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

By Patrick C. Mills

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
foot per foot (ft/ft)	0.3048	meter per meter
foot per day (ft/d)[1]	0.3048	meter per day
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
part per billion (ppb)	1.00	microgram per liter

Sea level: In this report, "sea level" refers to the 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]In this report, foot per day is used as the mathematically reduced form of cubic feet per day per square foot of aquifer cross-sectional area.

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ABSTRACT

The U.S. Geological Survey 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 first phase of the investigation, from August through December 1990.

A packer assembly was used to isolate various depth intervals in three 150-foot-deep boreholes in the dolomite aquifer. Aquifer-test data include vertical distributions of vertical hydraulic gradient, horizontal hydraulic conductivity (K), and response of water levels in observation wells to borehole pumping. Water-quality data include vertical distributions of field-measured properties and laboratory determinations of concentrations of volatile organic compounds (VOC's).

Vertical hydraulic gradients in the aquifer were downward. The downward gradients ranged from less than 0.01 to 0.37 foot/foot. The largest gradient was associated with an elevated-K interval at 115 to 125 feet below land surface.

The hydraulic characteristics of strata within the aquifer seem to be generally consistent across the site. The strata can be subdivided into five hydraulic units with the following approximate depth ranges and K's: (1) a 1- to 5-foot-thick weathered surface at about 35 feet below land surface, 1-200 ft/d (feet per day); (2) 35-80 feet, 0.05-0.5 ft/d; (3) 80-115 feet, 0.5 ft/d; (4) 115-125 feet, 0.5-10 ft/d; and (5) 125-150 feet, 0.5 ft/d.

Water-level drawdowns were detected in one shallow bedrock observation well during pumping of some of the packed intervals in a nearby borehole, indicating that the degree of vertical connection between some intervals in the aquifer may be greater than that between others. During development pumping of one borehole, drawdowns were detected in a nearby well screened in the lower part of the overlying glacial-drift deposits, indicating hydraulic connection between the glacial drift aquifer and the bedrock aquifer.

VOC's were detected throughout the upper half (about 150 feet) of the bedrock aquifer beneath the site. The detected compounds were predominantly chlorinated ethenes and ethanes (maximum concentration was 570 ppb (parts per billion) of trichloroethylene. There was a positive correlation between concentrations of VOC's, specific conductance, and K.

The distribution of VOC concentrations indicate that the low-K dolomite beds in the Galena-Platteville aquifer may impede the downward migration of the VOC's and that the high-K beds and fissures may provide pathways for the lateral migration of VOC's through the aquifer. Contaminant migration is possibly affected by ground-water flow through vertical fractures that connect shallow beds with deeper beds in the aquifer, thus explaining the detections of some VOC species at intermittent depths.

INTRODUCTION

The Parson's Casket Hardware site in Belvidere, Boone County, Ill. (figs. 1 and 2), has been designated a Superfund site under the U.S. Environmental Protection Agency's (USEPA) Comprehensive Environmental Response, Compensation, and Liability Act program. Investigations of hydrogeology and contaminant migration at the site have been done by the Illinois Environmental Protection Agency (IEPA) and USEPA since 1984 (Science Applications International Corporation, 1990). The most recent investigation was done in 1990 by IEPA and USEPA as part of the remedial investigation/feasibility study phase 2 site investigation (Science Applications International Corporation, 1990). Previous investigations generally have been limited to evaluation of the hydrogeology and contaminant distribution in the surficial glacial drift aquifer. As part of the site investigation, the USEPA requested that the U.S. Geological Survey (USGS) investigate contaminant migration in the bedrock aquifer, the Galena-Platteville aquifer, which immediately underlies the glacial drift aquifer (fig. 3). Results of the USGS investigation will be used to improve definition of the vertical and horizontal extent of contamination in the Galena-Platteville aquifer and to develop strategies for effective aquifer remediation.

The USGS investigation was done in several phases. The first phase of the investigation, reported herein, determined the vertical distribution of horizontal hydraulic conductivity (K) and concentrations of volatile organic compounds (VOC's) in three boreholes that partially penetrate the Galena-Platteville aquifer. The second and third phases provided hydraulic and water-quality data from a borehole that fully penetrates the Galena-Platteville aquifer, hydraulic data from a multiple-well aquifer test of the Galena-Platteville aquifer, and water-quality data from the underlying St. Peter Sandstone aquifer (fig. 3) (Mills, 1993a, 1993b).

This report presents and interprets data collected during the first phase of the USGS investigation at the Parson's Casket Hardware site, from August through December 1990. Included in the report are data on the vertical distributions of K and concentrations of VOC's in the Galena-Platteville aquifer, as determined at three borehole locations. Also included are information on the responses of water levels in nearby observation wells to borehole pumping and the vertical distributions of vertical hydraulic gradient and water-quality field measurements (pH, temperature, specific conductance, and Eh) in the aquifer.

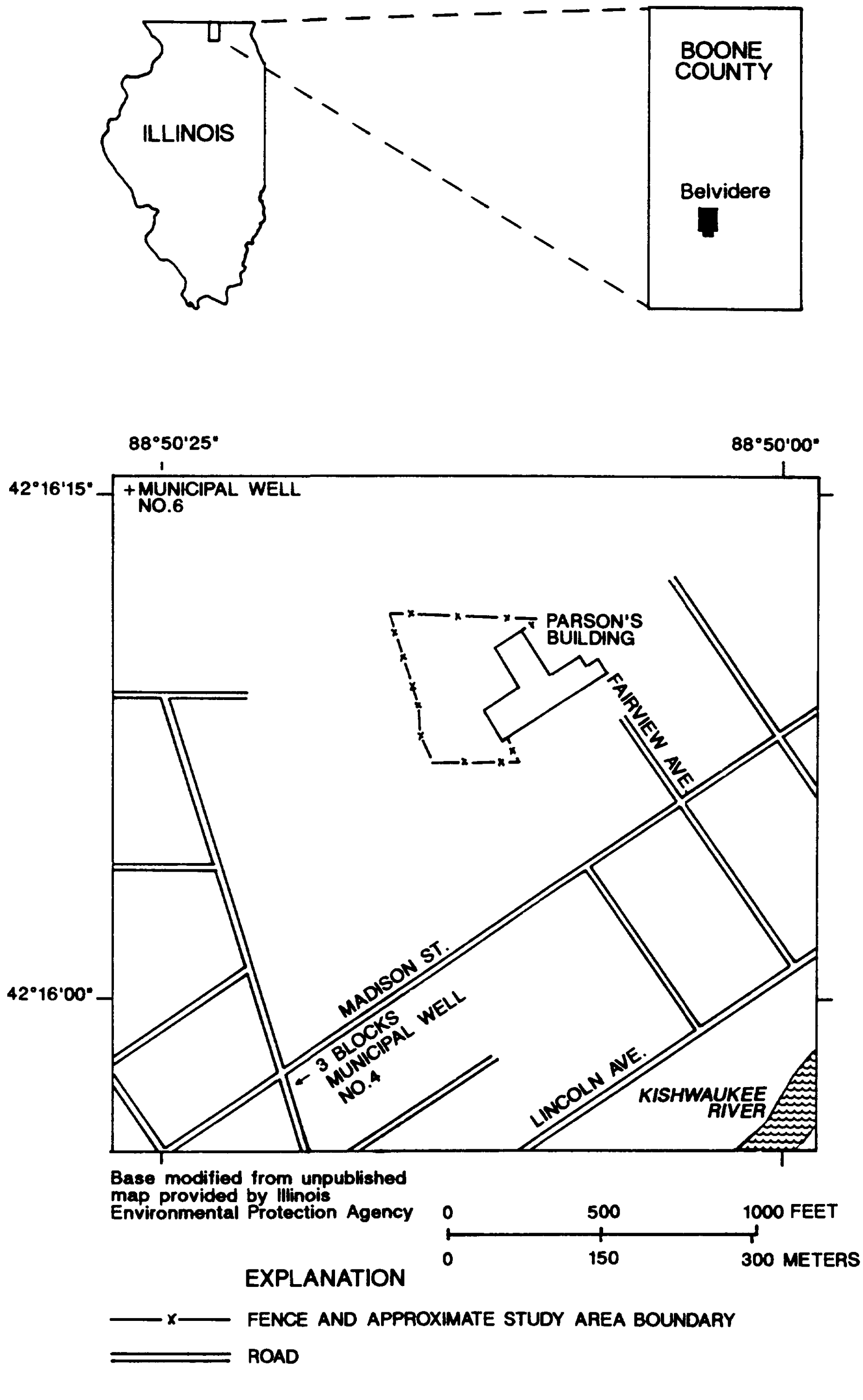
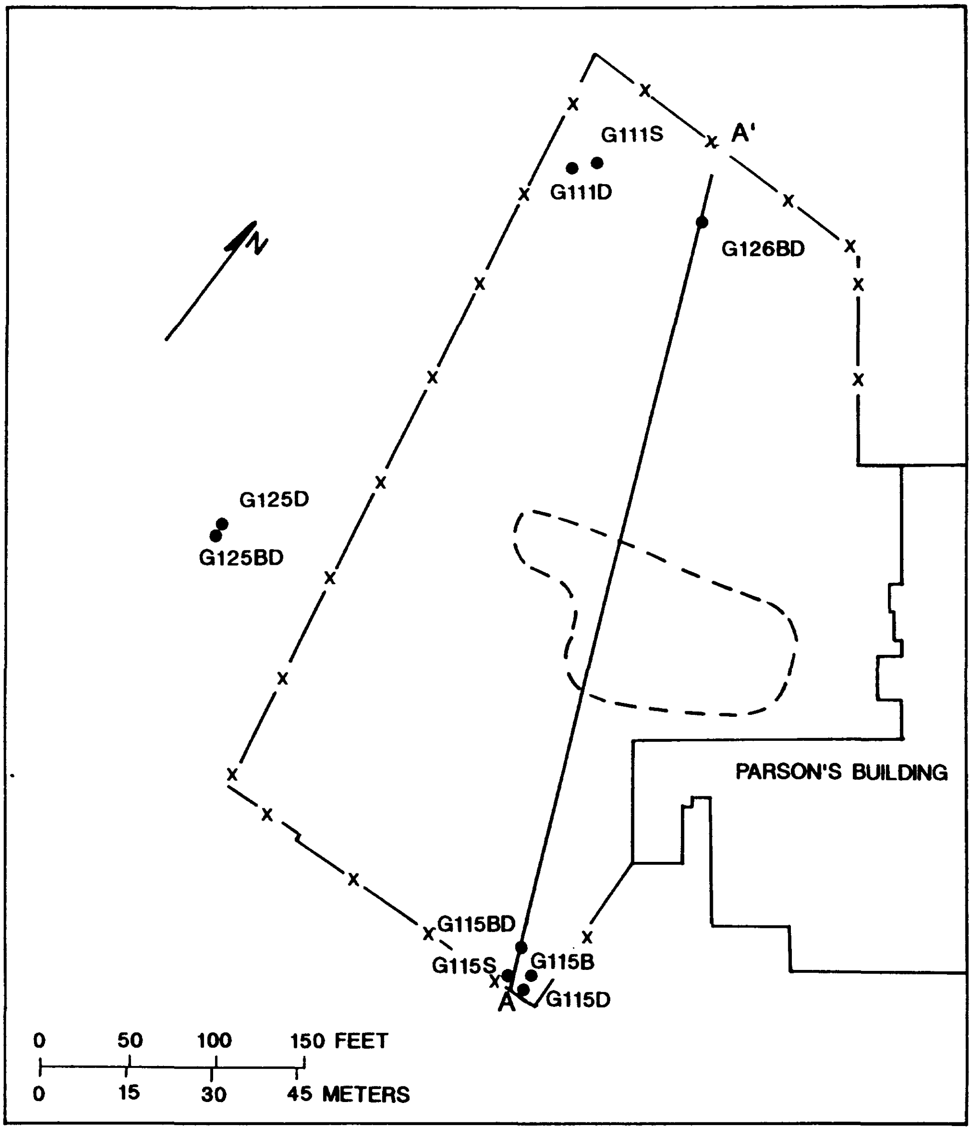


Figure 1.--Location of Parson's Casket Hardware Superfund site.



Base modified from unpublished map provided by Illinois Environmental Protection Agency

EXPLANATION

—x— FENCE AND APPROXIMATE STUDY-AREA BOUNDARY

– – – – – APPROXIMATE LOCATION OF FORMER WASTE-DISPOSAL POND

A——A' LINE OF SECTION

G115BD ● BOREHOLE OR WELL AND DESIGNATION

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

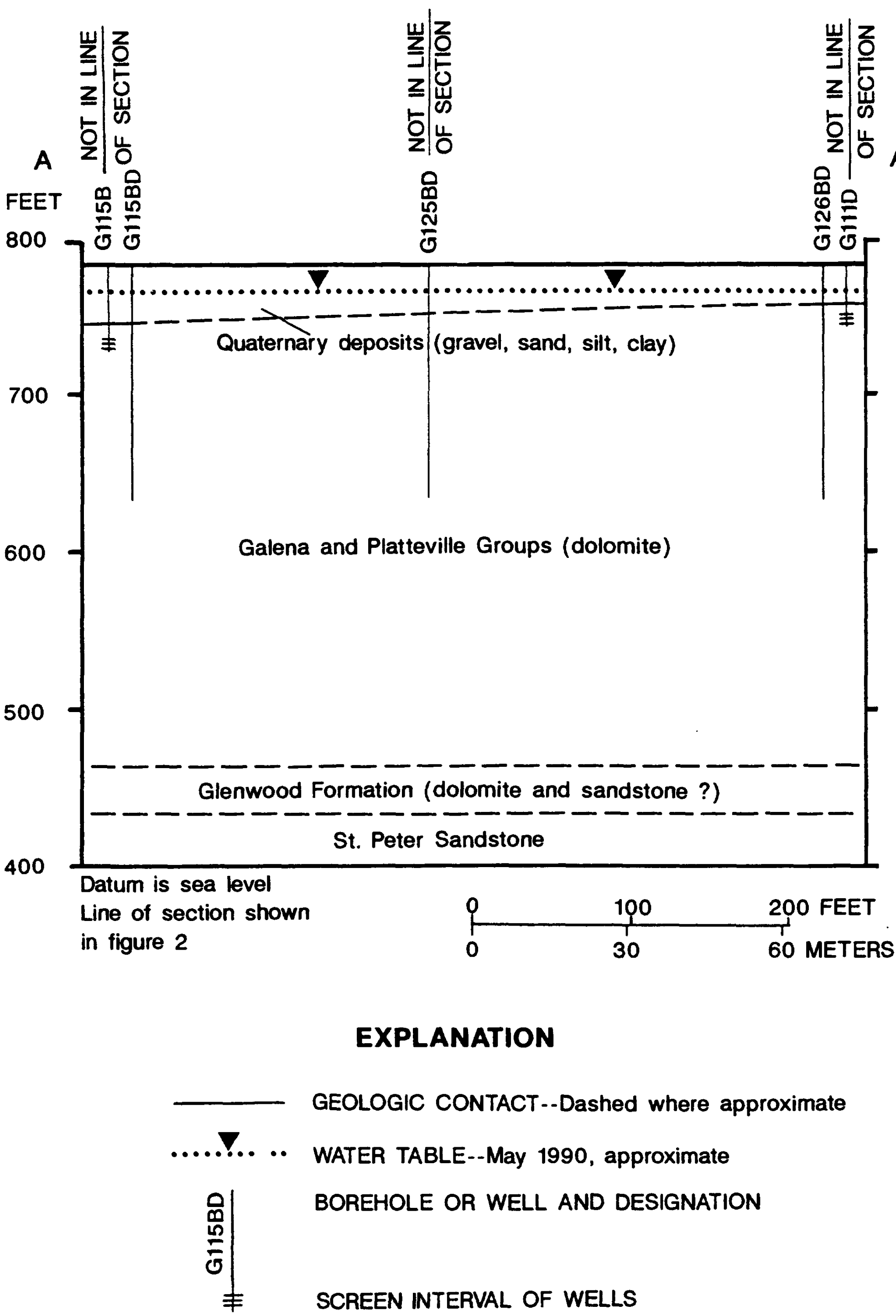


Figure 3.--Geologic section A-A' through the study site.

DESCRIPTION OF SITE

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. The Kishwaukee River is about 0.5 mi south of the site. Land surface at the site is virtually flat; land-surface altitudes near the site range from about 782 to 785 ft above sea level.

Hydrogeologic Setting

Quaternary hydrogeology presented in this report is the interpretation of the IEPA (Science Applications International Corporation, 1990). General descriptions of the bedrock hydrogeology are from Berg and others (1984), Willman and others (1975), and Willman and Kolata (1978). 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 uppermost geologic deposits at the site are glacial-drift deposits of Quaternary Age. The 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, Grayslake Peat, and Cahokia Alluvium. Clayey silt infills the site of an excavated waste-disposal pond (fig. 2). The glacial-drift deposits range in thickness from about 25 to 40 ft.

Fluvioglacial silt, sand, and gravel associated with the Belvidere Till Member and the Mackinaw Member compose a surficial aquifer. Where deposits of the Nimitz Till Member are present, localized semiconfined conditions are reported to exist within the aquifer (Science Applications International Corporation, 1990).

The Galena Group of Ordovician age is the uppermost bedrock unit beneath the study site (fig. 3). The Galena Group and the underlying Platteville Group, also of Ordovician age, generally are considered a single aquifer because of their similar hydraulic and lithologic properties and are referred to collectively as the "Galena-Platteville aquifer" (and where applicable, the "Galena-Platteville dolomite").

The Galena Group is a medium- to coarse-grained dolomite, part of which contain chert. Drill-rig response during drilling and rock-core inspection indicate that the upper surface of the Galena Group at the study site is weathered. The Platteville Group is a finely crystalline, dense, and partly argillaceous dolomite; its lower part may be sandy, and its upper part is cherty. The dolomite of the Galena and Platteville Groups was deposited as virtually horizontal beds a few inches to several feet thick. The beds are commonly visibly separated (parted) from overlying and underlying beds.

Driller's logs from Belvidere Municipal Wells No. 4 and No. 6 (well locations shown in fig. 1) indicate that Galena-Platteville dolomite is about 290 ft thick and that the base of the Platteville Group is about 320 ft below land surface (Woller and Sanderson, 1974, p. 7-8). Inclination (dip) of the dolomite bedrock is assumed to be virtually zero at the site scale.

The dolomite typically has extensive secondary permeability as a result of joints, fractures, bedding-plane partings, and solution openings. These features seem to be present in the dolomite beneath the study site, as indicated by geophysical-log data. The Galena-Platteville aquifer is a dependable source of ground water in most places and is capable of supplying moderate quantities of water for private wells. At the study site, the Galena-Platteville aquifer is immediately overlain by a glacial drift aquifer.

The Galena-Platteville dolomite is underlain by the Glenwood Formation of Ordovician age. The Glenwood Formation typically consists of shale, dolomite, and sandstone. In some localities the Glenwood Formation functions as a confining unit (Kay and others, 1989, p. 14); in other places, it is a source of small quantities of ground water. Driller's logs of the Belvidere municipal wells indicate that the Glenwood Formation is composed of dolomite and sandstone (Woller and Sanderson, 1974); the hydraulic characteristics of the formation are unknown in the vicinity of the study site. The base of the Glenwood Formation is about 345 to 380 ft below land surface.

Borehole and Well Network

Discrete-interval aquifer-test and water-quality data were collected from three boreholes (G115BD, G125BD, and G126BD) drilled through the glacial-drift deposits into the Galena-Platteville dolomite (table 1, fig. 1). The boreholes are about 6 in. in diameter and are cased through the glacial-drift deposits with 6-in.[1] polyvinyl chloride (PVC) tubing. The surface casings extend several feet into bedrock to depths of about 38, 31, and 29 ft for G115BD, G125BD, and G126BD, respectively. Each borehole is finished as an open hole in the dolomite to a depth of about 150 ft.

Logging the boreholes by downhole video camera indicated that the surface casing for borehole G115B may have been perforated at about 28 ft below land surface during rotary drilling of the bedrock. Aquifer tests or water-quality sampling in intervals open to the perforated section of the casing could be affected (tests in the open borehole and at the depth interval 37.5-40.0 ft) because of the possibility of direct hydraulic connection between the bedrock aquifer and the glacial drift aquifer. There seems to be little likelihood of a significant effect on the test data. Video analysis indicates that even if the casing is perforated, the perforation is small. Additionally, the casing exterior is surrounded by low-permeability portland-cement grout.

Logging of the boreholes with a three-arm caliper also indicated the possibility of "washout" (enlarged borehole diameter) at the base of the surface casing of borehole G115BD. Drilling and geophysical-log records indicate that the surface casing may only penetrate about 1 ft of the bedrock, which would locate the bottom of the surface casing at the interface between the weathered bedrock and the competent bedrock. Washout could have occurred if the surface casing had been inadequately sealed into the bedrock by grout. An inadequately sealed surface casing could affect the test data in a manner similar to that

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[1]Well-casing and other pipe sizes mentioned in this report are nominal inside diameters.

Table 1.--Description of boreholes and observation wells

Borehole or well number	Instal-lation date	Land-surface altitude, in feet above sea level	Total depth of hole, in feet below land surface[1]	Screened or open interval, in feet below land surface	Aquifer that well or borehole is open to
G111S	06-01-89	782.6	25.0	13.9- 24.4	Glacial drift
G111D	05-11-89	782.8	35.4	30.4- 35.4	Galena-Platteville
G126BD[2]	10-30-90	783.9	151.3	29.3-151.3	Galena-Platteville
G115S	06-06-89	782.3	20.6	9.6- 20.1	Glacial drift
G115D	05-15-89	782.2	37.8	32.8- 37.8	Glacial drift
G115B	05-23-89	782.3	49.0	43.6- 48.6	Galena-Platteville
G115BD[2]	10-11-90	782.5	150.8	37.5-150.8	Galena-Platteville
G125D	08-28-90	783.0	28.9	23.4- 28.4	Glacial drift
G125BD[2]	11-01-90	783.0	149.9	31.3-149.9	Galena-Platteville

[1] Total depth at time of sampling; depth may differ slightly from depth at time of drilling.

[2] Borehole; screened-interval entry represents open-borehole interval.

which would result from a perforated casing. Downhole video-camera logging of the borehole did not reveal glacial material near the bottom of the surface casing, indicating a tight seal between the surface casing and the bedrock.

Before data collection (1-3 days), each borehole was developed by lowering a pump to a depth of about 100 ft and pumping at a rate of about 10 gal/min; at least five well volumes were removed from each borehole.

Aquifer-test data also were collected at six observation wells (table 1) near the three bedrock boreholes (fig. 2). Two of the wells (G111D, G115B) were screened just below the upper surface (about 10 ft) of the bedrock aquifer, and four of the wells (G115S, G115D, G125D, G111S) were screened in the surficial glacial drift aquifer. The observation wells consisted of 2-in. stainless-steel risers (casings) and screens. Depths of the six observation wells ranged from about 21 to 49 ft.

METHODS OF STUDY

Aquifer-Isolation Procedures

A packer assembly (shown schematically in fig. 4) was used to isolate discrete intervals in the boreholes for aquifer testing and water-quality sampling. The packer assembly consisted of two 4- to 5-ft-long inflatable packers separated by an approximately 10-ft-long stainless-steel screen (pipe drilled with 0.5-in.-diameter holes). The packer assembly was lowered to a selected depth in a borehole with 2-in.-diameter drill-stem pipe, and the two packers were inflated against the borehole wall. Inflation of the two packers created three intervals--a packed interval between the two inflated packers, an interval above the upper packer, and an interval below the lower packer (fig. 4).

Packer-inflation pressures were determined by adding the packer-inflation pressure required at atmospheric pressure and the hydraulic pressure on a packer in the borehole; the determined pressure was increased by one-third to ensure that the packers were adequately inflated.

After both packers were fully inflated to isolate a particular interval, water levels in each of the three intervals were allowed to reach near static (within a few hundredths foot of static) to static levels before aquifer tests and water-quality sampling in a given packed interval. Water levels were measured by use of an electric measuring tape or monitored by pressure transducers.

Two measures were taken to ensure that the packed intervals were hydraulically isolated from the overlying and underlying intervals of the borehole during the aquifer tests and water-quality sampling. First, packer-inflation pressures were monitored continuously. Second, water levels were monitored above the packed interval, in the packed interval, and below the packed interval.

Packer-inflation pressures remained constant during all tests and samplings. With one exception, water levels above and below the packed interval did not change significantly during pumping. During tests in borehole G125BD, however, water level in the interval below the packed interval declined 4 ft when the packed interval was pumped 135.5 to 145.5 ft below land surface. The observed decline in water level in the below-packed interval from 149.4 to 149.9 ft below land surface is attributed to slow equilibration of hydraulic pressure in the short, low-K interval after packer inflation (water levels were declining very slowly) and not to hydraulic connection between the packed interval and the interval below because of inadequate packer inflation.

The aquifer tests and water-quality sampling were begun at the base of each borehole and continued at progressively shallower intervals (however, not all successive intervals were investigated in each borehole). Because land-surface elevations differ by as little as +/- 1 ft (table 1) at each of the tested boreholes and because bedding inclination appears to be minimal at the site scale, it was assumed that similar test-depth intervals in the three boreholes represent similar altitudes and stratigraphic horizons.

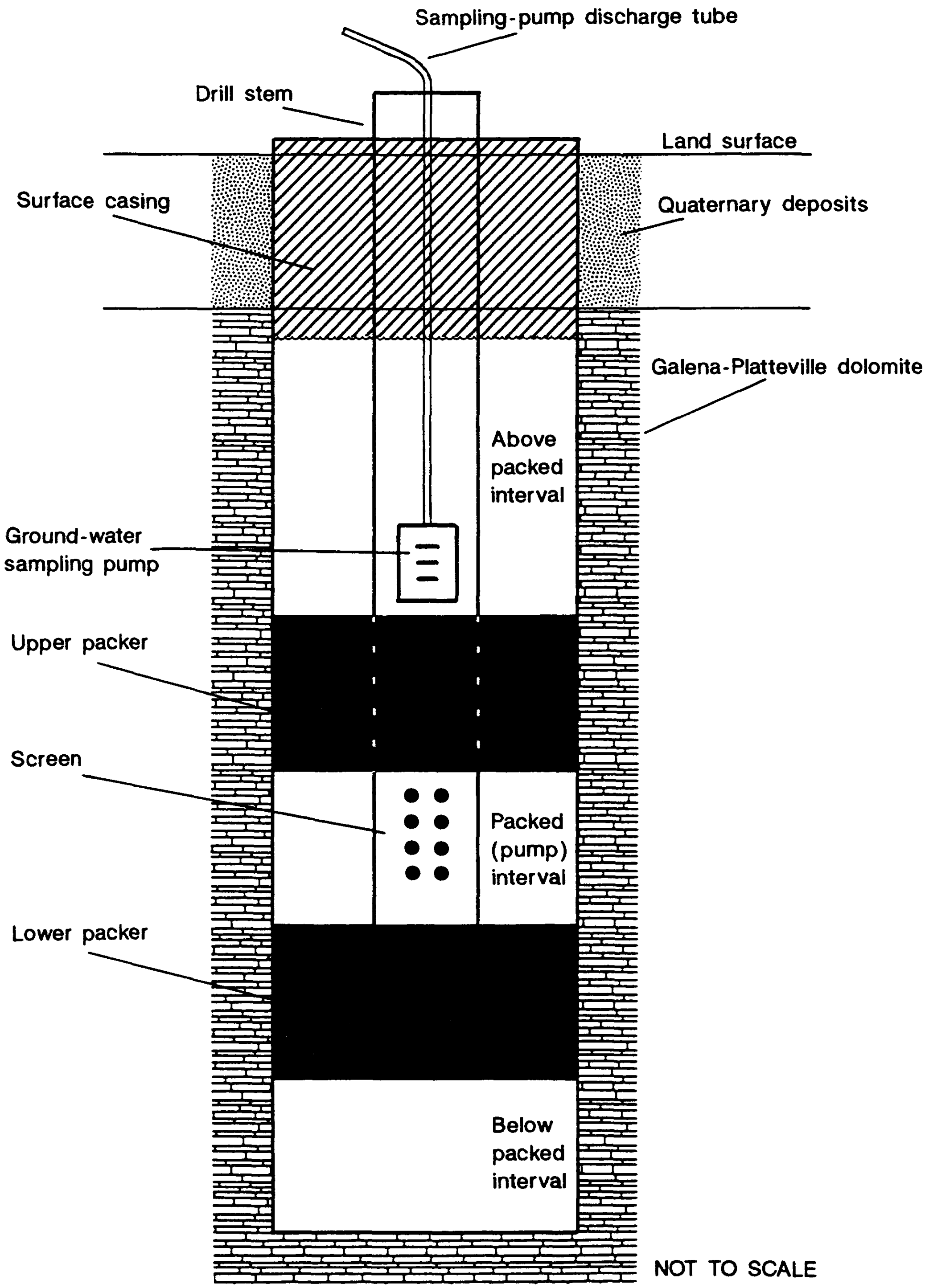

Figure 4.--Generalized view of the packer assembly and ground-water-sampling pump in a borehole.

The truck-mounted hoisting rig (used to lower the packer assembly down a borehole), all drill-stem pipe, and the packer assembly were decontaminated before and after use at each borehole by means of a high-pressure hot-water sprayer. The electric water-level measuring tape and pressure transducers were rinsed with soapy water followed by deionized water before and after each use.

Aquifer Tests

Water levels measured above, within, and below the packed interval in the boreholes were also used to determine static (or near static) vertical hydraulic gradients in the aquifer before the aquifer tests were done. The specific intervals were determined as follows: above the packed interval (base of the surface casing to top of upper packer), packed interval (base of the upper packer to top of lower packer), and below the packed interval (base of lower packer to base of borehole). Distances between the midpoint of the intervals were used to estimate the vertical hydraulic gradient--that is, the change in water level between intervals divided by the distance between intervals. For the analysis, it was assumed that the midpoint of each interval accurately represents water levels throughout the interval.

Horizontal hydraulic conductivity was estimated for each packed interval in the Galena-Platteville aquifer by means of the slug-test method described by Bouwer and Rice (1976) and the constant-discharge time-drawdown method of Cooper and Jacob (1946). Relative K for each packed interval was also estimated by means of a qualitative method based on drawdown in the pumped boreholes. Horizontal hydraulic conductivity was estimated by the Cooper and Jacob (1946) method and approximated by evaluating drawdown response during pumping (relative K) in order to provide hydraulic information for intervals in which there were no slug-test data and as verification of the K's estimated by the slug-test method.

The Bouwer and Rice (1976) aquifer-test method is appropriate for estimating K in partially and fully penetrating boreholes (and wells) in confined and unconfined aquifers. The value of K can be estimated from both increasing- and decreasing-head data (the tests are referred to as rising-head and falling-head tests, respectively) provided that the equilibrium water level is above the packed (screened) interval. In the Bouwer and Rice (1976) method, the aquifer is assumed to be a homogeneous, isotropic medium. This assumption may not be fully met at the study site. Because of the influence of secondary permeability, the Galena-Platteville aquifer is considered a heterogeneous, anisotropic aquifer (Kay and others, 1989, p. 1); however, the effect of this discrepancy on the slug-test results is considered to be minimal, because the aquifer can be assumed to be homogeneous and isotropic within the small spatial domain analyzed by the test. In cases where this assumption is less appropriate, such as for packed intervals that may include conductive fissures, the test is assumed to provide a reliable estimate of the "average" K of the interval.

Slug tests were done within each packed interval before sampling. A pressure transducer with a range of 0 to 10 lb/in^2 was lowered through the drill-stem pipe to about 10 ft below the water surface to determine water levels during the tests. A falling-head slug test then was done by rapidly lowering a weighted PVC slug into the water column. Water levels were recorded on a logarithmic time scale by a data logger. After water-level equilibration, a rising-head slug test was done. The slug was rapidly extracted from the water column and water levels allowed to recover to near static levels.

The PVC slug was washed with soapy water and rinsed with deionized water before and after each use. New polypropolene rope that was washed with soapy water and rinsed with deionized water was attached to the slug for each test.

The Cooper and Jacob (1946) aquifer-test method is best applied to analysis of K in extensive confined aquifers of uniform thickness and permeability in which fully penetrating wells are pumped. The method also requires sufficient aquifer stress (represented by sufficient duration and extent of drawdown) and discharge at a steady rate. Under favorable conditions, primarily no significant delayed yield, the method can be applied in unconfined aquifers with variable permeability in which partially penetrating wells are pumped. As with the Bouwer and Rice (1976) method, application of the Cooper and Jacob (1946) method is considered generally appropriate for estimating K in the Galena-Platteville aquifer. The spatial domain analyzed by the test was small (although larger than that analyzed by the slug tests) because of low pump-discharge rates (about 1 gal/min) and short discharge durations (about 100 minutes). Within the small spatial domain of the tests, the aquifer can be assumed to be homogeneous and isotropic and to have no significant delay in yield during pumping.

The use of the Cooper and Jacob (1946) aquifer-test method in this study, although assumed to be generally appropriate, should be considered semiquantitative. Constant discharge (pumping) rates were not rigorously maintained and recorded. A discharge rate of 1 gal/min, the maximum rate of the sampling pump used for the tests, is assumed in all calculations. This assumption generally is reliable for the first 30 minutes of pumping (within about 0.1 gal/min); beyond that time, discharge rates tended to decline slightly because of a drop in battery voltage to the pump.

The aquifer tests of Cooper and Jacob (1946) were done during pumping (purging) of the packed intervals before water-quality sampling. Water-level drawdown in the packed intervals was monitored during pumping, and water-level recovery was monitored after pumping was completed (for about 30 minutes). Water levels in the packed intervals were monitored by use of a pressure transducer with a range of 0 to 30 lb/in^2.

Relative K was estimated for each packed interval on the basis of the extent of drawdown during pumping. The method used in estimating relative K is explained in detail in the section "Hydraulic Conductivity." The method was feasible because the extent of drawdown during pumping of an aquifer is related, in part, to the K of the aquifer material, as indicated in this equation developed by Cooper and Jacob (1946, p. 528):

$$Kb = 2.303Q/4\pi\Delta s, \quad (1)$$

where K is hydraulic conductivity (L/T),
b is aquifer thickness (L),
Q is discharge of the well (V/T), and
Δs is difference in drawdown over one logarithmic cycle.

The K values were classified according to the following scheme: Packed 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 value of K; packed intervals in which the water level was drawn down to the pump-intake level when pumping at a constant rate of 1 gal/min, but not when pumping at a rate less than 1 gal/min, were assumed to have an intermediate value of K; and packed 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 value of K.

Water-Quality Sampling

Water samples were obtained from each packed interval by use of a submersible, positive-displacement pump consisting of a stainless-steel pump head and Teflon[2] tubing. During sampling, the pumping rate was less than 0.5 gal/min to minimize the loss of VOC's.

To ensure that representative aquifer water was sampled, investigators monitored pH, temperature, specific conductance, and Eh as water was purged from the boreholes. Field measurements were allowed to stabilize before water samples were collected. Grab samples were used for the above-listed field measurements during the August 1990 sampling; a water-quality monitor with a flow-through cell was used for the field measurements during the November-December 1990 sampling. The water-quality monitors were calibrated daily according to prescribed procedures.

Values for the field-measured properties of water quality were recorded after each one-half borehole (packed interval) volume was purged, beginning with the first borehole volume; purging was considered complete when stable values were recorded for three consecutive one-half borehole volumes. Generally, at least three borehole volumes were purged (table 2) from the packed intervals. In some poorly conductive intervals, the water level in the drill-stem pipe open to the intervals was lowered to the pump-intake level (fig. 4) during pumping. For these intervals, less than three borehole volumes were purged (however, no less than one borehole volume was purged) because it was necessary to repeatedly allow water levels to recover sufficiently for pumping. Stability of field measurements was still required, but stability was determined from fewer consecutive one-half borehole volumes. Water samples were analyzed for VOC's by an IEPA contract laboratory using gas chromatography/mass spectrometry. Select analyses for the petroleum-related compounds benzene, ethylbenzene, toluene, and xylene were done on the basis of field observations of a floating substance in some water samples.

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

Table 2.--Purging and sampling summary for boreholes G115BD, G125BD, and G126BD

Depth of packed interval below land surface, in feet	Borehole volume, in gallons	Borehole volume purged, in gallons	Number of borehole volumes purged	Date borehole purged and sampled
		Borehole G115BD		
37.5- 40.0	28.1	125	4.4	08-15-90
40.0- 50.4	18.6	18.6	1.0	08-17-90
48.1- 58.6	20.5	22	1.1	08-14-90
58.6- 69.0	22.2	35	1.6	08-10-90
69.0- 79.4	23.8	53	2.2	08-08-90
69.0- 96.6	49.2	115	2.3	08-08-90
76.0- 86.0	22.1	44	2.5	11-15-90
86.0- 96.0	25.2	80	3.2	11-14-90
96.0-106.0	25.3	80	3.2	11-14-90
106.0-116.0	26.9	90	3.3	11-13-90
116.0-126.0	30.1	95	3.2	11-13-90
126.0-136.0	29.5	90	3.1	11-12-90
136.0-146.0	31.8	90	2.8	11-08-90
136.0-150.8	30.4	100	3.3	11-09-90
		Borehole G125BD		
31.3- 41.3	16.4	50	3.0	11-30-90
45.5- 55.5	17.1	39	2.5	11-30-90
65.5- 75.5	20.3	35	2.0	11-29-90
85.5- 95.5	23.5	108	4.6	11-29-90
105.5-115.5	28.3	105	3.7	11-28-90
115.5-125.5	28.0	70	2.5	12-04-90
125.5-135.5	31.0	60	1.9	12-03-90
135.5-145.5	31.4	95	3.0	11-28-90
		Borehole G126BD		
36.5- 46.5	16.1	22.5	1.4	11-21-90
56.5- 66.5	20.6	26	1.3	11-20-90
86.5- 96.5	25.2	85	3.4	11-20-90
116.5-126.5	30.2	105	3.5	11-19-90
136.5-146.5	31.6	100	3.2	11-26-90
136.5-151.3	37.3	120	3.2	11-19-90

The sampling pump was decontaminated before and after use in each packed interval. Soapy tap water, tap water, and deionized water were pumped through the sampling pump in sequence from separate containers to decontaminate the pump and the interior of the tubing. The tubing exterior and the tube reel were sprayed with soapy tap water, scrubbed with a brush, and rinsed with tap water followed by deionized water.

VERTICAL DISTRIBUTION OF HYDRAULIC CHARACTERISTICS

Evaluation of the hydraulic properties of an aquifer is necessary for understanding and predicting where and how fast ground water and contaminants are distributed through an aquifer and in developing effective strategies for remediating aquifer contamination. Hydraulic properties of an aquifer that are important to evaluate include hydraulic gradients and hydraulic conductivities. Additionally, evaluating the response of aquifers to stresses, such as those imposed by pumping, provide information regarding conveyance of water and contaminants through the aquifer matrix and fracture connections that may be present.

Hydraulic Gradients

Vertical hydraulic gradients between depth intervals in the three boreholes are shown in table 3. With one possible exception, vertical hydraulic gradients between all depth intervals were downward. Downward gradients ranged from 0 (0.004, if not adjusted for significant figures) in borehole G126BD, 36.5 to 46.5 ft below land surface, to 0.37 ft/ft in borehole G125BD, 116.0 to 126.0 ft below land surface.

The gradients generally were similar for equivalent depth intervals in the three boreholes. The magnitude of the gradients tended to increase with depth, correlating well with the general increase in K with depth (to be discussed subsequently in the section "Hydraulic Conductivity").

The largest downward gradients were identified in the lower parts of boreholes G115BD (0.37 ft/ft) and G126BD (0.20 ft/ft) and are probably related to increased water movement through the elevated-K interval at 115 to 125 ft below land surface. The absence of substantial hydraulic gradients at depth in borehole G125BD is probably related to the absence of water-level data from the packed interval at 115 to 125 ft below land surface.

The smallest downward gradient was associated with water movement down to the packed interval 36.5 to 46.5 ft below land surface in borehole G126BD. The small downward gradient indicates considerable vertical hydraulic connection between the weathered surface of the bedrock aquifer and the glacial drift aquifer. This explanation is consistent with the water-level response to pumping (to be discussed in the subsequent section "Response of Water Levels in Observation Wells to Borehole Pumping"). Small downward gradients were also noted in the uppermost interval in boreholes G115BD and G125BD.

Table 3.--Water-level altitudes and vertical hydraulic gradients in boreholes G115BD, G125BD, and G126BD

[--, no data available]

Depth below land surface, in feet			Date	Time	Water-level altitude, in feet above sea level[1]			Downward hydraulic gradient, in foot per foot	
Above packed interval	Packed interval	Below packed interval			Above packed interval	Packed interval	Below packed interval	Above packed/ packed interval	Packed/ below packed interval
				Borehole G115BD					
--	37.5- 40.0	44.8- 96.6	08-15-90	0957	--	763.59	762.76	--	0.03
--	40.0- 50.4	55.2- 96.6	08-16-90	1215	--	763.52	762.74	--	.02
37.5- 43.3	48.1- 58.6	63.4- 96.6	08-13-90	1532	763.65	763.48	763.02	0.01	.02
37.5- 43.3	48.1- 58.6	63.4- 96.6	08-14-90	0956	763.62	763.50	762.96	.01	.02
37.5- 53.8	58.6- 69.0	73.8- 96.6	08-09-90	1622	763.76	763.46	762.86	.02	.03
37.5- 56.7	61.5- 72.0	76.8- 96.6	08-07-90	1352	763.79	763.66	763.00	.01	.03
37.5- 64.2	69.0- 79.4	84.2- 96.6	08-08-90	1050	763.74	762.96	762.54	.03	.03
37.5- 64.2	69.0- 96.6	--	08-08-90	1904	763.75	762.18	--	.05	--
37.5- 71.2	76.0- 86.0	90.1-150.8	11-15-90	0650	762.86	762.23	760.96	.02	.03
37.5- 81.2	86.0- 96.0	100.1-150.8	11-14-90	1330	762.93	761.81	760.93	.04	.03
37.5- 91.2	96.0-106.0	110.1-150.8	11-14-90	0625	762.97	761.70	760.96	.04	.02
37.5-101.2	106.0-116.0	120.1-150.8	11-13-90	1125	762.92	761.44	761.08	.04	.02
37.5-111.2	116.0-126.0	130.1-150.8	11-13-90	0610	762.95	761.95	754.84	.02	.37
37.5-121.2	126.0-136.0	140.1-150.8	11-12-90	1422	762.88	757.30	754.58	.11	.19
37.5-131.2	136.0-146.0	150.1-150.8	11-08-90	1420	762.92	752.55	761.67	.18	[2].97
37.5-131.2	136.0-150.8	--	11-09-90	0630	762.96	753.20	--	.18	--
				Borehole G125BD					
--	31.3- 41.3	45.4-149.9	11-30-90	1242	--	763.30	761.92	--	.02
31.3- 40.7	45.5- 55.5	59.6-149.9	11-29-90	2303	763.38	763.30	761.92	.01	.02
31.3- 60.7	65.5- 75.5	79.6-149.9	11-29-90	1225	763.22	762.85	761.63	.02	.03
31.3- 80.7	85.5- 95.5	99.6-149.9	11-28-90	1746	763.18	762.53	761.38	.02	.03
31.3-100.7	105.5-115.5	119.6-149.9	11-28-90	1352	763.18	761.96	761.59	.03	.02
31.3-130.7	135.5-145.5	149.6-149.9	11-28-90	0540	763.14	760.62	760.30	.04	.03
				Borehole G126BD					
29.3- 31.7	36.5- 46.5	50.6-151.3	11-20-90	2315	764.54	764.50	762.25	[3].00	.04
29.3- 51.7	56.5- 66.5	70.6-151.3	11-20-90	1145	764.44	763.92	761.65	.02	.05
29.3- 81.7	86.5- 96.5	100.6-151.3	11-20-90	0600	764.22	762.64	761.71	.04	.03
29.3-111.7	116.5-126.5	130.6-151.3	11-19-90	1400	763.78	762.80	758.91	.02	.20
29.3-131.7	136.5-151.3	--	11-19-90	0750	763.77	759.99	--	.06	--

[1] Water-level altitudes for boreholes G125BD and G126BD are approximate (+/- 0.1 foot) because surveyed altitudes of measuring points (top of temporary surface casings) were not available.

[2] Upward gradient; data appear to represent artificial pressure gradient related to packer inflation.

[3] If three significant figures are accepted, then gradient is 0.004 foot/foot downward.

The one upward gradient was 0.97 ft/ft up to the packed interval 136.0 to 146.0 ft below land surface in borehole G115BD. This upward gradient should be viewed with caution. An upward gradient was not identified at that depth in the other two boreholes. The upward gradient is assumed to be the result of artificially high water levels below the packed interval because of slow water-level equilibration after packer inflation. The possibility of upward gradients at this depth is being evaluated in the ongoing investigation.

Hydraulic Conductivity

Horizontal hydraulic conductivities (K) estimated by use of the Bouwer and Rice (1976) slug-test method are shown in table 4 and figure 5. K values derived from rising-head tests typically were similar to K values derived from falling-head tests, as would be expected. Because of the similarity of the two sets of values and for ease of discussion, only K values derived from falling-head tests will be discussed unless otherwise indicated.

The K values, as determined from the slug tests, ranged from 0.054 to 12 ft/d in borehole G115BD, 0.19 to 170 ft/d in borehole G125BD, and 0.067 to 0.57 ft/d in borehole G126BD. The data indicate a vertical trend in the magnitude of K that is generally consistent from borehole to borehole. Between the boreholes, the variability in K for equivalent depth intervals was generally less than an order of magnitude.

If water level is plotted as a function of time on a semilog scale for analysis of slug tests, a straight-line plot is expected (fig. 6). In some of the slug tests in this study, plots of the water-level data were not straight lines (fig. 7). For the test intervals in which deviations from straight lines occurred in the plotted data, the K values in table 4 are presented as ranges. Analysis of the early- and late-time water-level data indicates early-time K values are higher than late-time K values. The difference between early- and late-time values of K typically was small (less than an order of magnitude).

The change in slope of the slug-test data plots has several possible explanations. The explanations, presented in order of decreasing likelihood, are as follows:

First, the aquifer may not be homogeneous and isotropic in the spatial domain analyzed by the slug tests. If, for example, fractures are present within the tested domain, then the data could be representing the effect of dual porosity. Under conditions of dual porosity, the introduction of the slug would initially displace water in the fractures and then displace water in the less permeable rock matrix surrounding the fractures. This explanation is likely, given evidence from geophysical logs and descriptions of the hydraulic properties of the Galena-Platteville aquifer in northern Illinois (Kay and others, 1989, p. 1).

Second, the packed intervals may not have been at hydraulic equilibrium at the time the tests were done; water levels could have been responding to pumping of the nearby municipal wells, natural causes, or pressure induced by

Table 4.--Horizontal hydraulic conductivities of the Galena-Platteville aquifer in boreholes G115BD, G125BD, and G126BD

[All data except test intervals are hydraulic conductivities in feet per day; --, no data available]

Test interval, in feet below land surface	Slug test (Bouwer and Rice, 1976)		Constant-discharge aquifer test (Cooper and Jacob, 1946)	
	Falling head	Rising head	Pumping	Recovery
		Borehole G115BD		
[1]37.5- 40.0	$1.2x10^{1}$	$1.1x10^{1}$	$9.9x10^{1}$	--
[1]37.5- 96.6	--	--	$1.4x10^{-1}$	$1.2x10^{-1}$
40.0- 50.4	$5.4x10^{-2}$	$7.8x10^{-2}$	--	$3.8x10^{-1}$
	--	--	--	$3.8x10^{-1}$
	--	--	--	$4.8x10^{-1}$
48.1- 58.6	$6.1x10^{-2}$	$4.7x10^{-2}$	--	$2.5x10^{-1}$
	--	$7.0x10^{-2}$	--	--
58.6- 69.0	[2]$2.3-7.5x10^{-1}$	$1.7x10^{-1}$	$7.1x10^{-2}$	$3.7x10^{-1}$
	$1.9x10^{-1}$	$2.9-7.6x10^{-1}$	$1.9x10^{-1}$	$1.3x10^{-1}$
69.0- 79.4	--	--	$1.1x10^{-1}$	$1.3x10^{-1}$
	--	--	--	$1.0x10^{-1}$
	--	--	--	$1.2x10^{-1}$
69.0- 96.6	--	--	$1.6x10^{-1}$	$1.4x10^{-1}$
76.0- 86.0	$6.0x10^{-2}$	$2.4-4.0x10^{-2}$	--	--
86.0- 96.0	$2.3-4.2x10^{-1}$	$3.9x10^{-1}$	$1.9x10^{0}$	--
96.0-106.0	$5.7x10^{-1}$	$5.5x10^{-1}$	$2.5x10^{0}$	$2.6x10^{0}$
106.0-116.0	$5.9x10^{-1}$	$5.6x10^{-1}$	$2.8x10^{0}$	$2.6x10^{0}$
116.0-126.0	$3.4x10^{-1}-6.1x10^{0}$	$6.5x10^{-1}-1.6x10^{1}$	$2.6x10^{1}$	$3.7x10^{1}$
126.0-136.0	$3.1x10^{-1}$	$1.8-2.6x10^{-1}$	--	$3.6x10^{0}$
136.0-146.0	$5.5x10^{-1}$	$4.7x10^{-1}$	$3.6x10^{0}$	$3.5x10^{0}$
136.0-150.8	$4.2x10^{-1}$	$3.2-5.5x10^{-1}$	$4.0x10^{0}$	$1.1x10^{1}$
		Borehole G125BD		
31.3- 41.3	$1.7x10^{2}$	$1.8x10^{2}$	--	--
	--	$1.7x10^{2}$	--	--
44.5- 55.5	$5.1x10^{-1}$	$4.3x10^{-1}$	--	--
65.5- 75.5	$1.9x10^{-1}$	$1.1x10^{-1}$	--	--
85.5- 95.5	$4.5x10^{-1}$	$4.3x10^{-1}$	$1.2x10^{0}$	$1.2x10^{0}$
105.5-115.5	$4.8x10^{-1}$	$4.8x10^{-1}$	$1.7x10^{0}$	--
115.5-125.5	$1.0x10^{1}$	$9.8x10^{0}$	$3.7x10^{1}$	--
125.5-135.5	$2.3x10^{-1}$	$2.8x10^{-1}$	--	--
135.5-145.5	$3.9-4.4x10^{-1}$	$4.9-5.6x10^{-1}$	$2.0x10^{0}$	$2.5x10^{0}$
		Borehole G126BD		
29.3-151.3	--	--	$1.9x10^{1}$	--
36.5- 46.5	$1.3x10^{-1}$	$1.3x10^{-1}$	$2.3x10^{0}$	--
56.5- 66.5	$6.7x10^{-2}$	--	$9.4x10^{-1}$	--
86.5- 96.5	$3.7x10^{-1}$	$3.2x10^{-1}$	$9.7x10^{-1}$	$1.1x10^{0}$
116.5-126.5	$3.4x10^{-1}$	$3.5x10^{-1}$	$1.6x10^{0}$	--
136.5-151.3	$2.0-5.7x10^{-1}$	$3.4-6.7x10^{-1}$	$3.8x10^{0}$	--

[1] Suspected hole in casing installed in overlying glacial drift aquifer; hydraulic conductivities may be affected by direct hydraulic connection with the glacial drift aquifer.

[2] Ranges represent late and early time values, respectively.

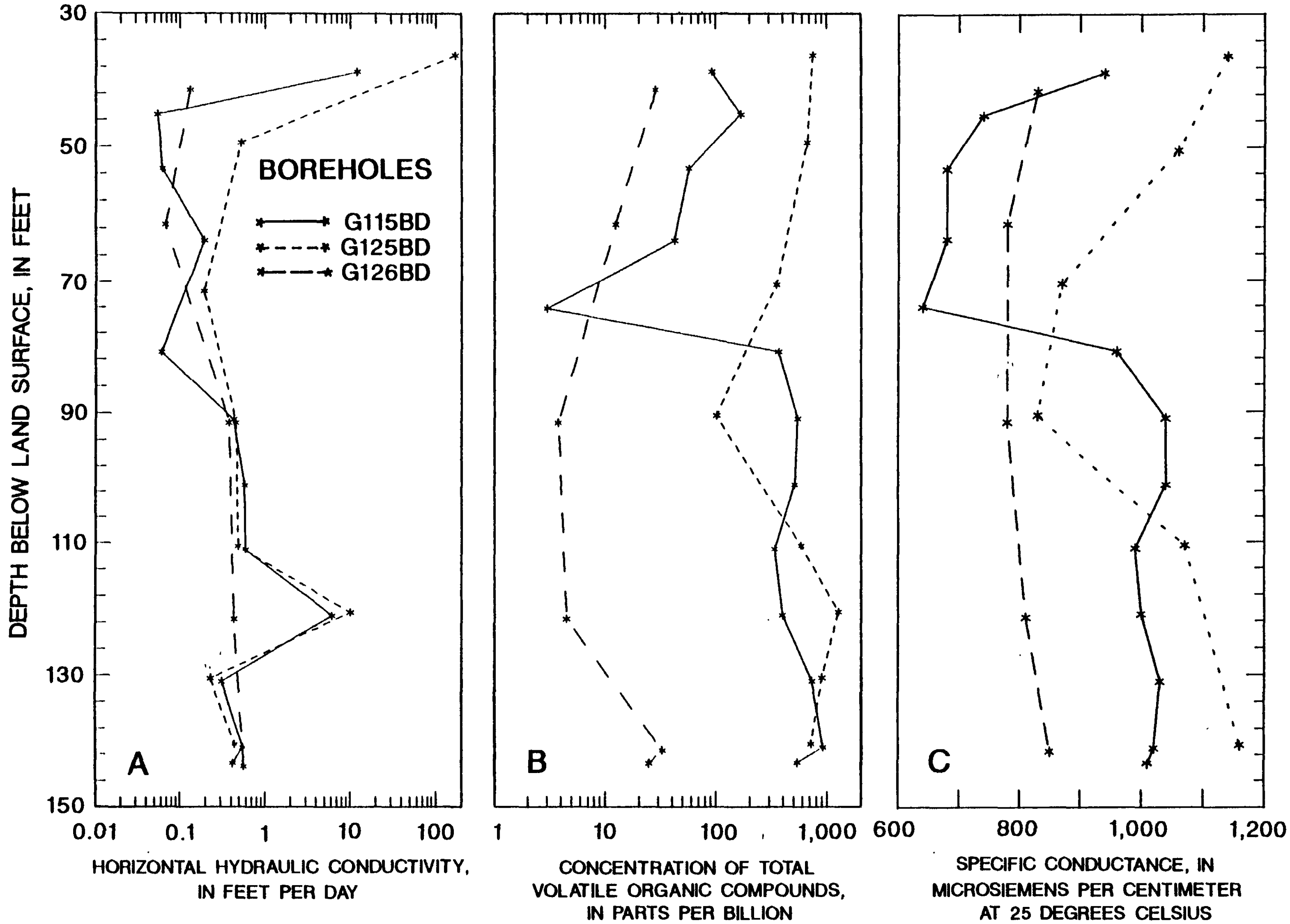

Figure 5.--Horizontal hydraulic conductivity, concentration of total volatile organic compounds, and specific conductance, with respect to depth in boreholes G115BD, G125BD, and G126BD.

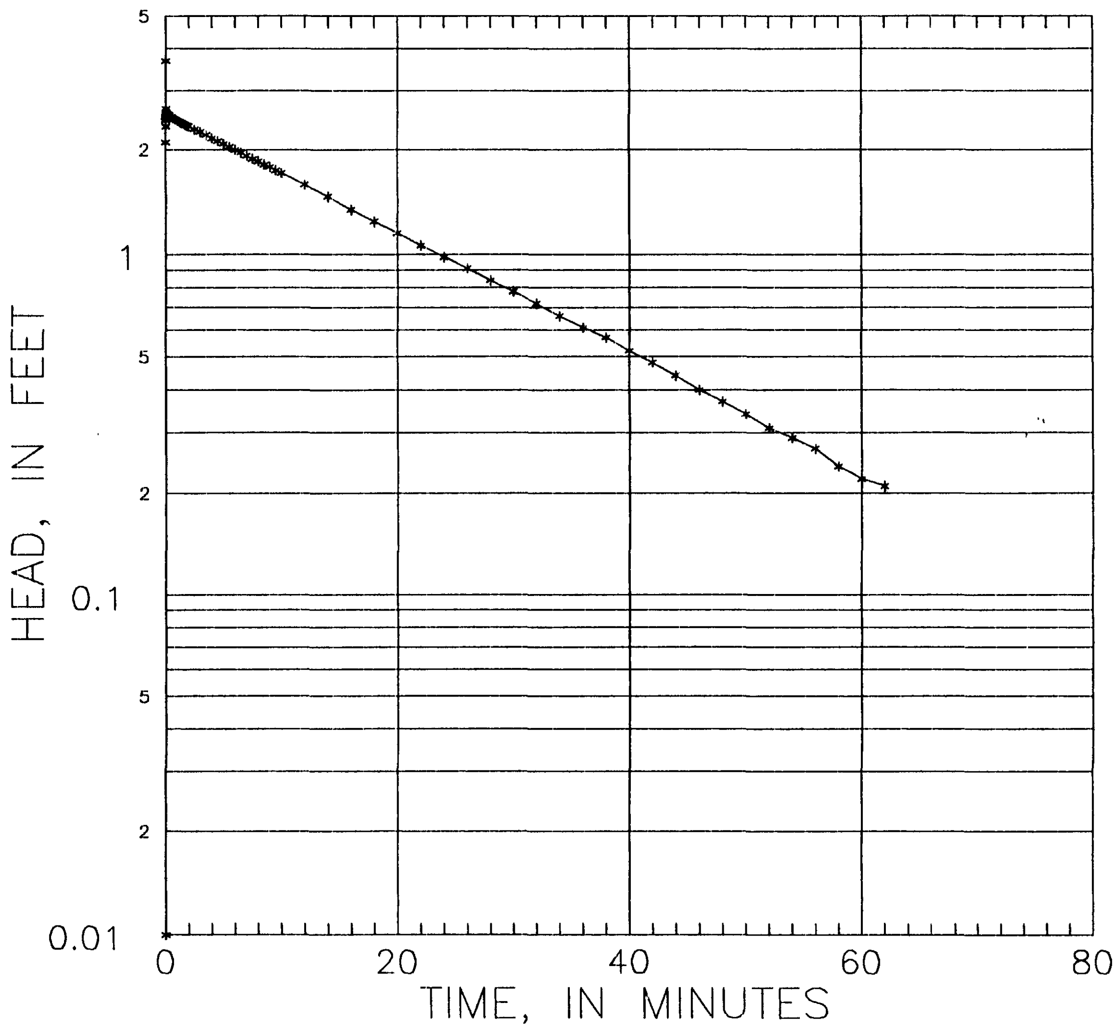

Figure 6.--Typical plot of water level as a function of time, as used for estimating horizontal hydraulic conductivity by the Bouwer and Rice method.

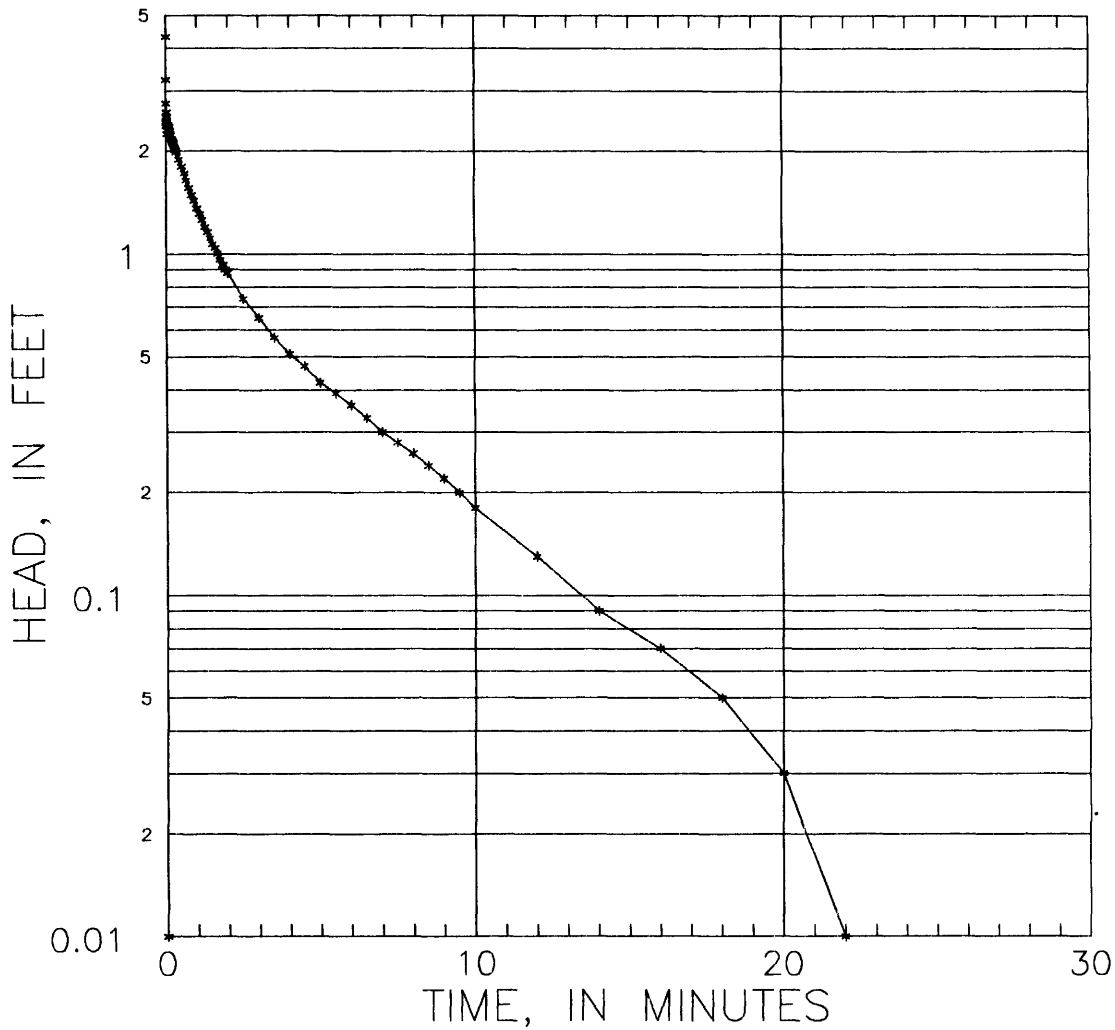

Figure 7.--Atypical plot of water level as a function of time, as used for estimating horizontal hydraulic conductivity by the Bouwer and Rice method.

packer inflation. Response of the aquifer beneath the study site to municipal-well pumping seems possible, given that two municipal wells are within 0.5 mi of the site; however, preliminary investigation of this possibility (Douglas Yeskis, U.S. Environmental Protection Agency, oral commun., 1990) indicates that pumping of the municipal wells has little to no effect on either the bedrock aquifer or the glacial drift aquifer beneath the site.

Third, the borehole walls may not have been free of drilling residue, and a resulting "skin effect" may have reduced water movement into and out of the dolomite during some of the slug tests. This explanation is the least likely, given that the boreholes were drilled by means of the water-rotary method and developed by means of a high-capacity discharge pump. Additional investigation is being done to better determine factors that may have affected results of the slug tests.

The vertical trend of K values estimated by use of the Cooper and Jacob (1946) constant-discharge-test method correlate well with the vertical trend of K values estimated by use of the Bouwer and Rice (1976) slug-test method; however, the K values estimated by use of the constant-discharge-test method are generally about an order of magnitude greater than the values estimated by use of the slug-test method. The discrepancy between the two sets of K values may be explained by the following: (1) difference in the size of the spatial domain of aquifer evaluated by the two tests; (2) factors related to deviations from test assumptions, such as nonconstant discharge rates, aquifer heterogeneity, and inadequate stress on the aquifer (that is, insufficient duration and rate of discharge; see "Aquifer Tests"); and (or) (3) one or more of the three factors previously suggested as possible contributors to the deviations in the straight-line plots of the slug-test data.

For most packed intervals for which the Cooper and Jacob (1946) method was used to estimate K, the semilog plots of water-level drawdown and recovery data deviated from the expected straight line. Any one factor or any combination of the three factors suggested as an explanation for the high estimated K values from the Cooper and Jacob (1946) method (relative to estimated K values from the Bouwer and Rice (1976) method) could probably also account for deviations from the straight line. The deviations probably occurred in more tests and were more pronounced in the test data analyzed by the Cooper and Jacob (1946) method than in the test data analyzed by the Bouwer and Rice (1976) method, because of the tendency toward nonconstant discharge rates after the first 30 minutes of pumping and the larger volume of the aquifer evaluated as a result of pumping. As the volume of aquifer that is tested increases, the likelihood of encountering heterogeneities in the aquifer increases. For many packed intervals, the deviation of the test data from a straight-line plot was so extreme that the Cooper and Jacob (1946) method could not be reliably applied to analysis of K. Data from these packed intervals, as well as from the interval 31.3 to 41.3 ft below land surface in borehole G125BD (where no drawdown was recorded during pumping), are omitted from table 4.

The relative K values estimated by qualitative evaluation of drawdown during pumping of the packed intervals are presented in table 5. The relative K values correlate well with the K values derived from slug tests of the individual packed intervals. In most cases, the intervals that were not pumped dry

Table 5.--Relative horizontal hydraulic conductivities in boreholes G115BD, G125BD, and G126BD

Pumping interval in feet below land surface	Relative horizontal hydraulic conductivity[1]	Pumping interval in feet below land surface	Relative horizontal hydraulic conductivity[1]
Borehole G115BD		Borehole G125BD	
37.5- 40.0	High	31.3- 41.3	High
40.0- 50.4	Low	45.5- 55.5	Medium
48.1- 58.6	Low	65.5- 75.5	Medium
58.6- 69.0	Low	85.5- 95.5	High
61.5- 72.0	High	105.5-115.5	High
69.0- 79.4	Medium	115.5-125.5	High
69.0- 96.6	High	125.5-135.5	High
76.0- 86.0	Low	135.5-145.5	High
86.0- 96.0	High		
96.0-106.0	High	Borehole G126BD	
106.0-116.0	High	36.5- 46.5	High
116.0-126.0	High	56.5- 66.5	Low
126.0-136.0	High	86.5- 96.5	High
136.0-146.0	High	116.5-126.5	High
136.0-150.8	High	136.5-151.3	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 at a rate of 1 gallon per minute, not drawn down to pump-intake level when pumped at a lower rate; low, water level drawn down to pump-intake level when pumped at the minimum rate of about 0.2 gallon minute.

at a "constant" pumping rate of 1 gal/min had the highest K values; intervals that were pumped dry at a rate of 1 gal/min, but not at a lower rate had intermediate K values, and intervals that were pumped dry at the minimum pumping rate of about 0.2 gal/min had the lowest K values. Deviations in the correlation between the two methods of estimating K probably are attributable to the variability in pumping duration (controlled primarily by the variability in required purge volumes) and the noted inconsistency in pumping rates.

On the basis of the K values derived from slug tests (and supported by the K values derived from constant-discharge tests and by rock-core and geophysical-log data), the Galena-Platteville aquifer (to a depth of 150 ft) can be subdivided into five "hydraulic" units. For the most part, the hydraulic properties of the units seem to be laterally consistent across the site (fig. 5). The approximate depth and range of K of the hydraulic units are as follows:

Unit 1 consists of the 1- to 5-ft-thick weathered surface of the dolomite bedrock, which, depending on site location, is about 25 to 40 ft below land surface. This unit has the highest K values of the five units. The estimated K values range from 12 to 170 ft/d. Slug-test data were not obtained at the depth of unit 1 in borehole G126BD, but the falling-head K value in the nearest shallow bedrock observation well (G111D, about 75 ft to the west of borehole G126BD, fig. 2) is reported to be 9.6 ft/d (Vanderpool and Yeskis, 1991).

Unit 2 consists of the dolomite beds between about 40 to 85 ft below land surface. This unit has the lowest K values of the five units. The estimated K values range from 0.054 to 0.75 ft/d but are typically less than about 0.1 ft/d. The low-K unit is not readily evident in borehole G125BD; K values at the depth of unit 2 were generally higher in borehole G125BD than in the other tested boreholes (table 4, fig. 5).

Unit 3 consists of the dolomite beds between about 85 to 115 ft below land surface. This unit has K values slightly higher than those in unit 2; the estimated K values range from 0.23 to 0.59 ft/d.

Unit 4 consists of the dolomite beds between about 115 to 125 ft below land surface. This unit has K values that are exceeded only by those in unit 1. The estimated K values range from 0.34 to 10 ft/d. Unit 4 is less evident in borehole G126BD than in the other tested boreholes (table 4, fig. 5). It is uncertain why the K value at the depth of unit 4 is relatively low in borehole G126BD. Geophysical logs indicate the presence of a bedding-plane fissure at a depth of about 125 ft in each of the tested boreholes, including borehole G126BD, and that fissure is assumed to contribute to the relatively high K values in unit 4.

Unit 5 consists of the dolomite beds between about 125 and 150 ft below land surface. This unit has K values similar to the values in unit 4; the estimated K values range from 0.20 to 0.57 ft/d.

Although the hydraulic properties of the identified units seem to be generally consistent laterally across the site, slug-test analysis only allows estimation of K within the immediate vicinity of a borehole. The aquifer could be hydraulically heterogeneous, but slug-test results may provide no evidence of flow-influencing features, such as vertical fractures, that may be remote from the boreholes.

Response of Water Levels in Observation Wells to Borehole Pumping

Water levels were measured in the observation wells nearest each of the three tested boreholes within 5 minutes of the start and the completion of pumping of each packed interval. The water-level data were intended to provide an indication of the hydraulic properties (permeability and vertical hydraulic connections) of the bedrock beyond the immediate vicinity of the boreholes.

Water-level altitudes in the observations wells before and after pumping of the boreholes are presented in tables 6, 7, and 8. The maximum drawdown, 1.73 ft, was recorded in well G115B (screened just below the surface of the bedrock at a depth of 43.6 to 48.6 ft). The maximum drawdown was recorded when borehole G115BD was developed at pumping rate of about 10 gal/min.

Drawdowns in the observation wells were much smaller in response to the lower pumping rate (about 1 gal/min) associated with the pumping of the packed intervals. The maximum drawdown measured during pumping of packed intervals was 0.48 ft, recorded in well G115B, during pumping of the interval 48.1 to 58.6 ft in borehole G115BD. This interval had the lowest K value in borehole G115BD (table 4).

Pumping of most packed intervals in borehole G115BD induced small drawdowns in water level in well G115B. Other than the observed relation between K and drawdown for the interval 48.1 to 58.6 ft below land surface, the value of K did not seem to relate to the occurrence or magnitude of drawdown induced by pumping discretely packed intervals. The fact that drawdown was induced in well G115B from pumping of some, but not all, packed intervals in borehole G115BD indicates that some intervals in the aquifer may be more vertically connected than others. It is likely that vertical fractures provide the connections between intervals of comparatively high K in the lower part of the bedrock aquifer. The variability noted in drawdown in the nearby observation wells during pumping of the various intervals in the aquifer may also depend on the proximity of individual packed (pumped) intervals to the network of interconnecting fractures.

During development of borehole G115BD, a drawdown of 0.24 ft was detected in well G115D. Drawdown in the well, screened in the lower part of the overlying glacial drift aquifer, indicates a hydraulic connection between the glacial drift aquifer and the bedrock aquifer. These data support a previous conclusion, based on water-level data, that there is hydraulic connection between the two aquifers (Scientific Applications International Corporation, 1990). No drawdown was detected in well G115D or well G115S (screened in the upper part of the glacial drift aquifer) during the pumping of packed intervals in borehole G115BD.

Pumping of packed intervals in borehole G125BD induced virtually no drawdown in well G125D (screened in the lower part of the glacial drift aquifer). The maximum drawdowns recorded were 0.09 ft in well G125D during pumping of the interval from 115.5 to 125.5 ft in borehole G125BD (an interval with a relatively high K value (table 4)) and 0.12 ft during pumping of the interval from 85.5 to 95.5 ft (an interval with a low K value). Water levels in well G125D showed no response to pumping in the high-K interval from 31.1 to 41.3 ft below land surface. This pattern indicates that the drawdowns in well G125D that were recorded during pumping of the lower intervals in borehole G125BD may be the result of other factors, such as response to changes in barometric pressure or municipal-well pumping rates.

Pumping of packed intervals in borehole G126BD induced no drawdowns in nearby wells G111S or G111D. The lack of response is attributed to the large distance between the pumped well and the observation wells (about 75 ft) and to the low pumping rate.

Table 6.--Water-level altitudes in observation wells G111S, G115D and G115B before and after pumping in borehole G115BD

[--, no data available]

Pumping interval, in feet below land surface	Date	Time	Water-level altitude, in feet above sea level G115S	G115D	G115B	Remarks
37.5- 40.0	08-15-90	1049	768.31	763.56	763.44	Before pumping[1]
37.5- 40.0	08-15-90	1324	768.31	763.56	763.20	After pumping[2]
37.5-150.8	11-07-90	0800	768.22	762.98	762.90	Before pumping
37.5-150.8	11-07-90	1705	768.22	762.74	761.17	After pumping
40.0- 50.4	08-16-90	0930	768.25	763.54	763.52	Before pumping[3]
40.0- 50.4	08-16-90	2230	768.25	763.54	763.18	After pumping
48.1- 58.6	08-14-90	0800	--	--	763.53	Before pumping[3]
48.1- 58.6	08-14-90	1828	--	--	763.05	After pumping
58.6- 69.0	08-10-90	0933	--	--	763.66	Before pumping
58.6- 69.0	08-10-90	1755	--	--	763.50	After pumping
76.0- 86.0	11-15-90	0732	--	--	762.76	Before pumping[3]
76.0- 86.0	11-15-90	1225	--	--	762.76	After pumping
86.0- 96.0	11-14-90	1400	--	--	762.86	Before pumping
86.0- 96.0	11-14-90	1600	--	--	762.80	After pumping
96.0-106.0	11-14-90	0752	--	--	762.83	Before pumping
96.0-106.0	11-14-90	0915	--	--	762.80	After pumping
106.0-116.0	11-13-90	1344	--	--	762.83	Before pumping
106.0-116.0	11-13-90	1506	--	--	762.83	After pumping
116.0-126.0	11-13-90	0647	--	--	762.83	Before pumping
116.0-126.0	11-13-90	1022	--	--	762.72	After pumping
126.0-136.0	11-12-90	1130	--	--	762.86	Before pumping
126.0-136.0	11-12-90	1711	--	--	762.80	After pumping
136.0-146.0	11-08-90	1805	768.22	762.99	762.96	Before pumping
136.0-146.0	11-08-90	1900	768.22	762.98	762.87	After pumping
135.0-150.8	11-09-90	0803	--	--	762.94	Before pumping
135.0-150.8	11-09-90	0947	--	--	762.94	After pumping

[1] Water level measured within 5 minutes of start of pumping.
[2] Water level measured within 5 minutes of end of pumping.
[3] Pumping was intermittent because of excessive drawdown in the test interval.

Table 7.--Water-level altitudes in observation well G125D before and after pumping in borehole G125BD

Pumping interval, in feet below land surface	Date	Time	Water-level altitude, in feet above sea level G125D	Remarks
31.3- 41.3	11-30-90	1448	763.55	Before pumping[1]
31.3- 41.3	11-30-90	1452	763.55	After pumping[2]
45.5- 55.5	11-30-90	0801	763.55	Before pumping[3]
45.5- 55.5	11-30-90	1201	763.51	After pumping
65.5- 75.5	11-29-90	1416	763.55	Before pumping[3]
65.5- 75.5	11-29-90	1846	763.51	After pumping
85.5- 95.5	11-29-90	0800	[4]763.55	Before pumping
85.5- 95.5	11-29-90	1680	763.43	After pumping
105.5-115.5	11-28-90	1352	763.55	Before pumping
105.5-115.5	11-28-90	1680	763.55	After pumping
115.5-125.5	11-28-90	1111	763.55	Before pumping
115.5-125.5	11-28-90	1409	763.46	After pumping
135.5-145.5	11-28-90	0540	763.55	Before pumping
135.5-145.5	11-28-90	0820	763.55	After pumping

[1] Water level measured within 5 minutes of start of pumping.

[2] Water level measured within 5 minutes of end of pumping.

[3] Pumping was intermittent because of excessive drawdown in the test interval.

[4] Water level was not measured after 11-28-90. Water-level altitudes after that date were assumed to be 763.55 feet above sea level before pumping; water-level altitudes after pumping were determined on the basis of drawdown indicated by downhole pressure transducers.

Table 8.--Water-level altitudes in observation wells G111S and G111D before and after pumping in borehole G126BD

[--, no data available]

Pumping interval, in feet below land surface	Date	Time	Water-level altitude, in feet above sea level G111S	G111D	Remarks
36.5- 46.5	11-21-90	0635	765.50	764.79	Before pumping[1]
36.5- 46.5	11-21-90	1200	765.50	764.77	After pumping[2]
56.5- 66.5	11-20-90	1145	--	764.80	Before pumping[3]
56.5- 66.5	11-20-90	1650	--	764.80	After pumping
86.5- 96.5	11-20-90	0700	765.50	764.78	Before pumping
86.5- 96.5	11-20-90	0935	765.51	764.76	After pumping
116.5-126.5	11-19-90	1511	765.53	--	Before pumping
116.5-126.5	11-19-90	1700	765.53	--	After pumping
136.5-146.5	11-26-90	1549	765.41	764.69	Before pumping
136.5-146.5	11-26-90	1747	765.41	764.69	After pumping
136.5-151.3	11-19-90	0830	765.53	764.80	Before pumping
136.5-151.3	11-19-90	1120	765.53	764.80	After pumping

[1] Water level measured within 5 minutes of start of pumping.

[2] Water level measured within 5 minutes of end of pumping.

[3] Pumping was intermittent because of excessive drawdown in the test interval.

VERTICAL DISTRIBUTION OF WATER QUALITY

Evaluating the distribution of waste constituents in an aquifer requires understanding of the general chemistry of the aquifer water. In the first phase of the USGS investigation, evaluation of aquifer-water chemistry was limited to field measurements of pH, temperature, specific conductance, and Eh, and analysis of synthetic VOC's. On the basis of analysis of water from the glacial drift aquifer, VOC's were considered to be the principal waste constituent in the Galena-Platteville aquifer (Tinka Hyde, U.S. Environmental Protection Agency, oral commun., 1990). Future phases of the bedrock-aquifer investigation are intended to also include analysis of inorganic water chemistry.

Field-Measured Properties

The field measurements of pH, temperature, specific conductance, and Eh (table 9) generally were consistent vertically within the boreholes and horizontally between the boreholes. The range of pH was 6.8 to 8.4. The pH of 8.4, which was measured in the interval 37.5 to 40.0 ft below land surface in borehole G115BD, may be attributed to the chemical effect of the portland-cement grout used to secure the surface casing because no pH this high has been recorded in either the bedrock aquifer or the glacial drift aquifer (Shirley Baer, Illinois Environmental Protection Agency, written commun., 1990). Excluding the pH of 8.4, the maximum pH was 7.9 (in the interval 69.0 to 79.4 ft below land surface, borehole G115BD).

Ground-water temperatures ranged from 9.2 to 17.0°C. All the water temperatures, which were measured outside the boreholes, can be expected to be affected by ambient air temperatures. This effect is most apparent for water temperatures obtained during the August 1990 sampling, when ambient air temperatures were significantly higher than in situ water temperatures. Excluding water samples from August 1990, the maximum water temperature was 13.7°C. Water temperatures of about 11°C probably are most representative of in situ water temperatures.

Specific conductance was the most vertically and horizontally variable of the field measurements. Specific conductance ranged from 640 to 1,160 µS/cm in the three tested boreholes. High specific conductances generally corresponded with high VOC concentrations and K values (fig. 5). In boreholes G115BD and G125BD, where specific conductances were among the highest and most variable, VOC concentrations were highest. In borehole G126BD, where conductance values were generally lowest and least variable, VOC concentrations were the lowest. The relation between specific conductance and VOC concentrations is considered representative of the relation between specific conductance and the concentration of dissociated inorganic ions in solution in the ground water (Heath, 1983, p. 65). Volatile organic compounds, which generally exist as unchanged compounds and are present at very low concentrations, are not expected to contribute to the measured specific conductance of the ground water. The relation between specific conductance and VOC concentrations indicates that the distribution of VOC's in the Galena-Platteville aquifer is similar to that of the inorganic-waste constituents. Additionally, because of the apparent relation between VOC and inorganic-waste distributions at the Parson's Casket Hardware site, measurement of specific conductance may be useful (easy and inexpensive) for generalized mapping of the distribution of VOC's in the aquifer.

Oxidizing conditions were indicated by the Eh of ground water in all three boreholes. Values of Eh ranged from 28 to 180 millivolts. There were no apparent trends associated with the distribution of Eh values.

Volatile Organic Compounds

VOC's were detected throughout each of the three sampled boreholes (table 10, fig. 5), indicating contamination of at least the upper half (about 150 ft) of the Galena-Platteville aquifer beneath the Parson's Casket Hardware

Table 9.--Water-quality field measurements in boreholes G115BD, G125BD, and G126BD

[°C, degrees Celsius; µS/cm at 25°C, microsiemens per centimeter at 25 degrees Celsius; --, no data available]

Sample interval, in feet below land surface	Date	pH, in standard units	Temperature, in °C	Specific conductance, in µS/cm at 25°C	Eh, in millivolts	Remarks
			Borehole G115BD			
37.5- 40.0	08-15-90	8.4	[1]15.0	940	--	Suspected hole in casing installed in overlying drift; water-quality data may represent mixed water from drift and stated depth interval in bedrock.
40.0- 50.4	08-17-90	7.8	[1]16.3	740	--	
48.1- 58.6	08-14-90	7.6	[1]17.0	680	--	Droplets of floating substance; water seems to sting on contact with skin.
58.6- 69.0	08-10-90	7.5	[1]15.9	680	--	Water cloudy, reddish; contains fine grains of pyrite(?); small air bubbles.
69.0- 79.4	08-08-90	7.9	[1]13.3	640	--	Small air bubbles in water.
69.0- 96.6	08-08-90	7.6	[1]12.2	690	--	
76.0- 86.0	11-15-90	7.2	[2]13.7	960	100	
86.0- 96.0	11-14-90	7.0	11.8	1,040	69	
96.0-106.0	11-14-90	7.0	11.5	1,040	130	
106.0-116.0	11-13-90	7.1	11.5	990	77	
116.0-126.0	11-13-90	7.0	11.3	1,000	100	
126.0-136.0	11-12-90	6.9	11.1	1,030	97	
136.0-146.0	11-08-90	7.0	11.2	1,020	130	
136.0-150.8	11-09-90	7.0	11.2	1,010	150	

Table 9.--Water-quality field measurements in boreholes G115BD, G125BD, and G126BD--Continued

Sample interval, in feet below land surface	Date	pH, in standard units	Temperature, in °C	Specific conductance, in μS/cm at 25°C	Eh, in millivolts	Remarks
				Borehole G125BD		
31.3- 41.3	11-30-90	6.8	12.1	1,140	180	
45.5- 55.5	11-30-90	7.0	11.7	1,060	140	Water slightly cloudy
65.5- 75.5	11-29-90	7.2	9.2	870	69	
85.5- 95.5	11-29-90	7.1	10.7	830	28	
105.5-115.5	11-28-90	7.1	10.9	1,070	65	
115.0-125.5	12-04-90	--	--	--	--	
125.0-135.5	12-03-90	--	--	--	--	
135.5-145.5	11-28-90	7.0	11.2	1,160	100	
				Borehole G126BD		
36.5- 46.5	11-21-90	7.2	12.5	830	140	
56.5- 66.5	11-20-90	7.4	11.0	780	100	
86.5- 96.5	11-20-90	7.5	10.8	780	100	
116.5-126.5	11-19-90	7.2	10.9	810	29	
136.5-146.5	11-26-90	7.1	11.3	850	168	
36.5-151.2	11-18-90	7.1	11.2	850	90	

[1] Flow-through cell not used. Water temperature reflects response to ambient air temperature during sampling.

[2] Flow-through cell used. Water temperature probably reflects response to ambient air temperature during sampling.

Table 10.--Volatile organic compounds detected in boreholes G115BD, G125BD, and G126BD

[Concentrations, in parts per billion (ppb); --, less than 0.3 ppb reporting limit; x, less than 0.5 ppb reporting limit; **, less than 3.0 ppb reporting limit; NA, not analyzed; 1,1-DCA, 1,1-dichloroethane; 1,1,1-TCA, 1,1,1-trichloroethane; 1,1,2-TCA, 1,1,2-trichloroethane; 1,1-DCE, 1,1-dichloroethylene; t-1,2-DCE, trans-1,2-dichloroethylene; c-1,2-DCE, cis-1,2-dichloroethylene; TCE, trichloroethylene; PCE, tetrachloroethylene]

Sample interval, in feet below land surface	1,1-DCA	1,1,1-TCA	1,1,2-TCA	1,1-DCE	t-1,2-DCE	c-1,2-DCE	TCE	PCE	Benzene	Chloro-benzene	Toluene	Ethyl-benzene	m-Xylene, p-Xylene	o-Xylene
						Borehole G115BD								
37.5- 40.0	92	--	--	--	--	NA	--	--	x	0.5	119	x	10	1.7
37.5- 96.6	--	--	--	--	--	NA	257	35	NA	NA	NA	NA	NA	NA
37.5-150.8	2.5	132	--	4.9	--	11.3	--	--	NA	NA	NA	NA	NA	NA
40.0- 50.4	8.5	133	25.5	--	--	NA	--	--	NA	NA	NA	NA	NA	NA
48.1- 58.6	34.5	--	--	--	--	NA	--	--	2.7	1.1	x	4.1	9.6	5
58.6- 69.0	42	--	--	--	--	NA	--	--	NA	NA	NA	NA	NA	NA
69.0- 79.4	--	--	--	--	--	NA	--	--	NA	NA	NA	NA	NA	NA
69.0- 96.6	--	[1]103	--	--	8	NA	227	85	NA	NA	NA	NA	NA	NA
76.0- 86.0	**	[1]72.5	**	11.9	**	4.4	[1]236	40.4	NA	NA	NA	NA	NA	NA
86.0- 96.0	--	[1]147	--	--	--	8.9	[1]324	64.3	NA	NA	NA	NA	NA	NA
96.0-106.0	--	[1]133	--	6.0	--	8.1	[1]304	58.1	NA	NA	NA	NA	NA	NA
106.0-116.0	--	89.3	--	--	--	--	[1]211	34.7	NA	NA	NA	NA	NA	NA
116.0-126.0	--	112	--	--	--	4.4	[1]245	33.7	NA	NA	NA	NA	NA	NA
126.0-136.0	**	[1]206	**	--	**	11.0	[1]440	75.4	NA	NA	NA	NA	NA	NA
136.0-146.0	--	[1]260	--	127	--	[1]23.2	[1]376	[1]132	NA	NA	NA	NA	NA	NA
136.0-150.8	1.7	137	--	10.1	--	12.3	306	[1]77	NA	NA	NA	NA	NA	NA
						Borehole 125BD								
31.3- 41.3	2.8	[1]361	--	4.4	--	26.2	[1]302	[1]48.7	NA	NA	NA	NA	NA	NA
45.5- 55.5	2.1	[1]331	--	3.8	--	14.8	[1]285	[1]27.8	NA	NA	NA	NA	NA	NA
65.5- 75.5	1.2	[1]145	--	2.9	--	11.9	[1]168	[1]21.2	NA	NA	NA	NA	NA	NA
85.5- 95.5	--	[1]40.1	--	1.4	--	2.1	[1]52	4.9	NA	NA	NA	NA	NA	NA
105.5-115.5	1.4	[1]262	--	3.3	--	15.0	[1]266	[1]34.7	NA	NA	NA	NA	NA	NA
115.5-125.5	7.1	[1]410	0.6	8.2	0.4	49.0	[1]570	[1]220	NA	NA	NA	NA	NA	NA
125.5-135.5	4.4	[1]442	--	4	--	36.2	[1]338	[1]72.7	NA	NA	NA	NA	NA	NA
135.5-145.5	2.4	[1]354	--	3.0	--	10.0	[1]303	[1]48.8	NA	NA	NA	NA	NA	NA
						Borehole 126BD								
36.5- 46.5	--	13.2	--	--	--	--	14.0	1.1	NA	NA	NA	NA	NA	NA
56.5- 66.5	--	4.8	--	--	--	--	7.6	--	NA	NA	NA	NA	NA	NA
86.5- 96.5	--	2.0	--	--	--	--	1.8	--	NA	NA	NA	NA	NA	NA
116.5-126.5	--	2.2	--	--	--	--	2.3	--	NA	NA	NA	NA	NA	NA
136.5-146.5	--	14.9	--	--	--	--	17.8	--	NA	NA	NA	NA	NA	NA
136.5-151.3	--	11.7	--	--	--	--	13.1	--	NA	NA	NA	NA	NA	NA

[1] Concentrations exceeded analytic calibration limits and are estimated.

site. The detected VOC's were predominantly chlorinated ethenes and ethanes. The most commonly detected VOC species, at the highest concentrations, were trichloroethylene (TCE); 1,1,1-trichloroethane; and tetrachloroethylene. These VOC species were previously detected in several of the site observation wells screened in the glacial drift aquifer and in the upper part (within 15 ft of the top) of the Galena-Platteville aquifer (Shirley Baer, Illinois Environmental Protection Agency, written commun., 1990).

Thirteen VOC species were identified in borehole G115BD (table 10). The maximum concentration was 440 ppb of TCE, detected in the interval 126.0 to 136.0 ft below land surface. Three benzene and two xylene compounds, with a maximum concentration of 10 ppb, also were identified in select analysis of water sampled from intervals 37.5 to 40.0 ft and 48.1 to 58.6 below land surface in borehole G115BD. Toluene, at 119 ppb, was also detected, but the presence of this constituent is assumed to represent laboratory contamination. This common laboratory contaminant was detected intermittently in water samples from other site wells.

Eight VOC species were identified in borehole G125BD; the maximum concentration was 570 ppb of TCE, detected in the interval 115.5 to 125.5 ft below land surface. Three VOC species were identified in borehole G126BD; the maximum concentration was 17.8 ppb of TCE, detected in the interval 136.5 to 146.5 ft below land surface.

Overall, the VOC concentrations increase with depth, particularly in intervals with comparatively high K values. The distribution of VOC species was often stratified. Stratification was most evident in borehole G115BD. For example, 1,1-dichloroethane was present in all the upper (above 70 ft below land surface) intervals and the lowest (136.0 to 150.8 ft) interval; 1,1-dichloroethylene was intermittently detected through the lower (below 75 ft) intervals in the borehole; and trans-1,2-dichloroethylene was present in only one intermediate-depth (69.0 to 96.6 ft) interval. In boreholes G125BD and G126BD, VOC species generally were distributed through all intervals that were sampled.

The water-quality and aquifer-test data indicate a positive correlation between VOC concentrations and K values (fig. 5); the correlation was least evident in borehole G126BD, where VOC concentrations were generally low throughout the borehole. Concentrations of VOC's were relatively high in most of unit 1 (uppermost 5 ft of bedrock; 25 to 40 ft below land surface), the unit with the highest K values. Concentrations were lowest in the underlying units 2 and 3 (40 to 115 ft below land surface), decreasing with depth through these units with the lowest K values. In borehole G115BD, several VOC species were not detected below units 2 and 3; these included 1,1,2-trichloroethane, trans-1,2-dichloroethylene, and the benzene and xylene compounds. Concentrations of VOC's generally were highest in or immediately below unit 4 (115 to 125 ft below land surface), the unit with the relatively high K values. In borehole G125BD, some VOC species (albeit at very low concentrations) were detected only in this unit. In the underlying unit 5 (125 to 150 ft below land surface), concentrations generally decreased to levels similar to those in units 2 and 3.

The VOC-concentration distributions indicate that the low-K dolomite beds in the Galena-Platteville aquifer impede the downward migration of the VOC's and that the high-K beds and fissures provide pathways for the lateral migration VOC's through the aquifer. Contaminant migration is possibly affected by ground-water flow through vertical fractures that connect shallow beds with deeper beds in the aquifer, thus explaining the detections of some VOC species at intermittent depths and the presence of some VOC species in only the high-K interval at 115 to 125 ft below land surface in borehole G125BD.

SUMMARY AND CONCLUSIONS

The USGS is investigating contaminant migration in the Galena-Platteville aquifer at the Parson's Casket Hardware site in Belvidere, Ill. This report presents the results of the first phase of the investigation, from August through December 1990.

A packer assembly was used to isolate intervals in three 150-ft-deep boreholes in the dolomite aquifer for hydraulic characterization and water-quality sampling. Hydraulic data include vertical distributions of vertical hydraulic gradients, horizontal hydraulic conductivity (K), and response of water levels in observation wells to borehole pumping. Water-quality data include vertical distributions of field-measured pH, temperature, specific conductance, and Eh values and laboratory determinations of VOC concentrations.

Vertical hydraulic gradients were downward with one anomalous exception. The downward gradients ranged from less than 0.01 to 0.37 ft/ft. The gradients generally increased with depth and correlated positively with K. The highest gradient was associated with an elevated-K interval at 115 to 125 ft below land surface. The 0.97-ft/ft upward gradient identified at the base (150 ft below land surface) of borehole G115BD seems to be the result of packer-induced pressures.

With few exceptions, the K values for each of the tested depth intervals in the aquifer were similar from borehole to borehole; the hydraulic characteristics of individual strata therefore seem to be generally consistent across the site. The strata can be subdivided into five hydraulic units with the following approximate depth ranges and K's: (1) a 1- to 5-ft-thick weathered surface at about 35 ft below land surface, 1-200 ft/d; (2) 35-80 ft, 0.05-0.5 ft/d; (3) 80-115 ft, 0.5 ft/d; (4) 115-125 ft, 0.5-10 ft/d; and (5) 125-150 ft, 0.5 ft/d.

Water-level drawdowns were detected in the shallow bedrock observation well G115B during pumping of some, but not all, of the packed intervals in nearby borehole G115BD. The drawdown data indicate that some intervals in the aquifer may be more vertically connected than others. Drawdowns were detected in well G115D (screened in the lower part of the overlying glacial drift aquifer) during development pumping of borehole G115BD, indicating hydraulic connection between the glacial drift aquifer and the bedrock aquifer.

Volatile organic compounds were detected throughout each of the three sampled boreholes, indicating contamination of at least the upper half (about 150 ft) of the bedrock aquifer beneath the site. The detected VOC's were predominantly chlorinated ethenes and ethanes; several benzene and xylene compounds also were detected in a select analysis for petroleum-related compounds in water from two shallow depth intervals in borehole G115BD.

The highest VOC concentrations were detected in boreholes G115BD and G125BD (440 and 570 ppb, respectively, of TCE). The VOC concentrations, specific conductance values, and K are positively correlated. Concentrations of VOC's generally were elevated near the weathered surface of the bedrock (about 35 ft below land surface), the interval with the highest K values. Concentrations generally were highest in or immediately below the interval 115 to 125 ft below land surface, the interval with the second-highest K values.

The VOC-concentration distributions indicate that the low-K dolomite beds in the Galena-Platteville aquifer may impede the downward migration of the VOC's and that the high-K beds and fissures may provide pathways for the lateral migration of VOC's through the aquifer. Contaminant migration is possibly affected by ground-water flow through vertical fractures that connect shallow beds with deeper beds in the aquifer, thus explaining the detections of some VOC species at intermittent depths.

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