosity?); reduced resistance at about 260 ft below land surface, correlates with peaks in 3-arm caliper, SP, and natural-gamma logs
	Temperature
48.0- 89.0	Reduction in water temperature by about 0.2°C; gradient about 4.9×10^{-3} °C/ft; water temperature influenced by ambient air temperature
89.0-261.0	Reduction in water temperature by about 0.075°C; gradient about 4.4×10^{-4} °C/ft
261.0-301.0	Sharp reduction in water temperature of about 0.2°C starting about 261.0 ft below land surface; gradient about 5.0×10^{-3} °C/ft

APPENDIX 3.--Borehole ground-penetrating radar interpreted reflectors from borehole G127GP

[Table modified from Niva (1991, table 3.1, p. 10)]

Depth below land surface, in feet	Type of reflector	Dip angle, in degrees	Dip orientation	Strike orientation
106.6	Fracture[1]	50.1	Not determined	Not determined
124.7	Bedding-plane fissure	5.0	N. 60° E.	N. 30° W
187.0	Fracture	37.2	Not determined	Not determined
202.0	Fracture	42.0	Not determined	Not determined
212.6	Bedding-plane fissure	0.0	Not determined	Not determined
262.8	Bedding-plane fissure	7.0	N. 50° E.	N. 40° W.

[1] Interpreted as a bedding-plane fissure in acoustic-televiewer log.

APPENDIX 4.--Downhole-camera log interpretations for wells G115BD, G125BD, G126BD, and borehole G127GP

[Crystalline sizes follow the convention of Folk (1974, p. 167)]

Depth below land surface, in feet	Borehole characteristics
	Well G115BD
37.5- 40.0	Cavity, borehole diameter increases; possible washout zone at the base of the surface casing
40.0- 67.6	Generally smooth surface; rare to common small (less than 0.25-in.-diameter) vugs; fine to medium crystalline; massive bedding
67.6- 71.2	Somewhat irregular surface; fine to medium crystalline; massive bedding
71.2- 90.8	Generally smooth surface; rare to common small (less than 0.25-in.-diameter) vugs; fine to medium crystalline; massive bedding
90.8-120.8	Generally smooth surface; rare to common small (less than 0.25-in.-diameter) vugs; rare thin (less than 0.1-in.-thick) bedding-plane solution features; fine to medium crystalline; massive bedding
	Well G125BD
31.3- 31.8	Weathered bedrock; poorly sorted with sub-angular, granular dolomite intermixed (about 50 percent) with finer grained sand- and silt-sized particles
31.8- 40.0	Somewhat irregular surface; common thin (less than 0.25-in.-thick) bedding-plane solution features or fractures; fine to medium crystalline
40.0-119.0	Generally smooth surface with rare to common, small (less than 0.25-in.-diameter) vugs; vugs infilled with sparry calcite at 80 ft below land surface; rare thin (less than 0.1-in-thick) bedding-plane solution features with thin fissure at about 109 ft below land surface; fine to medium crystalline; massive bedding

APPENDIX 4.--Downhole-camera log interpretations for wells G115BD, G125BD, G126BD, and borehole G127GP--Continued

Depth below land surface, in feet	Borehole characteristics
	Well G126BD
50.0-105.0	Generally smooth surface; rare small (less than 0.25-in.-diameter) vugs; fine to medium crystalline; massive bedding
105.0-115.0	Somewhat irregular surface; common small (less than 0.25-in.-diameter) vugs; fine to medium crystalline; massive bedding
115.0-122.0	Generally smooth; small (less than 0.25-in.-diameter) vugs; fine to medium crystalline; massive bedding
	Borehole G127GP
41.0- 57.0	Generally smooth surface; rare small (less than 0.25-in.-diameter) vugs; fine to medium crystalline; massive bedding
57.0- 82.0	Generally smooth surface; rare to common small (less than 0.25-in.-diameter) vugs; rare vugs up to 1-in. diameter; fine to medium crystalline; massive bedding
82.0-110.0	Somewhat irregular surface; rare to increasingly common, small (less than 0.25-in.-diameter) vugs; rare to common vugs up to 1-in. diameter; medium crystalline; massive bedding with rare bedding planes evident
110.0-117.0	Increasingly irregular surface; common small (less than 0.25-in.-diameter) vugs; rare to common vugs up to 1.5-in. diameter; rare fossil molds; medium crystalline; chert nodules at 111 ft below land surface; massive bedding
117.0-125.0	Irregular surface; common small (less than 0.25-in.-diameter) vugs; rare to common vugs up to 1.5-in. diameter; rare to common fossil molds; medium to coarsely crystalline; massive bedding

APPENDIX 4.--Downhole-camera log interpretations for wells G115BD, G125BD, G126BD, and borehole G127GP--Continued

Depth below land surface, in feet	Borehole characteristics
	Borehole G127GP--Continued
125.0-130.0	Somewhat irregular surface; rare to common small (less than 0.25-in.-diameter) vugs; fine to medium crystalline; massive bedding