HYDROGEOLOGY AND WATER QUALITY OF THE GALENA-PLATTEVILLE AQUIFER AT THE PARSON'S CASKET HARDWARE SUPERFUND SITE, BELVIDERE, ILLINOIS, 1991-92

by Patrick C. Mills

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PREFACE

The Parson's Casket Hardware site in Belvidere, Ill., is designated a Superfund site under the U.S. Environmental Protection Agency (USEPA) Comprehensive Environmental Response, Compensation, and Liability Act program. As part of the site investigation, the USEPA requested that the U.S. Geological Survey (USGS) investigate contaminant migration in the uppermost bedrock aquifer, the Galena-Platteville aquifer. The USGS investigation, beginning in August 1990, has been done in three phases. The following Open-File Report, originally prepared as an interagency letter (USGS Administrative Letter Report) to the USEPA, describes the results of the third phase of the investigation.

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March 15, 1993

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Dear Sir or Madam:

The purpose of this letter is to describe the results of the final phase (phase 3) of the U.S. Geological Survey's (USGS) ground-water investigation at the Parson's Casket Hardware site, Belvidere, Ill. (figs. 1 and 2), for the U.S. Environmental Protection Agency (USEPA). Included in this letter are brief descriptions of (1) study methods employed in the phase 3 investigation that have not been previously described in earlier reports, and (2) results of the phase 3 investigation as they relate to the results of the previous phases of the investigation. The data from the phase 3 investigation that are presented and described herein were collected during November 1991-January 1992.

The Galena-Platteville aquifer is the uppermost bedrock aquifer beneath the site. The Glenwood Formation of Ordovician age, a potential confining unit, separates the Galena-Platteville aquifer from the underlying St. Peter Sandstone aquifer (fig. 3). The St. Peter Sandstone aquifer is an important source of ground water to Belvidere and other cities in the region.

The phase 3 investigation was done (1) to determine the lithology of the Glenwood Formation; (2) to determine the vertical distribution of horizontal hydraulic conductivity (K) and concentrations of volatile organic compounds (VOC's) in the upper 150 ft (feet) of the Galena-Platteville aquifer at an existing monitoring location, borehole G127GP (figs. 2 and 3); and (3) to confirm the presence or absence of VOC's in the St. Peter Sandstone aquifer at a new monitoring location, well G127SP (figs. 2 and 3). Additional components of the site investigation described in this letter include determination of vertical hydraulic gradients between the Galena-Platteville and St. Peter Sandstone aquifers and in situ measurement of selected water-quality characteristics (pH, temperature, specific conductance, Eh, and dissolved oxygen) in borehole G127GP.

The results of the first and second phases of the USGS investigation at the Parson's Casket Hardware site are presented in two previous USGS Open-File Reports prepared for the USEPA (Mills, 1993a, 1993b). These reports describe the hydrogeology of the study site, principally the Galena-Platteville aquifer, and the distribution of VOC concentrations in the Galena-Platteville aquifer. (The stratigraphic nomenclature used in this report is that of the Illinois State Geological Survey (Willman and others, 1975, p. 47-87) and does not necessarily follow the usage of the USGS. The aquifer nomenclature is that generally used by the Illinois State Geological Survey and the U.S. Environmental Protection Agency.) The previous two reports also describe most of the study methods employed in the phase 3 investigation.

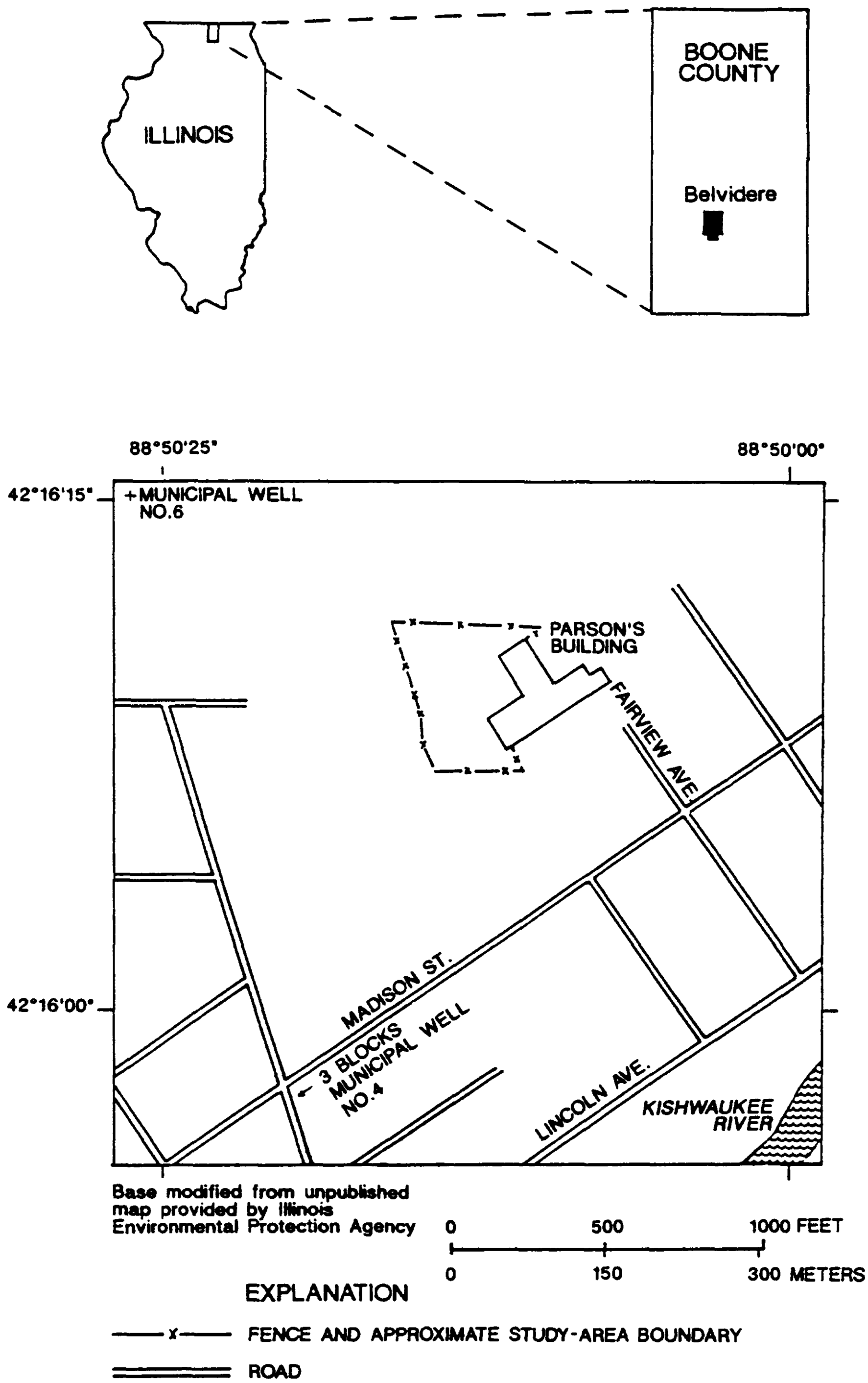
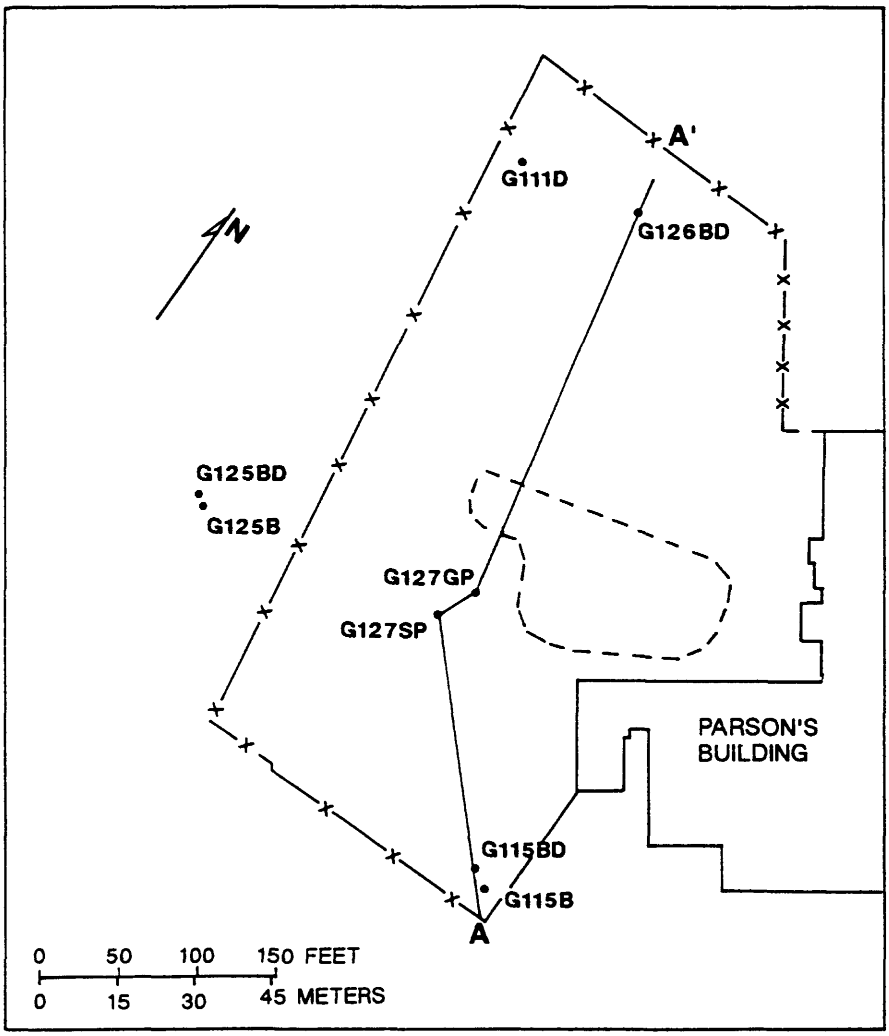


Figure 1.--Location of Parson's Casket Hardware Superfund site.



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 IN FIGURE 3

•G127SP BEDROCK BOREHOLE OR WELL AND DESIGNATION

Figure 2.--Location of boreholes and observation wells in the study area.

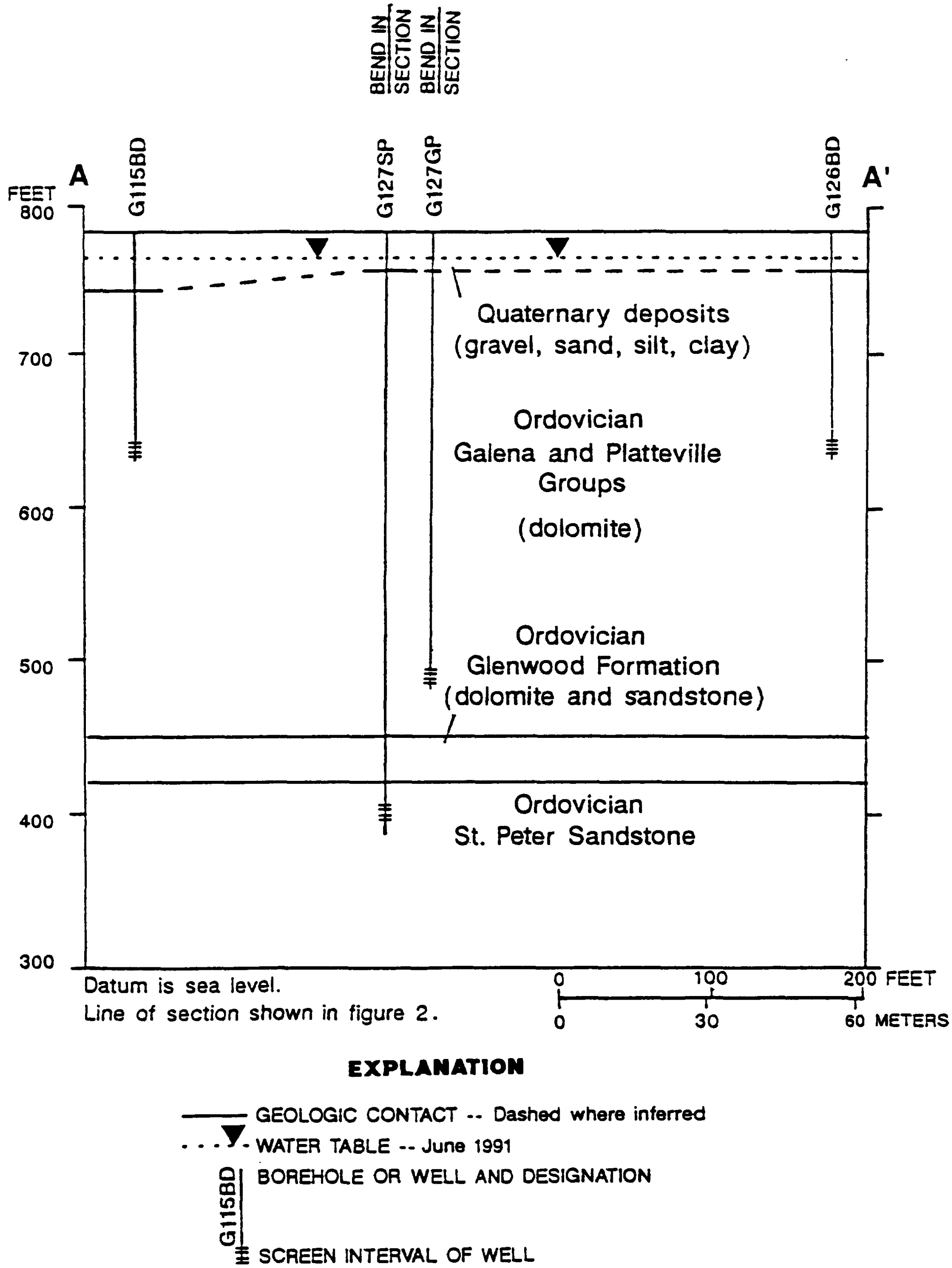


Figure 3.--Geologic section A-A' of the study site.

Information regarding drilling of the existing monitoring location, borehole G127GP, is presented in Mills (1993b). The diameter of borehole G127GP was 6 in. (inches); construction characteristics of the borehole are presented in table 1. After the completion of all tests in borehole G127GP, a 2-in.-inside-diameter, stainless-steel screen and riser were installed in the borehole, and it was redesignated as well G127GP. Construction characteristics of well G127GP are presented in table 1.

Well G127SP was installed as part of the phase 3 investigation to allow ground-water sampling in the St. Peter Sandstone aquifer and to provide lithologic information from the lower part (below a depth of 300 ft below land surface) of the Galena-Platteville aquifer and the Glenwood Formation. The well was constructed by cementing an 8-in.-inside-diameter, black-steel surface casing through the entire 24 ft of surficial glacial-drift deposits and the upper 11 ft of the dolomite bedrock. By use of an air hammer, a 6-in.-diameter borehole was drilled to a depth of 300 ft. The bedrock was then cored from 300 to 394 ft by use of a core bit with a 5-in. outside diameter and a 3-in. inside diameter. The materials used to construct well G127SP were similar to the materials used to construct well G127GP. Well-completion information for well G127SP is presented in table 1.

Borehole G127GP was developed prior to the phase 2 (Mills, 1993b) and phase 3 (table 2) investigations. Well G127GP was developed about 2 weeks after it was constructed (table 2). About 6 well volumes (225 gallons) were removed from the well at a rate of about 5 gal/min (gallons per minute).

The borehole drilled for well G127SP was not developed because discrete-depth interval tests were not done in the borehole. Well G127SP, finished in cored sandstone that was generally free of fine-grained materials, was developed about 2 weeks after it was constructed (table 2). About 10 well volumes (500 gallons) were removed from the well at a rate of about 5 gal/min.

Turbidity was not monitored during development of wells G127GP and G127SP, however, the discharge water was visibly free of fine-grained material within four well volumes for well G127GP and within one well volume for well G127SP. Specific conductance, pH, and Eh were monitored for stability when the wells were purged before sampling.

Borehole G127SP was geophysically logged, as was the borehole drilled for well G127SP. Borehole G127GP was logged for natural-gamma activity, temperature, and fluid resistivity. Logging in well G127SP included 3-arm-caliper, natural-gamma, spontaneous-potential, single-point-resistance, temperature, and fluid-resistivity logs. Because borehole G127GP was logged extensively during the phase 2 investigation (Mills, 1993b), logging during the phase 3 investigation was limited to a few log types. Boreholes G115BD, G125BD, and G126BD (fig. 2) also were geophysically logged during the phase 2 investigation (Mills, 1993b).

The results of geophysical logging in borehole G127GP and well G127SP during the phase 3 investigation generally corroborated the results of logging in boreholes G127GP, G115BD, G125BD, and G126BD during the phase 2 investigation.

Table 1.--Description of borehole and observation wells

Borehole or well number	Instal-lation date	Land-surface altitude, in feet above sea level	Measuring-point altitude, in feet above sea level[1]	Total depth of hole, in feet below land surface[2]	Open or screened interval, in feet below land surface	Aquifer that well or borehole is open to
[3]G127GP	04-27-91	783.8	--	301.0	41.0-301.0	Galena-Platteville
G127GP	12-11-91	783.8	785.20	301.0	[4]288.9-293.9	Galena-Platteville
G127SP	12-12-91	783.5	785.28	394.3	[5]370.6-375.7	St. Peter Sandstone

[1] Measuring point is top of well riser (casing).

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

[3] Borehole; data represents open-borehole interval.

[4] Gravel-pack interval before installation of the overlying bentonite seal was 279.2 to 301.0 feet below land surface.

[5] Gravel-pack interval before installation of the overlying bentonite seal was 361.9 to 379.2 feet below land surface.

Table 2.--Purging and sampling summary for borehole G127GP and observation wells G127GP and G127SP

Test interval, in feet below land surface	Borehole or well volume, in gallons	Borehole or well volume, in gallons	Number of borehole or well volumes purged	Date borehole or well purged/sampled
		Borehole G127GP		
55.6- 75.6	33.7	102	3.0	11-26-91
75.6- 95.6	37.3	120	3.2	11-25-91
95.6-115.6	40.7	123	3.0	11-22-91
115.6-135.6	43.0	129	3.0	11-21-91
135.6-155.6	44.7	138	3.1	11-21-91
273.8-301.0	77.9	235	3.0	11-20-91
41.0-301.0	380	2,125	5.6	11-18-91
		Well G127GP		
288.9-293.9	38	225	5.9	12-27-91
	38	114	3.0	01-30-92
		Well G127SP		
370.6-375.7	52	500	9.6	12-27-91
	52	164	3.1	01-06-92
	52	312	[1]6.0	01-30-92

[1] Ground water was sampled for analysis of volatile organic compounds after three well volumes were purged and again after six well volumes were purged.

One notable difference between the logs of boreholes G127GP and G127SP was the amount or type of clay indicated by the natural-gamma log in the lower part of the Platteville Group (the lowermost stratigraphic unit in the Galena-Platteville aquifer). The log of borehole G127GP indicates that the clay content of the dolomite increases below a depth of about 260 ft. The log of well G127SP indicates that the clay content of the dolomite decreases below a depth of about 260 ft. The high natural-gamma activity recorded in the lower part of borehole G127GP may also represent a difference in the type of matrix clay at this depth and location. In a study of the Galena-Platteville dolomite at a site about 40 miles southwest of the Parson's Casket Hardware site, it was determined that potassium clays with one radioactive signature and uranium and thorium clays with other radioactive signatures are both present within the dolomite unit (F.L. Paillet, U.S. Geological Survey, written commun., 1991). The apparent difference in the clay content or type in the dolomite appears to be the result of natural depositional variability. This finding is somewhat unexpected, because geohydrologic data from 150-ft-deep boreholes G115BD, G125BD, and G126BD indicated that, generally, horizontal variability of the lithologic and hydraulic properties of the dolomite is minimal (Mills, 1993a).

There also was a difference in the temperature and fluid-resistivity logs from borehole G127GP and well G127SP. The difference in the logging results is attributed to differences in the logging procedures for the two sites. Borehole G127GP was logged after the borehole was developed and borehole-flow conditions were allowed to stabilize. Well G127SP was logged in the undeveloped borehole about 24 hours after the completion of drilling. It is assumed that the temperature- and fluid-resistivity-log data from well G127SP represent the homogenous mixing of water in the borehole, which occurred during drilling.

Rock-core data (table 3) and geophysical-log data from well G127SP indicate that the base of the Platteville Group is at a depth of about 332 ft. The underlying Glenwood Formation extends to a depth of about 361 ft. The upper 22 ft of the Glenwood Formation is composed primarily of dolomite, the lower 6 ft primarily of sandstone. The Harmony Hill Shale Member of the Glenwood Formation is absent beneath the study site.

Where present, the Harmony Hill Shale Member of the Glenwood Formation is known to function as a semiconfining unit (Kay, 1989). With the absence of this shale unit beneath the site, it is likely that the Galena-Platteville aquifer and the St. Peter Sandstone aquifer are hydraulically connected. Additionally, it is assumed that the dolomite strata of the Glenwood Formation are hydraulically similar to the overlying Galena-Platteville aquifer and the sandstone strata to the underlying St. Peter Sandstone aquifer. Although the likelihood of hydraulic connection between the two aquifers is supported by the presence of VOC's in the St. Peter Sandstone aquifer (as will be described subsequently), additional aquifer-test and water-level data are necessary to determine the extent of the connection.

The absence of the Harmony Hill Shale Member beneath the site, as determined during the phase 3 investigation, has implications with regard to the multiple-well aquifer test done at the site in June 1991. One of the implied assumptions of the aquifer test was that the Galena-Platteville aquifer is underlain by a confining unit. If the Glenwood Formation does not function as a confining unit, then a substantial amount of water supplied to the pumped well during the test may have been derived from the St. Peter Sandstone aquifer. The aquifer-test data presented in Mills (1993b) probably should be qualified or reevaluated in light of the subsequent finding regarding the local absence of the Harmony Hill Shale Member.

A packer assembly (Mills, 1993a, 1993b) was used in borehole G127GP to do aquifer tests. The objective of the aquifer tests was to determine the K of discrete-depth intervals of the Galena-Platteville aquifer. As in previous phases of the investigation at the site (Mills, 1993a, 1993b), the aquifer tests included slug tests and constant-discharge tests. The tests were done in five 20-ft intervals from 56 to 156 ft below land surface and in the interval from 274 to 301 ft below land surface. Tests previously were done in the interval from 41 to 56 ft below land surface (the uppermost interval open to the bedrock aquifer) and in seven 20-ft intervals from 145 to 301 ft below land surface (Mills, 1993b).

Table 3.--Lithologic log for well G127SP

Grab samples of cuttings from 250 to 300 feet below land surface are briefly described. Cores were collected continuously from 300 to 394 feet below land surface; the cores were 2.5 in. (inches) in diameter.

Depth below land surface, in feet	Core or cutting description
	Platteville Group (?)
242	Dolomite, buff
266	Dolomite, gray
282	Dolomite, buff to gray
	Platteville Group
300.0-304.6	Dolomite, light gray; dense; beds generally 12 in. thick; solution (up to 1 in.) along bedding planes common; medium- to dark-gray clay partings, wavy; finely crystalline; vesicles and vugs (shell molds) rare; rare fossils (gastropods, brachiopods)
304.6-306.3	Dolomite, light- to medium-gray, buff mottling; reddish-brown clay partings on bedding planes, otherwise similar to overlying interval
306.3-311.5	Dolomite, buff with medium-gray mottling; black to grayish-brown clay partings on bedding planes, otherwise similar to overlying interval
311.5-315.0	Dolomite, buff with medium-gray mottling; dense; beds generally 3 to 6 in. thick; solution (up to 1 in.) along bedding planes common; black to grayish-brown clay partings, wavy; finely crystalline; vesicles and vugs rare; rare fossils (gastropods, brachiopods), ribbon bryozoans on bedding planes; bioturbation common with small, medium- to dark-gray reticulation
315.0-325.0	Dolomite, buff with light- to medium-gray mottling; dense; beds 12 to 20 in. thick; solution along bedding planes rare; medium-brown clay partings, wavy; partings thinner, less distinct than in overlying interval; finely crystalline; vesicles and vugs rare, vugs less than 0.25 in. in diameter; rare fossils; bioturbation common with small, medium- to dark-gray reticulation

Table 3.--Lithologic log for well G127SP--Continued

Depth below land surface, in feet	Core or cutting description
	Platteville Group--Continued
325.0-330.0	Dolomite, buff with light- to medium-gray mottling; clay partings thicker, more distinct than in overlying interval, otherwise similar
330.0-332.0	Dolomite, buff with light- to medium-gray mottling; dense; beds 0.8 to 1 in. thick; solution along bedding planes rare; reddish-brown clay partings, thin, wavy; finely crystalline; vesicles and vugs rare; rare fossils; bioturbation rare to common with small, medium- to dark-gray reticulation; dolomite is arenaceous in lower part of interval; basal 0.1 in. is reddish-brown clay seam, wavy; clay seam penetrates into underlying beds
	Glenwood Formation
332.0-333.8	Sandstone, argillaceous, light-gray; medium dense; beds 0.2 to 0.8 in. thick; sand medium grained, subrounded; clay in matrix and in fine layers that are more common in basal 6 in. of interval
333.8-341.0	Calcitic dolomite, greenish-light- to medium-gray, very finely crystalline, glauconitic; medium dense; beds 12 to 34 in. thick; bioturbation common in uppermost 1 in.; thin arenaceous clay layers at 334.0 and 334.3 ft; clean, distinct fractures about 45 degrees to bedding at 335.3 ft and 336.0 ft; thin zone of coarsely crystalline dolomite around bedding plane at 334.8, minor dissolution; small vesicles common at about 334.8 and 335.6 ft; very common glauconite at 337.1 to 337.8 ft and 338.8 to 339.6 ft, increasing glauconite near midsection to base of each interval as sand content (very fine grained) increases
341.0-341.2	Sandstone, greenish-gray; glauconitic; quartz sand medium grained, subrounded to well rounded
341.2-342.6	Calcitic dolomite, greenish-light- to medium-gray, very finely crystalline, glauconitic; rare to common very fine to fine grained sand; medium dense; beds 12 to 34 in. thick

Table 3.--Lithologic log for well G127SP--Continued

Depth below land surface, in feet	Core or cutting description
	Glenwood Formation--Continued
342.6-342.8	Sandstone, greenish-gray; glauconitic; quartz sand fine grained, subrounded to well rounded
342.8-355.8	Calcitic dolomite, light- to medium-greenish-gray, very finely crystalline; argillaceous, glauconitic; quartz sand rare to common, very fine to fine grained, subrounded to well rounded, variable distribution through interval; sand and glauconite increasingly common in basal 2 ft of interval; medium-dark-green glauconite in zones around bedding planes at 347.0 to 348.0 ft; medium dense; beds 12 to 24 in. thick, as thin as 3 in. in uppermost 2 ft; small vesicles rare to common in uppermost 3 ft of interval, otherwise rare to nonexistent; rare fine-grained pyrite
355.8-356.0	Sandstone, light- to medium-gray; rare glauconite; quartz sand very fine to fine grained; moderately friable; rare fine-grained pyrite; sharp contact overlying interval; gradational basal contact
356.0-356.2	Dolomite-pebble conglomerate, light- to medium-gray argillaceous with very fine grained sand; pebbles subangular, 0.06 to 0.2 in. long, subparallel bedding; thin zone of pyrite near base of interval; gradational basal contact
356.2-357.2	Sandstone, light- to medium-gray; rare glauconite; quartz sand very fine to fine grained; moderately friable; gradational basal contact
357.2-360.0	Calcitic sandstone, medium-gray, with light-gray mottling; quartz sand fine to medium grained, very fine grained near base of interval; vesicles common, vugs rare; rare fine pyrite
360.0-360.4	Sandstone, medium-green-gray; quartz sand fine to medium grained, subrounded, moderately friable; gradational basal contact
360.4-361.1	Calcitic sandstone, medium-green-gray; quartz sand fine grained; slightly argillaceous; pyrite common along bedding planes and penetrating into matrix; sharp basal contact

Table 3.--Lithologic log for well G127SP--Continued

Depth below land surface, in feet	Core or cutting description
	St. Peter Sandstone
361.1-394.3	Sandstone, very light to light-green; glauconitic, with glauconite variably distributed through the matrix and in thin laminations; quartz sand fine to medium grained, well rounded, friable

The slug tests were analyzed by use of the method of Bouwer and Rice (1976), and constant-discharge tests were analyzed by use of the method of Cooper and Jacob (1946). The reader is referred to the cited references and to Mills (1993a, 1993b) for information regarding the controlling assumptions and the applied procedures of the tests. The analytic results of the aquifer tests are presented in table 4.

Table 4.--Estimated horizontal hydraulic conductivities of the Galena-Platteville dolomite, as determined from slug tests and constant-discharge aquifer tests in borehole G127GP

[All data except test intervals are hydraulic conductivities in feet per day; ND means test was not done; dashes (--) mean test data were not interpretable because of significant violations of operating assumptions of the analytic methods of Bouwer and Rice (1976) and Cooper and Jacob (1946)]

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
55.6- 75.6	$5.0x10^{-2}$	$3.5x10^{-2}$	ND	ND
	$4.0x10^{-2}$	ND		
75.6- 95.6	$2.4x10^{-1}$	$2.7x10^{-1}$	ND	ND
95.6-115.6	$4.7x10^{-1}$	$4.2x10^{-1}$	ND	ND
115.6-135.6	$3.2x10^{-1}$	$3.4x10^{-1}$	$1.4x10^{-1}$	$1.1x10^{-1}$
135.6-155.6	--	--	--	--
273.8-301.0	$7.4x10^{-1}$	--	--	--

The aquifer tests in borehole G127GP were affected to varying degrees by pumping of the nearby Belvidere municipal wells (Well No. 4 and Well No. 6; fig. 1). The effects of municipal-well pumping on the Galena-Platteville aquifer beneath the site and on previous aquifer tests at the site are described in Mills (1993a, 1993b). The transient effects of municipal-well pumping on some tests were significant enough to preclude reliable estimation of K by the Bouwer and Rice (1976) and the Cooper and Jacob (1946) analytic methods. Data from these test intervals are omitted from table 4. As described in Mills (1993a, 1993b), other factors, including aquifer heterogeneity and anisotropy, also may have affected the aquifer tests. It is presumed that the effects of aquifer heterogeneity and anisotropy on the tests would be less than the effects of municipal-well pumping because of the limited spatial domain tested by the slug tests and the low-discharge (about 1 gal/min) pumping tests.

The aquifer tests in the depth interval from 135.6 to 155.6 ft were the tests most affected by municipal-well pumping. This indicates that the best hydraulic connection between borehole G127GP and the municipal wells may be at this depth; however, K values from this depth interval in other boreholes at the site indicate otherwise. The K values at this depth interval typically were about 0.5 ft/d (foot per day). The unique water-level trends during the aquifer tests in the 135.6 to 155.6 ft interval may have been in response to municipal-well pumping rates that were substantially greater during the tests in that interval than during the tests in other intervals.

The vertical distribution of K in the Galena-Platteville aquifer, as determined at boreholes G115BD, G125BD, G126BD, and G127GP (fig. 2), was discussed previously in Mills (1993a, 1993b). The K values determined from tests in borehole G127GP during the phase 3 investigation (table 4) support previous findings concerning the vertical distribution of K in the aquifer. The K data from borehole G127GP and other site boreholes (Mills, 1993a) indicate an interval of relatively low K, about 0.05 ft/d, near the top of the aquifer (about 40 to 80 ft below land surface). The interval seems to be continuous across the site, although K may be slightly higher in the vicinity of borehole G125BD. Previous testing indicates that this low-K interval is between intervals of higher K. The overlying interval, composed of the approximately 5-ft-thick weathered bedrock surface, has a K of about 1 to 200 ft/d (Mills, 1993a). The underlying 80-ft-thick interval has a K of about 0.5 ft/d (Mills, 1993a, 1993b).

The hydraulically important bedding-plane fissure identified at a depth of about 125 ft by downhole flowmeter and acoustic-televiewer logging in borehole G127GP (Mills, 1993b) and by discrete-interval aquifer testing in other site boreholes (Mills, 1993a) was not revealed by the phase 3 aquifer-test results from borehole G127GP. Previous testing indicated a K of about 0.5 to 10 ft/d (Mills, 1993a) for the depth interval of the fissure. The phase 3 testing indicated a K of about 0.3 ft/d. It seems that the 20-ft packer interval used in the phase 3 tests was insensitive to the hydraulic effects of the thin (aperture less than about 6 in.), elevated-K interval. Packer intervals of 10 ft were used in the phase 1 tests in other boreholes at the site (Mills, 1993a).

Water levels measured in wells G115BD, G126BD, G126BD, G127GP and G127SP (fig. 2) were used to determine vertical hydraulic gradients within the lower part of the Galena-Platteville aquifer and between the Galena-Platteville and St. Peter Sandstone aquifers. Data used to calculate the vertical hydraulic gradients are presented in table 5. Vertical hydraulic gradients between the overlying glacial drift and Galena-Platteville aquifers and between the upper and middle parts of the Galena-Platteville aquifer have been described previously (Mills, 1993a, 1993b, respectively).

Table 5.--Water-level altitudes and vertical hydraulic gradients in observation wells G127GP and G127SP

Open interval,[1] in feet below land surface				Water-level altitude, in feet above sea level		Vertical hydraulic gradient	
Well G127GP	Well G127SP	Date	Time	Well G127GP	Well G127SP	Magnitude, in foot per foot	Direction
279.2-301.0	361.9-379.2	01-06-92	1040	735.66	725.49	0.13	Down
		01-30-92	1000	717.18	722.37	.06	Up

[1] Gravel-pack interval before installation of the overlying bentonite seal.

Hydraulic gradients between about the midpoint and the base of the Galena-Platteville aquifer ranged from 0.13 to 0.18 ft/ft. The gradients were slightly higher than gradients determined in shallower parts of the aquifer. Gradients are reported to be 0.07 to 0.12 ft/ft between the upper and middle parts of the Galena-Platteville aquifer and about 0.03 ft/ft between the overlying glacial drift aquifer and the uppermost part of the Galena-Platteville aquifer (Mills, 1993b).

The slightly elevated gradients in the lower part of the Galena-Platteville aquifer indicate that strata of low K may be present at depth. This possibility seems to be supported by data collected from aquifer tests and ground-water sampling (Mills, 1993b). If present, the low K strata do not seem to have affected the downward movement of VOC's throughout the aquifer (as will be described subsequently).

It is also possible that the gradients determined for the lower part of the aquifer may not be representative of actual gradients in the aquifer because the hydraulic data collected at the wells were not ideally vertically nested. With horizontal distances between the shallow wells and the deep well of 170 to 270 ft, the gradient data may be affected by lateral heterogeneity in hydraulic properties of the aquifer.

The direction and the magnitude of the vertical hydraulic gradient between the Galena-Platteville and the St. Peter Sandstone aquifers changes with time. On January 6, 1992, the gradient was downward at 0.12 ft/ft; on January 30, 1992, it was upward at 0.05 ft/ft. The relatively low hydraulic gradient between the aquifers indicates that the intermediary Glenwood Formation is not a significant barrier to ground-water flow between the Galena-Platteville and St. Peter Sandstone aquifers. This conclusion is supported by the rock-core and geophysical-log data that indicate the relative absence of low-permeability geologic materials in the Glenwood Formation.

The change in the direction and magnitude of the vertical hydraulic gradient is attributed to the effects of municipal-well pumping. Similar changes previously have been detected during ground-water-flow measurements in the Galena-Platteville aquifer (Mills, 1993b).

The vertical distribution of water quality in the Galena-Platteville and St. Peter Sandstone aquifers was characterized by means of three approaches. First, the packer assembly was used as a means for collecting water samples from discrete depth intervals in borehole G127GP. Second, a downhole monitor was used to measure selected water-quality characteristics in situ at selected depths in borehole G127GP. Third, water samples were collected from wells G127GP and G127SP. Multiple water samples were collected from the wells for the purpose of verifying water-quality analytic results and for determining the potential for remediating water-quality problems in the aquifers by pumping.

Collection of the water samples from borehole G127GP and wells G127GP and G127SP followed previously described procedures (Mills, 1993a, 1993b). The purging summary for the water sampling is presented in table 2. Selected water-quality characteristics for the water samples were measured in the field by use of a flow-through cell attached to the discharge outlet of the sampling pump. The field measurements of the water quality were recorded (table 6), and the samples were analyzed for selected inorganic constituents (tables 7 and 8) and VOC's (table 9). The vertical distribution of field-measured water-quality characteristics, selected inorganic constituents (calcium, magnesium, sodium, sulfate, fluoride, and chloride), and VOC's in the Galena-Platteville aquifer, as determined at related depth intervals in boreholes G115BD, G125BD, G126BD, and G127GP (fig. 3) was described previously in Mills (1993a, 1993b).

In situ water quality was measured in borehole G127GP (table 10) by use of a Hydrolab Surveyor II downhole water-quality monitor. (Use of trade and brand names in this report are for identification purposes only and does not constitute endorsement by the USGS.) For the borehole water-quality screening, the monitor was lowered to the base of the borehole, and ground-water conditions in the borehole were allowed to equilibrate for about 2 hours before in situ measurements were recorded. The monitor was moved up the borehole in 5- to 20-ft increments. Five minutes were allowed for equilibration of ground-water conditions at each depth increment before measurements were made.

As a note of caution, the possible effect of temporal bias must be considered in the evaluation of the spatial distribution of water quality. Constituent concentrations and values of water-quality indicators presented in the following evaluation of the spatial distribution of water quality were determined over a period of as long as 2 years. Inspection of water-quality data from monitoring locations that have been sampled repetitively indicates that, at some locations, water quality has changed with time. For the most part, however, the following conclusions regarding the spatial distribution of water quality are considered to be valid irrespective of these temporal changes in water quality.

Table 6.--Selected field measurements of water-quality characteristics of ground water in borehole G127GP and observation wells G127GP and G127SP

[--, no data]

Test interval, in feet below land surface	Date of sample	Water-quality characteristics: pH, in standard units	Temperature, in degrees Celcius	Specific conductance, in microsiemens per centimeter at 25 degrees Celsius	Eh, in millivolts	Dissolved oxygen, in milligrams per liter
		Borehole G127GP				
55.6- 75.6	11-26-91	7.2	10.9	580	-26	--
75.6- 95.6	11-25-91	7.2	10.6	740	-54	--
95.6-115.6	11-22-91	7.0	11.7	750	-59	--
115.6-135.6	11-21-91	7.2	11.0	730	-32	--
135.6-155.6	11-21-91	7.3	11.3	700	-30	--
273.8-301.0	11-20-91	7.1	11.0	700	-29	--
		Well G127GP				
288.9-293.9	01-30-92	6.8	11.3	740	73	0.45
		Well G127SP				
370.6-375.7	01-06-92	7.1	10.8	1,030	150	--
	01-30-92	7.0	10.7	1,040	190	.40

Table 7.--Inorganic-constituent (cation) concentrations in ground water from borehole G127GP and observation wells G127GP and G127SP

[All concentrations in part(s) per billion (ppb); NA, not analyzed; dashes (--) mean concentration below instrument reporting limits]

Test interval, in feet below land surface	Date of sample	SMO number[1]	Calcium	Iron	Magne-sium	Manga-nese	Sodium	Zinc	Alumi-num	Anti-mony
					Borehole G127GP					
55.6- 75.6	11-26-91	USGS	77,000	NA	29,000	NA	5,000	NA	NA	NA
75.6- 95.6	11-25-91	USGS	92,000	NA	35,000	NA	15,000	NA	NA	NA
95.6-115.6	11-22-91	USGS	92,000	NA	36,000	NA	17,000	NA	NA	NA
115.6-135.6	11-21-91	USGS	87,000	NA	36,000	NA	17,000	NA	NA	NA
135.6-155.6	11-21-91	USGS	86,000	NA	36,000	NA	12,000	NA	NA	NA
273.8-301.0	11-20-91	USGS	87,000	NA	34,000	NA	11,000	NA	NA	NA
					Well G127GP					
[2]288.9-293.9	01-30-92	MEPY29	77,400	42.4	32,900	48.3	15,700	--	--	--
					Well G127SP					
[3]370.6-375.7	01-06-92	USGS	110,000	NA	42,000	NA	40,000	NA	NA	NA
	01-30-92	MEPY28	105,000	67.5	40,700	216	37,800	--	21.3	--

Test interval, in feet below land surface	Arsenic	Barium	Chromium	Cobalt	Cyanide	Nickel	Potas-sium	Sele-nium
				Borehole G127GP				
55.6- 75.6	NA	NA	NA	NA	NA	NA	NA	NA
75.6- 95.6	NA	NA	NA	NA	NA	NA	NA	NA
95.6-115.6	NA	NA	NA	NA	NA	NA	NA	NA
115.6-135.6	NA	NA	NA	NA	NA	NA	NA	NA
135.6-155.6	NA	NA	NA	NA	NA	NA	NA	NA
273.8-301.0	NA	NA	NA	NA	NA	NA	NA	NA
				Well G127GP				
[2]288.9-293.9	9.7	144	3.8	--	NA	17.7	2,190	14.7
				Well G127SP				
[3]370.6-375.7	NA	NA	NA	NA	NA	NA	4,700	NA
	5.2	110	--	10.6	--	140	4,490	14.7

[1] U.S. Environmental Protection Agency Sample Management Office (analyzed by contract Laboratory); otherwise analyzed by U.S. Geological Survey National Water Quality Laboratory, Arvada, Colo. (designated as USGS).

[2] Also detected: copper, 5.10 ppb; lead, 3.0 ppb.

[3] Also detected: copper, 21.2 ppb; lead, 2.3 ppb.

Table 8.--Inorganic-constituent (anion) concentrations in ground water from borehole G127GP and observation well G127GP

[All concentrations in part(s) per million; NA, not analyzed; --, concentration below instrument reporting limits]

Test interval, in feet below land surface	Date of sample	SMO number[1]	Nitrite-nitrate	Sulfate	Fluoride	Chloride	Akalinity, as calcium carbonate[2]
				Borehole G127GP			
55.6- 75.6	11-26-91	USGS	NA	18	0.20	4.2	330
75.6- 95.6	11-25-91	USGS	NA	52	.20	9.4	360
95.6-115.6	11-22-91	USGS	NA	59	.20	9.8	350
115.6-135.6	11-21-91	USGS	NA	58	.20	9.7	340
135.6-155.6	11-21-91	USGS	NA	48	.20	9.0	330
273.8-301.0	11-20-91	USGS	NA	46	.20	9.0	340
				Well G127GP			
288.9-293.9	01-30-92	7050E-16	--	346	NA	13.2	350
				Well G127SP			
370.6-375.7	01-06-92	USGS	NA	98	.40	42	410
	01-30-02	7050E-17	4.4	[3]84	NA	37	400

[1] U.S. Environmental Protection Agency Sample Management Office (analyzed by contract laboratory); otherwise analyzed by U. S. Geological Survey, National Water Quality Laboratory, Arvada, Colo. (designated as USGS).

[2] Concentrations were determined in the laboratory.

[3] Concentrations are estimated.

Table 9.--Volatile organic compound concentrations in ground water from borehole G127GP and observation wells G127GP and G127SP

[All concentrations in part(s) per billion (ppb); 1,1-DCA, 1,1-dichloroethane; 1,1,1-TCA, 1,1,1-trichloroethane; 1,1-DCE, 1,1-dichlorethylene; 1,2-DCE, 1,2--dichloroethylene (total); TCE, trichloroethylene; PCE, tetrachloroethylene; dashes (--) mean concentration below instrument reporting limit; NA, not analyzed.]

Test interval, in feet below surface	Date of sample	Analytic laboratory number[1]	1,1-DCA	1,1,1-TCA	1,1-DCE	1,2-DCE	TCE	PCE	Toluene	Methylene chloride	Carbon disulfide
				Borehole G127GP							
[2]55.6- 75.6	11-26-91	USGS	4.5	160	3.0	[3]3	220	--	19	--	NA
75.6- 95.6	11-25-91	USGS	.2	5.7	--	[3].2	9.7	--	4.2	--	NA
95.6-115.6	11-22-91	USGS	.2	3.8	--	--	6.0	--	1.9	--	NA
115.6-135.6	11-21-91	USGS	1.1	6.7	.2	[3].2	14	--	1.9	--	NA
135.6-155.6	11-21-91	USGS	4.6	19	.8	[3].6	40	0.2	6.9	--	NA
273.8-301.0	11-20-91	USGS	1.3	11	.4	[3]1.4	31	[4].2	3.5	--	NA
				Well G127GP							
288.9-293.9	01-30-92	CRL	4	[5]48	1	[6]5	150	6	--	--	NA

Table 9.--Volatile organic compound concentrations in ground water from borehole G127GP and observation wells G127GP and G127SP--Continued

Test interval, in feet below surface	Date of sample	Analytic laboratory number[1]	1,1-DCA	1,1,1-TCA	1,1-DCE	1,2-DCE	TCE	PCE	Toluene	Methylene chloride	Carbon disulfide
				Well G127SP							
[7]370.6-375.7	01-06-92	USGS	6.4	500	9.1	[3]25	710	49	--	--	NA
	01-30-92	CRL	7	610	10	[6]31	880	50	--	--	--
	01-30-92	CRL	--	450	--	[4,6]21	670	36	--	--	--
	01-30-92	USGS	7.7	500	36	[3]31	650	42	--	--	NA

[1] USGS, U.S. Geological Survey, National Water Quality, Arvada, Colo., analyses have a reporting limit of 3 ppb, concentrations below that limit are estimated; CRL, U.S. Environmental Protection Agency, Region 5, Central Regional Laboratory, Chicago, Ill.

[2] Also detected 1,2-dichloroethane, 0.2 ppb; 1,1,2-trichloroethane, 0.5 ppb.

[3] Cis 1,2-dichloroethylene.

[4] Concentration is estimated.

[5] Concentration detected in sample duplicate.

[6] Total 1,2-dichloroethylene.

[7] First sample collected on January 30, 1992, was obtained after three well volumes were purged; second and third samples were obtained after six well volumes were purged. Chloroform, 3 ppb and 4.2 ppb, respectively, were also detected in the samples collected at three well volumes and analyzed by the CRL and at six well volumes and analyzed by the USGS.

Table 10.--In situ water-quality measurements of ground water in borehole G127GP determined by use of a downhole water-quality monitor[1]

[°C, degrees Celsius; μS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; -- no data]

Approximate monitoring depth, in feet below land surface	Monitoring depth below water surface, in feet	Depth to water surface, in feet[2]	Time	pH, in standard units	Temperature (°C)	Specific conductance (μS/cm)[3]	Eh, in millivolts	Dissolved oxygen (mg/L)
39.2	[4]1.6	39.60	1842	7.05	11.31	830	33	2.66
44.9	4.7	42.57	1834	7.04	11.27	840	30	2.22
49.8	9.4	42.76	1827	7.04	11.26	820	14	1.86
55.0	14.5	42.82	1820	7.07	11.24	760	7	1.68
59.7	19.4	42.66	1812	7.11	11.25	700	-6	1.52
64.4	23.9	--	1805	7.13	11.26	650	-21	1.23
69.4	28.9	42.79	1759	7.13	11.26	630	-28	.99
80.3	39.6	43.04	1750	7.13	11.28	610	-33	.66
90.1	[5]49.6	43.15	1739	7.11	11.31	650	-59	.20
95.1	54.3	43.13	1733	7.11	11.34	650	-67	.15
105.0	64.1	43.27	1726	7.13	11.31	650	-74	.10
115.2	74.0	--	1717	7.11	11.32	660	-74	.06
120.3	79.1	43.55	1712	7.11	11.33	660	-74	.05
125.2	84.0	--	1659	7.11	11.32	670	-74	[6].05
130.3	88.8	43.81	1652	7.11	11.33	660	-73	.04
135.7	93.7	--	1645	7.11	11.34	650	-72	.05
145.7	103.5	--	1638	7.11	11.34	650	-71	.05
165.7	123.4	44.63	1629	7.10	11.31	640	-72	.05
186.4	143.5	--	1621	7.10	11.28	630	-72	.04
206.0	162.8	--	1612	7.11	11.29	610	-72	.04

Table 10.--In situ water-quality measurements of ground water in borehole G127GP determined by use of a downhole water-quality monitor[1]--Continued

Approximate monitoring depth, in feet below land surface	Monitoring depth below water surface, in feet	Depth to water surface, in feet[2]	Time	pH, in standard units	Temperature (°C)	Specific conductance (μS/cm)[3]	Eh, in millivolts	Dissolved oxygen (mg/L)
226.0	182.7	45.70	1607	7.11	11.27	620	-72	0.05
246.1	201.5	46.98	1559	7.10	11.27	620	-71	.03
257.2	210.5	49.07	1550	7.10	11.26	620	-70	.04
261.9	214.2	--	1544	7.10	11.26	620	-69	.04
266.9	219.4	--	1537	7.10	11.26	620	-62	.03
271.5	223.9	--	1530	7.08	11.23	610	-59	.03
281.9	234.5	--	1521	7.07	11.17	620	-60	.05
287.0	239.5	49.88	1514	7.08	11.17	630	-60	.03
292.2	244.7	49.87	1507	7.07	11.15	620	-62	.03
297.1	249.3	--	1501	7.04	11.14	620	-66	.03
301.7	254.1	49.93	1453	7.02	11.11	660	-76	.04

[1] Data collected with a Hydrolab Surveyor II Water-quality Monitor. (Use of trade and brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.) Data collected December 5, 1991.

[2] Depth to water measured from top of surface casing by use of an electric measuring tape. Measuring point is about 0.75 feet above land surface.

[3] Values tended to fluctuate by about +/- 15 units around approximate mean presented in the table.

[4] Meter was out of water when reading 1.6 feet.

[5] Approximate depth.

[6] Initial concentration was 0.11 milligram per liter; after about 1 minute, the concentration decreased to 0.5 milligram per liter.

Measurement of the specific conductance of water samples from borehole G127GP during the phase 3 (table 6) and phase 2 (Mills, 1993b) investigations indicates that the specific conductance of aquifer water is highest (940 µS/cm (microsiemens per centimeter at 25 degrees Celsius)) near the top of the borehole (41 to 56 ft; Mills, 1993b). Immediately below the interval of elevated specific conductance is an interval (56 to 76 ft) of relatively low specific conductance (580 µS/cm); the interval of low specific conductance is associated with an interval of relatively low K (10^{-2} ft/d; table 4). Below the depth of about 76 ft, the specific conductances are generally intermediate in value, declining slightly with depth. The specific conductance of water in the Galena-Platteville aquifer at borehole G127GP generally was lower than specific conductances recorded at other sampling locations in the aquifer at the site (Mills, 1993a).

The specific conductances of water sampled from the St. Peter Sandstone aquifer were substantially higher than the specific conductances recorded in the Galena-Platteville aquifer at nearby borehole G127GP. The specific conductances of water from the St. Peter Sandstone aquifer were similar to those recorded at other sampling locations in the Galena-Platteville aquifer (Mills, 1993b).

No consistent trends were indicated by the measurements of Eh of water sampled from the Galena-Platteville aquifer at the site (table 6 and Mills, 1993a, 1993b). Eh is an indicator of the oxidation-reduction potential of water. The Eh of water in borehole G127GP during phase 3 sampling (table 6) and phase 2 sampling (Mills, 1993b) changed from positive (maximum value of 74 mv (millivolts)) to negative (minimum value of -59 mv) with depth and time of measurement. The latter change is exemplified by the fact that measured values of Eh in the depth interval 274 to 301 ft during initial packer sampling were -29 to -52 mv (table 6 and Mills (1993b), respectively). Subsequent Eh in well G127GP, at the generally equivalent depth of 290 to 295 ft, was 73 mv. The Eh in all other sampling locations in the Galena-Platteville aquifer at the site was positive and generally less than 150 mv (Mills, 1993a).

The Eh of water sampled from the St. Peter Sandstone aquifer ranged from 150 to 190 mv. These positive Eh values were greater than all Eh values recorded in the Galena-Platteville aquifer (Mills, 1993b).

Results of the in-situ measurement of water-quality characteristics in borehole G127GP are presented in table 10. Dissolved-oxygen concentrations decreased with depth throughout the extent of the borehole; however, the concentrations were relatively stable below the depth of about 100 ft.

In situ specific conductance decreased with depth in borehole G127GP to about 60 ft, then were relatively stable between the depths of about 60 ft and 300 ft; specific conductances were slightly lower in the interval from 200 to 300 ft. There was a slight increase in specific conductance at the lowermost measurement depth (below about 297 ft).

In situ specific conductances were generally similar to the specific conductance recorded during packer sampling; however, above the depth of about 150 ft, the in situ measurements were slightly lower than the packer-sampling measurements. Additionally, the relatively low specific conductance recorded at a depth of 56 to 76 ft during packer measurements was not indicated by the in situ measurements. As expected, the distribution of specific conductances generally mirrored the values of fluid resistivity logged in the borehole--that is, specific conductance increases as fluid resistivity decreases.

The lowest in situ values of pH in borehole G127GP were recorded above the depth of about 55 ft below land surface and at the lowermost measurement depths (below about 295 ft). The values of pH were highest between the depths of about 55 and 270 ft. Intermediate values of pH were recorded between the depths of about 270 and 295 ft. Equivalent trends in pH were not evident in measurements during packer sampling because pH measurements were significant only to one-tenth of a pH unit.

The in situ Eh in borehole G127GP decreased rapidly with depth to about 100 ft. There was a gradual increase in Eh with depth between about 100 and 265 ft. Eh between the depths of about 265 and 295 ft was generally stable but slightly greater than in the interval above (depths of about 100 to 265 ft). Eh increased slightly near the base of the borehole (depths of about 295 to 302 ft). The in situ Eh was similar in range (-76 to 33 mv) to the packer-sampling values; however, unlike the packer-sampling values, the in situ values were all positive below a depth of about 60 ft.

Inorganic-constituent concentrations in ground water from borehole G127GP (tables 7 and 8; Mills (1993b)) generally were highest in the shallowest sampling interval near the top of the aquifer (41 to 56 ft). This finding is consistent with the finding that specific conductances were highest near the top of the aquifer. Specific conductance is an indicator of the amount of dissolved solids in water. Inorganic-constituent concentrations generally were lowest or relatively low in the second shallowest sampling interval (56 to 76 ft). As previously noted, the dolomite strata at this depth generally have the lowest values of K and specific conductance. Inorganic-constituent concentrations generally were intermediate below the depth of 76 ft. Within this lower interval (76 to 301 ft), concentrations generally were highest above the depth of about 150 ft.

The vertical distribution of fluoride concentrations differed from the above-described distribution of other inorganic constituents. For the most part, fluoride concentrations change little with depth. Mills (1993b) previously observed a slight increase in concentrations at a depth of about 260 ft. This increase seems to be associated with a hydraulically important fissure at that depth.

Concentrations of the cationic constituents from the packer-sampled interval of 136 to 156 ft in borehole G127GP were typically less than the concentrations detected at equivalent depths in wells G115BD, G125BD, and G126BD (Mills, 1993b); concentrations in the wells were equivalent to the concentrations recorded in the shallowest sampling interval in borehole G127GP. Anionic data from these wells were unavailable for comparison with the anionic data from borehole G127GP. With the exception of fluoride, inorganic-constituent concentrations in ground water from well G127SP in the St. Peter Sandstone aquifer generally were equivalent to concentrations recorded in the shallowest sampling interval in nearby borehole G127GP and to concentrations recorded in wells G115BD, G125BD, and G126BD (Mills, 1993a).

Volatile-organic-compound data obtained during the phase 3 site investigation are presented in table 9. The types of VOC's detected in ground water from borehole G127GP during phase 3 and phase 2 sampling (Mills, 1993b) generally were similar to the types of VOC's detected in the 150-ft-deep bedrock boreholes G115BD, G125BD (fig. 3) (Mills, 1993a).

The VOC's present at the highest concentrations in borehole G127GP were trichloroethylene (TCE) and 1,1,1-trichloroethane (1,1,1-TCA) (1,300 and 900 ppb (parts per billion), respectively (Mills, 1993b)). Drinking water standards established by the USEPA for these VOC's are 5 ppb and 200 ppb, respectively. These VOC's also were those with the highest concentrations in the boreholes G115BD, G125BD, and G126BD (Mills, 1993a). Based on the water samples collected during packer sampling, the concentrations of all VOC's detected in borehole G127GP (table 9 and Mills (1993b)) were substantially higher near the top of the Galena-Platteville aquifer (41 to 76 ft) than in deeper parts of the aquifer (76 to 301 ft). Concentrations of TCE, for example, ranged from 220 to 1,300 ppb near the top of the aquifer and from less than 5 to 40 ppb in the deeper parts of the aquifer. The distribution of tetrachloroethylene (PCE) concentrations with depth was the only exception to this pattern. The compound PCE was not detected in the upper parts of borehole G127GP (above a depth of 135 ft). PCE was detected at depth in relatively small concentrations.

VOC concentrations in ground water sampled from well G127GP generally were higher than the concentrations for samples collected at an equivalent depth in borehole G127GP during packer sampling, but they were still significantly less than the highest concentrations detected near the top of the aquifer. There is no obvious explanation for the higher VOC concentrations in samples from well G127GP. Sampling of other boreholes and wells at the site has indicated close agreement between the VOC concentrations of water samples collected at equivalent borehole (isolated by packers) and well depths (Mills, 1993a).

Most of the VOC's detected in the Galena-Platteville aquifer were also detected in the underlying St. Peter Sandstone aquifer (table 9). The most notable VOC detections in ground water from well G127SP in the St. Peter Sandstone aquifer included TCE, at 650 to 880 ppb, 1,1,1-TCA at 450 to 610 ppb, and PCE at 36 to 50 ppb.

Visual inspection of the water-quality data from borehole G127GP and well G127SP indicates a low but positive correlation between VOC concentrations and specific conductance for the water samples. The correlation indicated that waste-related dissolved-solids plumes and VOC plumes may be distributed somewhat similarly in the aquifer. The correlation between VOC concentrations and specific conductance was identified in previous investigations at the site (Mills, 1993a, 1993b).

There were some notable differences between the concentrations of VOC's in well G127SP in the St. Peter Sandstone aquifer and the nearby 300-ft-deep borehole G127GP in the Galena-Platteville aquifer (fig. 2). The concentrations of all VOC's detected in well G127SP were substantially higher than those detected in all but the shallowest depths in borehole G127GP.

The variability in water chemistry with depth observed in the Galena-Platteville aquifer, as indicated by the distribution of field measured characteristics of water quality and inorganic-constituent concentrations in borehole G127GP, is likely associated with (1) natural differences between the hydrochemistry of the Galena-Platteville aquifer and the aquifers that overlie and underlie the Galena-Platteville aquifer (glacial drift aquifer and St. Peter Sandstone aquifer, respectively) and (2) the distribution of downward-moving waste solutes in the Galena-Platteville aquifer. Natural differences in the hydrochemistry of the three aquifers is related in part to differences in lithologic composition of the aquifer materials, age of the recharging ground water (deeper, older ground water has had more time than shallow ground water has had to interact with aquifer material), and the extent of aqueous-atmospheric interaction (shallow ground water is more subject to the effects of biologic and chemical activity near the water table than is deep ground water). As previously noted, the distribution of VOC's, the principal waste solute in the Galena-Platteville aquifer at the study site, has been shown to be related indirectly to the distribution of specific conductance (Mills, 1993a, 1993b). It is likely that relations also exist between the distributions of VOC's and other waste solutes present in the ground water beneath the site and the distributions of dissolved oxygen, pH, Eh, and the inorganic constituents in the ground water. On the basis of visual inspection of rock cores, heterogeneity in the hydrogeochemistry of the aquifer is less likely to account for spatial variability in water chemistry in the Galena-Platteville aquifer across the site than is spatial variability in waste-solute distribution in the aquifer.

The variability of Eh recorded in the study may be indicative of the technical difficulty of Eh measurement in ground-water systems (Hem, 1985, p. 160). Alternatively, the variability of the values may have implications regarding ground-water flow and VOC distribution beneath the study site. One generally would expect ground-water conditions to be more reducing (indicated by negative Eh) in the St. Peter Sandstone aquifer than in the shallower Galena-Platteville aquifer. The high, positive Eh (indicating oxidizing potential) in the St. Peter Sandstone aquifer (table 6) may represent preferential movement of water through the Galena-Platteville aquifer. Oxygenated water may be moving downward in the aquifer more rapidly through fractures and fissures in the dolomite (Mills, 1993b) than through the dolomite matrix. This interpretation is supported by the relatively high concentrations of inorganic constituents, such as nitrite-nitrate and chloride (table 8), that generally are associated with near-land-surface effects on ground-water chemistry. The variability of Eh may also reflect the transient effects of municipal pumping on ground-water flow through the Galena-Platteville aquifer.

Other aspects of the in situ water-quality data (table 10) also indicate that preferential flow may contribute to the distribution of water in the Galena-Platteville aquifer. Changes in pH and Eh are recorded at a depth of about 265 to 270 ft. The changes may be related to ground-water flow through a conductive fissure identified at a depth of about 260 ft. Changes in water temperature and ground-water flow rates previously have been associated with this conductive fissure (Mills, 1993b).

The presence of the relatively high VOC concentrations in the St. Peter Sandstone aquifer at well G127SP can be accounted for in several ways;

however, additional data are necessary for accurate determination of the source of the VOC concentrations in the well. One mechanism is downward movement of VOC's through the Galena-Platteville aquifer and the Glenwood Formation and into the St. Peter Sandstone aquifer from a source area within the Parson's Casket Hardware site. In this case, the high VOC concentrations detected near the top of the Galena-Platteville aquifer in borehole G127GP represent lateral ground-water flow and VOC movement through the high-K glacial drift and weathered-bedrock deposits. Because horizontal ground-water flow is south to southeastward in the glacial drift aquifer and in the uppermost part of the Galena-Platteville aquifer (Mills, 1993b), the likely source of the high VOC concentrations was the waste-disposal pond (fig. 2) upgradient from wells G127GP and G127SP.

For this mechanism to be plausible, the relatively low concentrations of VOC's at depth in borehole G127GP must be accounted for. At least two explanations are possible. First, the VOC's may have moved preferentially downward through the Galena-Platteville aquifer within inclined fractures and horizontal fissures that do not intersect borehole G127GP. This explanation seems unlikely, given the geophysical data from the borehole and the detection of VOC's throughout the vertical extent of the borehole. Second, two VOC plumes may have moved through the vicinity of borehole G127GP. The relatively low VOC concentrations in the lower part of the borehole represent the trailing edge of one plume, which has already moved downward into the St. Peter Sandstone aquifer. The high concentrations in the upper part of the borehole represent the second plume, which has moved downward only slightly to date. This explanation also seems unlikely, given the waste-disposal history of the site and the vertical flow rates that would be necessary for such a large distance to exist between the two plumes (at least 250 vertical feet). Additionally, neither explanation clearly accounts for the presence of elevated concentrations of PCE in the St. Peter Sandstone aquifer at well G127SP and the relative absence of PCE throughout most of the overlying Galena-Platteville aquifer at borehole G127GP.

Another possible mechanism that might account for the high VOC concentrations detected in well G127SP is lateral movement of VOC's through the St. Peter Sandstone aquifer from a source area hydraulically upgradient from the Parson's Casket Hardware site. On the basis of ground-water levels at a depth of 150 ft, borehole G125BD is upgradient and borehole G115BD is downgradient from well G127SP (fig. 2) (Mills, 1993b). The concentrations of VOC's detected throughout the 150-ft depths of boreholes G125BD and G115BD (Mills, 1993a) were more consistent with the VOC detections in well G127SP than with the VOC detections from all but the uppermost sample intervals of borehole G127GP (fig. 2). Additionally, as in well G127SP, PCE was detected at elevated concentrations in boreholes G125BD and G115BD; PCE was generally absent in borehole G127GP. The VOC's detected in the subsurface in the vicinity of hole G125BD may have moved downward through the Galena-Platteville aquifer and the underlying Glenwood Formation and into the permeable St. Peter Sandstone aquifer, then laterally through the St. Peter Sandstone aquifer in the general direction of well G127SP and borehole G115BD. Lateral water movement through the Galena-Platteville aquifer and Glenwood Formation also would be expected, although to a lesser extent and primarily through horizontal fissures in the

Galena-Platteville aquifer. On this basis, the relatively low VOC concentrations at depth in borehole G127GP likely represent the northern edge of the southeasterly trending VOC plume.

It should be noted that the above-described mechanisms for VOC movement are intended only as possible explanations for the source of VOC's detected in the St. Peter Sandstone aquifer at the location of well G127SP. Additional downward movement of VOC's through the Galena-Platteville aquifer and into the St. Peter Sandstone aquifer is likely at other locations at the study site, as indicated by the detection of VOC's throughout the 150-ft depths of boreholes G115BD and G126BD (Mills, 1993a). Finally, although not considered in the above-described explanations for VOC distribution in the Galena-Platteville and St. Peter Sandstone aquifers, detailed evaluation of VOC distribution in the aquifers needs to consider the possible effects of municipal-well pumping on VOC distribution. The transient effects of pumping could include increased downward movement of VOC's through the Galena-Platteville and St. Peter Sandstone aquifers, distortion of natural patterns of lateral movement of VOC's in the aquifers, and, possibly, upward movement of VOC's in the aquifers with the cessation of pumping.

SUMMARY

A summary of the findings of the multiple-phased investigation (Mills, 1993a, 1993b) of the Parson's Casket Hardware site is as follows:

1. Various volatile organic compounds (VOC's), principally TCE, 1,1,1-TCA, and PCE, are present at concentrations above USEPA drinking-water standards throughout most of the thickness of the Galena-Platteville aquifer (as deep as about 300 ft below land surface).

2. VOC's are present in the Galena-Platteville aquifer both beneath the site and upgradient from the site.

3. Various VOC's, principally TCE, 1,1,1-TCA, and PCE, are present at concentrations above USEPA drinking-water standards beneath the site in the uppermost part of the St. Peter Sandstone aquifer.

4. Ground-water flow and VOC movement through the Galena-Platteville aquifer seem to take place through the low-permeability dolomite matrix and through high-permeability horizontal fissures and inclined fractures. Rates of ground-water flow (and probably VOC movement) seem to be generally greater through the fissure and fractures than through the dolomite matrix.

   Hydraulically important horizontal fissures are present at depths of about 125 ft and 260 ft horizontal. The horizontal hydraulic conductivity (K) of the high-permeability strata, which include the fissures and the weathered surface of the dolomite unit, ranges from about 0.5 to 10 ft/d. The K of the low-permeability strata ranges from about 0.05 to 0.5 ft/d. The average K of the aquifer is about 0.5-1, as indicated by the multiple-well aquifer test.

5. Ground-water flow (and probably VOC distribution) is affected to an undetermined extent by pumping of nearby Belvidere Municipal Wells No. 4 and No. 6.

6. Vertical ground-water flow in the Galena-Platteville aquifer seems to be principally downward, with a transient upward component due to the effect of municipal-well pumping. Horizontal ground-water flow seems to be to the south to southeast, apparently directed away from Belvidere Municipal Wells No. 4 and No.6.

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