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Hydrogeology and Simulation of Ground-Water Flow in the Aquifers Underlying Belvidere, Illinois

By P.C. Mills (U.S. Geological Survey), J.E. Nazimek (U.S. Geological Survey), K.J. Halford (U.S. Geological Survey), and D.J. Yeskis (U.S. Environmental Protection Agency)

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

Multiply	By	To obtain
	Length	
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 mile (ft/mi)	0.1894	meter per kilometer
	Area	
acre (A)	4,047	square meter
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	2.590	square kilometer
	Flow rate	
inch per year (in/yr)	25.4	millimeter per year
foot per second (ft/s)	30.48	centimeter per second
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon per minute (gal/min)	3.785	liter per minute
million gallons per day (Mgal/d)	3.785	million liters per day
gallon per year (gal/yr)	3.785	liter per year
	Hydraulic conductivity*	
foot per day (ft/d)	0.3048	meter per day
	Transmissivity**	
foot squared per day (ft^2/d)	0.09290	meter squared per day

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

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

Altitude, as used in this report, refers to distance above or below sea level.

Horizontal datum used in this report is the North American Datum of 1927.

***Hydraulic conductivity:** The standard unit for hydraulic conductivity is cubic foot per day per square foot of aquifer cross-sectional area $(ft^3/d)/ft^2$. In this report, the mathematically reduced form, foot per day (ft/d), is used for convenience.

****Transmissivity:** The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness $[(ft^3/d)/ft^2]ft$. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Abbreviated water-quality units used in this report: Organic- and inorganic-constituent concentrations, water temperature, and other water-quality measures are given in metric units. Constituent concentrations are given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter are considered equivalent to parts per million at the reported concentrations. Micrograms per liter are considered equivalent to parts per billion at the reported concentrations. Constituent concentrations presented in the report may be estimated. Estimated concentrations are indicated in appendixes 2–4.

Tritium concentrations are given in picocuries per liter (pCi/L) and tritium units (TU). Picocuries per liter may be converted to tritium units as follows:

$$TU = pCi/L \times 0.3125$$

Specific conductance (SC) is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C). The unit is equivalent to micromhos per centimeter at 25 degrees Celsius (µmho/cm), formerly used by the U.S. Geological Survey.

Dissolved oxygen (DO) is given in milligrams per liter (mg/L).

Oxidation-reduction potential (Eh) is given in millivolts (mv).

Turbidity is given in nephelometric turbidity units (NTU).

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Abstract

The U.S. Geological Survey investigated the ground-water-flow system and distribution of contaminants in the vicinity of Belvidere, Illinois, during 1992–2000. The study included the compilation, collection, and analyses of hydrogeologic and water-quality data and simulation of the ground-water-flow system. Hydrogeologic data include lithologic, stratigraphic, geophysical, hydraulic-property, water-level, ground-water withdrawal, and streamflow data. Water-quality data include analyses of water samples primarily for volatile organic compounds (VOC's) and selectively for tritium and inorganic constituents. Data were collected from about 250 wells and 21 surface-water sites. These data were used (1) to describe the hydrogeologic framework of the ground-water-flow system, preferential pathways and directions of ground-water movement and contaminant distribution, ground-water/surface-water relations, and the water budget and (2) to develop and calibrate the ground-water-flow model.

The glacial drift (sand and gravel with some clay) and Galena-Platteville (fractured dolomite) aquifers and the sandstone aquifers of the Cambrian-Ordovician aquifer system compose the ground-water-flow system underlying Belvidere and vicinity. The Glenwood confining unit separates the Galena-Platteville aquifer from the underlying sandstone aquifers. The Galena-Platteville aquifer and confining unit may be absent in parts of the Troy Bedrock Valley, about 1.5 miles west of Belvidere.

Throughout the study area, the Kishwaukee River and its tributaries seem to be gaining flow from shallow ground-water discharge. Potentiometric levels in the glacial drift and Galena-Platteville aquifers range from about 900 feet above sea level in the upland areas to 740 feet along the Kishwaukee River.

Estimated horizontal hydraulic conductivity of the glacial drift aquifer ranges from about 0.13 to 280 feet per day. The Galena-Platteville aquifer is a dual-porosity unit with the greatest percentage of flow through fractures and bedding-plane partings. Estimated horizontal hydraulic conductivity ranges from about 0.005 to 2,500 feet per day. Estimated horizontal hydraulic conductivity of the St. Peter aquifer (the uppermost sandstone aquifer of the Cambrian-Ordovician aquifer system ranges from about 4.7 to 17.5 feet per day.

Volatile organic compounds have been detected in all aquifers underlying Belvidere. Trichloroethene and tetrachloroethene are the principal VOC's detected at concentrations above regulatory levels, with the largest number of detections and highest concentrations in the glacial drift aquifer. VOC's generally are not detected in the glacial drift aquifer farther than 1,000 feet from known or potential source areas (industrial or disposal sites), because most source areas are near the Kishwaukee River, where shallow ground water discharges. Across most of the study area, the Glenwood confining unit seems to restrict downward movement of VOC's into the underlying St. Peter aquifer; in the immediate vicinity of Belvidere, downward movement also seems restricted by lateral movement toward the municipal wells through permeable intervals in the

Galena-Platteville aquifer. Fractures and (or) unused wells that may penetrate the confining unit seem to provide local pathways for limited movement of VOC's to the sandstone aquifers. At least two municipal wells seem to intercept the bedding-plane partings at about 525 and 485 feet above sea level. Water levels in the lower one-third of the Galena-Platteville aquifer rapidly respond to withdrawals at these wells.

The ground-water-flow system underlying Belvidere was simulated to test the conceptual model of the system. The three-dimensional, steady-state model represents the glacial drift, Galena-Platteville, and sandstone aquifers separated by the Glenwood confining unit. The model was calibrated by adjusting values of hydrologic properties until differences in simulated and measured ground-water levels and ground-water discharge to streams were minimized. Within the limitations of the model design and available data, the simulation generally verified the conceptualized flow system.

Simulation results indicate (1) ground-water discharge is predominantly to local streams, (2) transmissivity of the glacial drift aquifer within the Troy Bedrock Valley and parts of the Galena-Platteville aquifer may be less than previously expected, and (3) till-dominated deposits in the southern part of the study area may include some previously unrecognized interbedded sand and gravel. The ground-water-flow model is considered useful for further analysis of the ground-water-flow system underlying Belvidere, including preliminary delineation of the areas contributing recharge to the principal water-supply wells.

INTRODUCTION

Volatile organic compounds (VOC's) have been detected in water samples from municipal and private water-supply wells open to the glacial drift and bedrock aquifers underlying Belvidere, Illinois (population of 18,000) and vicinity (figs. 1A, 1B) (Brown and Mills, 1995; Mills and others, 1998, 1999a). VOC's in ground water also seem to discharge to the Kishwaukee River (Roy F. Weston, Inc., 1988; Mills and others, 1999a), which flows through Belvidere (**fig. 1**). VOC's and other potentially hazardous wastes (contaminants) periodically have been disposed at industrial and commercial facilities and at three regulated solid-waste landfills in the area (fig. 1A). Currently (2001), one industrial facility and two landfills are Superfund sites on the U.S. Environmental Protection Agency (USEPA) National Priorities List established (in 1980) by the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and Superfund Amendment and Reauthorization Act of 1986 (SARA). With ground water as the sole source of public-water supply for Belvidere and expectations of increasing demand (the area's population has increased about 18 percent since 1990 (Belvidere Area Chamber of Commerce, 2000)), ground-water-remediation and protection efforts are a high priority.

In 1992, the U.S. Geological Survey (USGS), in cooperation with the USEPA, initiated a study of the hydrogeology and water quality of the aquifers underlying the vicinity of Belvidere (fig. 1). The objectives of the study were to (1) determine the regional distribution and factors affecting the occurrence and distribution of contaminants in the aquifers, with emphasis on explaining the presence of VOC's in water withdrawn by five of the eight Belvidere municipal wells; (2) assess the effect of ground-water contamination associated with non-Superfund hazardous-waste sites on investigations and remediation options at Superfund sites; and (3) provide the necessary data and analysis to assist other agencies and organizations in developing strategies for remediation of ground-water contamination and protection of the area's ground-water supplies.

In addition to other activities by the USGS to satisfy the study objectives (described in the section "Previous Investigations"), a numerical flow-simulation model was developed to assist data-collection planning and evaluate a conceptual model of the ground-water-flow system. In 1999, the USGS, in cooperation with the Illinois Environmental Protection Agency (IEPA), continued developing the ground-water-flow model with the additional objective of delineating the areas contributing recharge to the municipal wells in Belvidere. To aid calibration of the model and improve understanding of the ground-water-flow system, selected streamflow measurements were made and additional VOC and environmental tritium data were collected. Streamflow data appropriate for model calibration previously were not available for the study area.

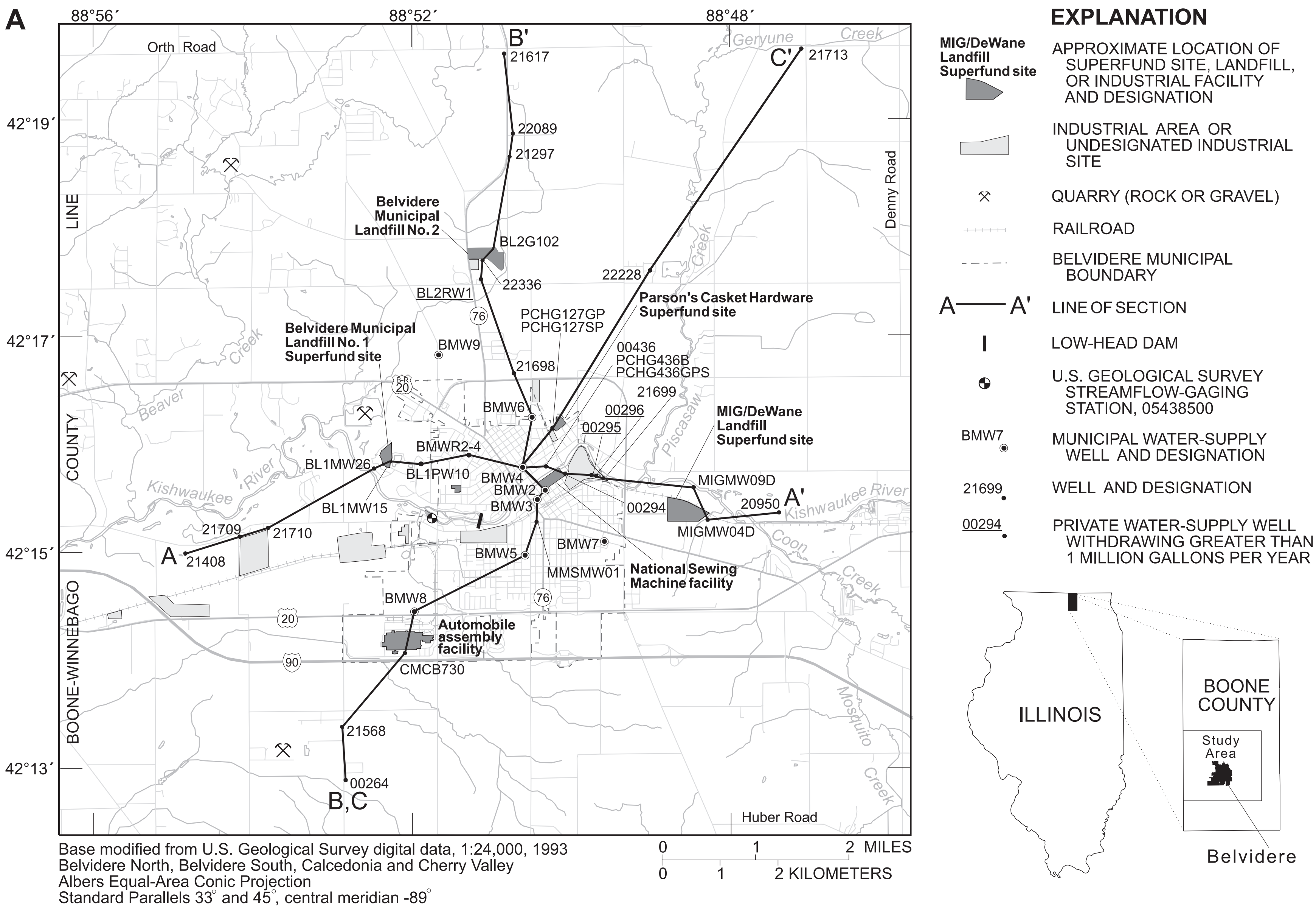


Figure 1. Study area in the vicinity of Belvidere, Illinois: (A) hazardous-waste-disposal and industrial sites, municipal water-supply wells, selected private wells, and lines of section A-A´, B-B´, and C-C´, (B) sites of surface-geophysical surveys and lines of section D-D´, E-E´, and F-F´, and (C) sites of surface-water-level and streamflow measurement.

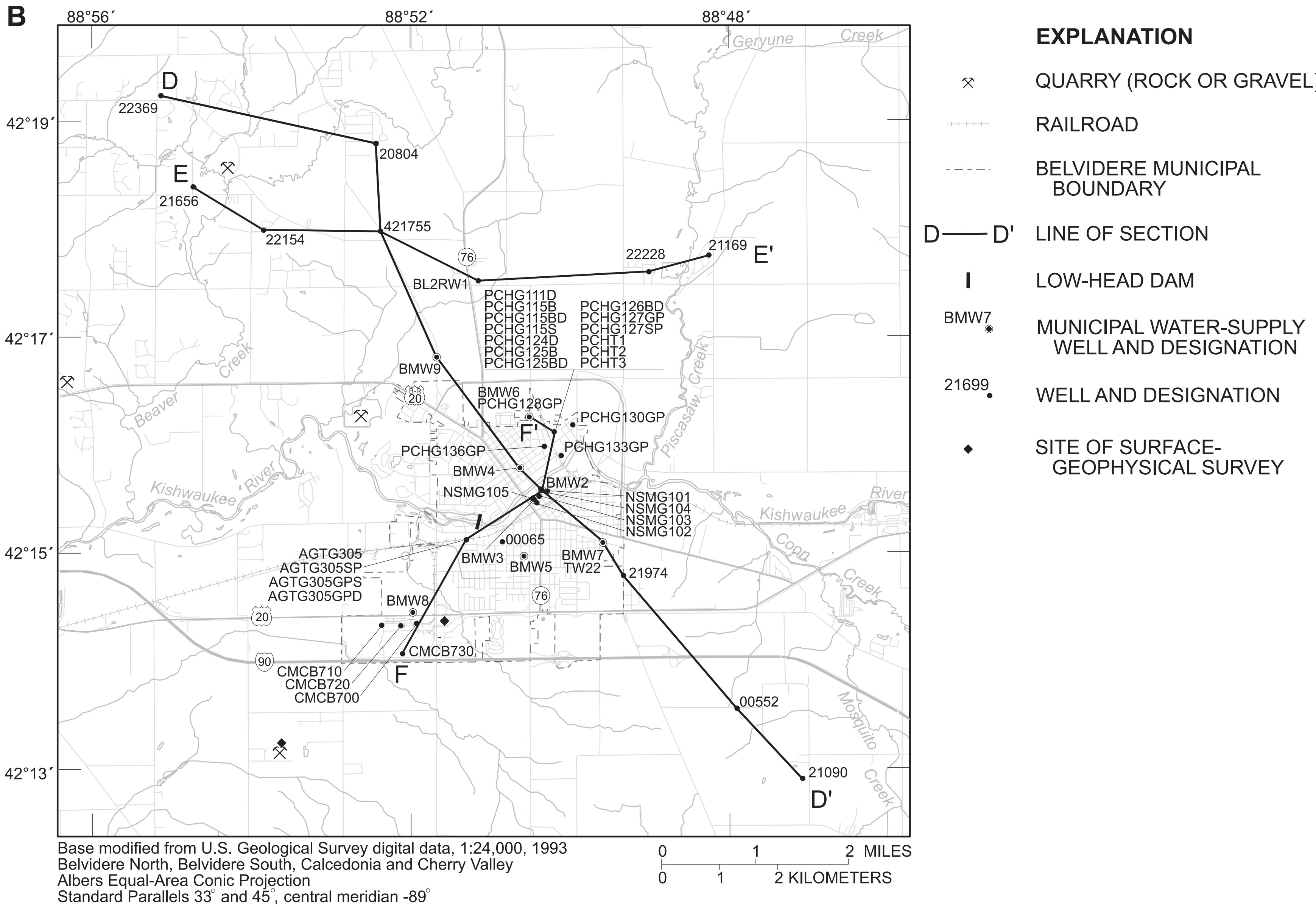


Figure 1. Study area in the vicinity of Belvidere, Illinois: (A) hazardous-waste-disposal and industrial sites, municipal water-supply wells, selected private wells, and lines of section A-A´, B-B´, and C-C´, (B) sites of surface-geophysical surveys and lines of section D-D´, E-E´, and F-F´, and (C) sites of surface-water-level and streamflow measurement–Continued.

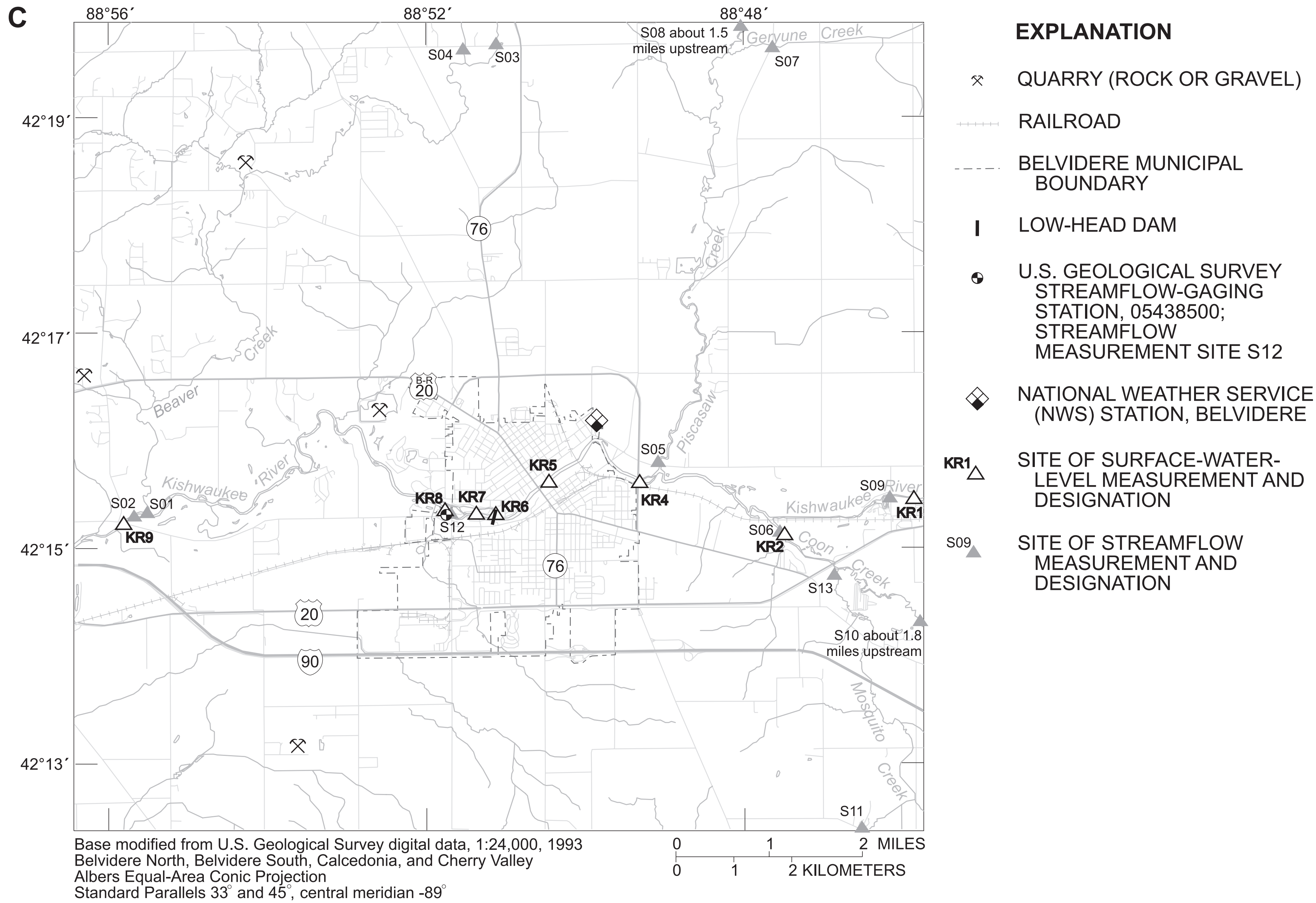


Figure 1. Study area in the vicinity of Belvidere, Illinois: (A) hazardous-waste-disposal and industrial sites, municipal water-supply wells, selected private wells, and lines of section A-A′, B-B′, and C-C′, (B) sites of surface-geophysical surveys and lines of section D-D′, E-E′, and F-F′, and (C) sites of surface-water-level and streamflow measurement–Continued.

Purpose and Scope

This report presents (1) the streamflow and ground-water-quality data collected in the vicinity of Belvidere during 1998–99, (2) a summary of the hydrogeologic and water-quality data collected as part of this and other studies in the area and resulting conceptual flow model, and (3) a description and analysis of the simulation of regional ground-water flow. Ground-water-related data presented are lithologic, stratigraphic, geophysical, hydraulic-property, water-level, withdrawal, and streamflow data. Water-quality data presented are field-determined characteristics, selected inorganic constituents, VOC's, and tritium. Data are from selected wells and boreholes open to the glacial drift and bedrock aquifers underlying Belvidere. The data are provided to describe the hydrogeologic framework of the ground-water-flow system, preferential pathways and directions of ground-water movement and contaminant distribution, ground-water/surface-water relations (primarily ground-water discharge to streams), possible effects of withdrawals from high-capacity water-supply wells on contaminant distribution, and the water budget. Data and model limitations, and possible areas of future study, also are discussed in the report.

Previous Investigations

Prior to the current phase (1998–2001) of the study, various activities had been completed to partially satisfy the study objectives. Available well-installation, hydrogeologic, and water-quality data were compiled in a geographic information system (GIS) data base for wells in the vicinity of Belvidere (Brown and Mills, 1995). Included in the initial data base and the accompanying report were well-installation and hydrogeologic data for 725 wells and water-quality data for 157 wells. The data base (maintained by the USGS, Illinois District) has been updated during 1995–98. Most data were from remedial investigation/feasibility studies of the three Superfund sites in the area: Parson's Casket Hardware, MIG/DeWane Landfill, and Belvidere Landfill No. 1 (fig. 1A). To supplement these data, additional hydrogeologic, geophysical, and ground-water-quality data were collected in and near Belvidere by the USGS during 1992–98. These data are from four boreholes drilled to complete four vertically nested well sites (Mills and others, 1998) and a series of synoptic (time-synchronous) water-quality and water-level surveys (Mills and others, 1999a).

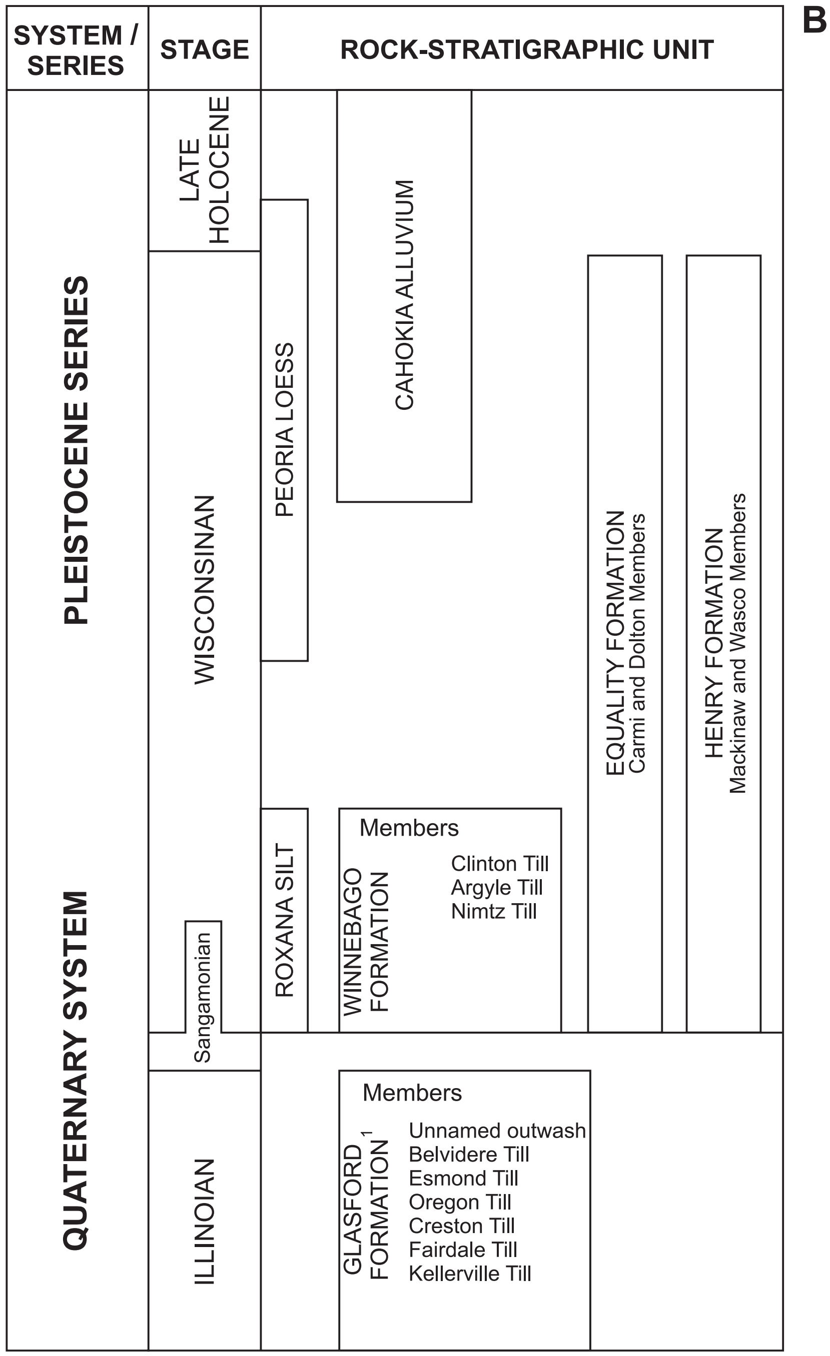
The hydrogeology and (or) water quality of the ground-water system underlying the study area have been described in numerous other studies. The studies are either of individual hazardous-waste or industrial sites or multicounty to multistate in scale. The following reports (grouped by site) provide the most detailed site descriptions: Science Applications International Corporation (1992, 1996), Mills (1993b, c, d), Kay and others (2000), Kay (2001), and Vanderpool and Yeskis (1991); Clayton Environmental Consultants, Inc. (1996), Roy F. Weston, Inc. (1988), GZA GeoEnvironmental, Inc. (1993, 1994a, b), and Fred C. Hart Associates, Inc. (1986a, b, c); and RMT, Inc. (1993). The reader is referred to Brown and Mills (1995) for a listing of ground-water-quality studies of limited scope. For those studies, sites are less than an acre and descriptions are restricted to that of lithologic materials, ground-water levels, and water quality encountered during soil sampling or installation of less than five shallow (less than 50 ft deep) monitoring wells. Few hydraulic-property data are available.

Berg and others (1984) describes the glacial and bedrock geology and hydrology in Boone and Winnebago Counties (fig. 1A). Hunter and Kempton (1967) describes the glacial geology of Boone County. Willman and Kolata (1978) describes the Galena and Platteville Groups of Ordovician age (fig. 2A), where the units are the uppermost bedrock deposits in northern Illinois. McGarry (2000) describes fracturing in the Galena and Platteville Groups in Boone and Winnebago Counties. Schumacher (1990) describes the hydrogeology of the Galena-Platteville aquifer in nearby De Kalb and Kane Counties. Willman and others (1975) describes the statewide distribution and character of glacial and bedrock units. Various investigations have been conducted of the Cambrian-Ordovician aquifer system for areas that range in coverage from northeastern Illinois to parts of six Midwestern States. Visocky (1993, 1997), Visocky and others (1985), and Young (1992) provide hydrogeologic descriptions, including water-level trends and background water quality. Burch (1991) and Young (1992) simulated ground-water flow in the aquifer system. Each large-scale investigation includes Belvidere and vicinity as a small part of their study area.

A

SYSTEM	ROCK-STRATIGRAPHIC UNIT	HYDRO-GEOLOGIC UNIT	LOG	THICK-NESS (FEET)	DESCRIPTION
QUATERNARY	Undesignated	Glacial drift aquifer and confining unit		0-385	Unconsolidated glacial deposits-pebbly clay (till), silt, sand and gravel Alluvial silts and sands of Holocene age along streams
				Fissure fillings	Shale, sandy, brown to black
ORDOVICIAN	Maquoketa Shale Group	confining unit		0-45	Shale, silty, dolomitic, greenish gray, weak (Upper unit) Dolomite and limestone, white, light gray, interbedded shale (Middle unit) Shale, dolomitic, brown, gray (Lower unit)
	Galena Group Platteville Group	Galena-Platteville aquifer (Ordovician aquifer system; Cambrian-Ordovician aquifer system)		0-300	Dolomite and/or limestone, cherty (Lower unit) Dolomite, shale partings, speckled Dolomite and/or limestone, cherty, sandy at base
	Glenwood Formation (Ancell Group)	confining unit		0-55	Dolomite, sandstone; silty
	St. Peter Sandstone (Ancell Group)	St. Peter aquifer		180-290	Sandstone, fine to coarse grained; locally cherty red shale at base
CAMBRIAN	Potosi Dolomite	confining unit		40-120	Dolomite, light colored, sandy, thin sandstones Dolomite, fine-grained, gray to brown, drusy quartz
	Franconia Formation			60-100	Dolomite, sandstone and shale, glauconitic, green to red, micaceous
	Ironton Sandstone Galesville Sandstone	Ironton-Galesville aquifer		115-160	Sandstone, fine to coarse grained, well sorted; upper part dolomitic
	Eau Claire Formation	confining unit		115-380	Shale and siltstone, dolomitic, glauconitic; sandstone, dolomitic, glauconitic
	Elmhurst Sandstone Member Mt. Simon Sandstone	Elmhurst-Mt. Simon aquifer		about 1,600	Sandstone, coarse grained, white, red in lower half; lenses of shale and silt-stone, red, micaceous in upper part
		confining unit (?)		unknown	Shale and siltstone (?)
PRECAM-BRIAN					Granitic rocks

Figure 2. Classification of (A) rock-stratigraphic and hydrogeologic units and (B) detailed stratigraphy of units of Quaternary age in the vicinity of Belvidere, Illinois.



[1]All Winnebago Formation tills might be of Illinoian rather than Wisconsinan age.

Figure 2. Classification of (A) rock-stratigraphic and hydrogeologic units and (B) detailed stratigraphy of units of Quaternary age in the vicinity of Belvidere, Illinois–Continued

Description of Study Area

The study area comprises about 80 mi^2 in southern Boone County and includes the city of Belvidere (fig. 1A). The boundary of the study area is based on the maximum area possibly affected by ground-water contamination from known and potential sources in and near Belvidere and its municipal wells. Assumptions concerning the location of the boundary are based on the (1) recognition of sources of contamination; (2) location of municipal wells and other high-capacity (industrial) supply wells; and (3) knowledge of the hydrogeologic setting, including the possible locations of natural barriers to ground-water flow and contaminant movement. Approximate boundaries of the study area include Orth Road to the north, Denny Road to the east, Huber Road to the south, and the Boone/Winnebago County line to the west (fig. 1A).

Methods of Investigation

Hydrogeologic or water-quality data collected by the USGS or USEPA for this study are from about 250 wells and borings distributed within the aquifers and confining units underlying the study area. A complete listing and description of the location, depth, and type of wells and borings are provided in reports by Mills and others (1998, 1999a); wells and borings referred to in this report are listed similarly in table 1. Surface-water levels were measured at seven sites on the Kishwaukee River and one site on Coon Creek at its confluence with the Kishwaukee River. Site locations are shown in figure 1C and listed in Mills and others (1999a). Streamflow was measured at 13 sites on the Kishwaukee River and its first- and second-order tributaries (fig. 1C).

Methods used to drill and construct the monitoring wells installed for this study are provided in Mills and others (1998). Methods used to collect geologic, geophysical, and aquifer-test data; measure water levels; and collect water-quality samples are described, in detail, in Mills and others (1998, 1999a). Sampling protocols included collecting and analyzing quality-assurance samples; information on the samples can be obtained from the USGS (Illinois District) on request. Methods used to measure streamflow are described below. Methods used for simulating ground-water flow are described in the section “Simulation of Ground-Water Flow.”

During September 8–10, 1999, streamflow measurements were made on the basis of methods described in Rantz and others (1982). Low-flow conditions, representing ground-water base flow, were present, as indicated by current and historical streamflow data from the USGS continuous-record, streamflow-gaging station Kishwaukee River at Belvidere (05438500) (fig. 1C) (LaTour and others, 2000). Selected stream sections between upstream and downstream streamflow-measurement sites (fig. 1C) were chosen to confirm or estimate rates of ground-water discharge to principal streams within the study area. One site of industrial discharge to the Kishwaukee River was identified from National Pollutant Discharge and Elimination System (NPDES) records (Sreedevi Yedavalli, U.S. Environmental Protection Agency, written commun., 1999). Daily discharges during the period of streamflow measurement were obtained from the site operator (Terry Wickler, Belvidere Waste Water Treatment Plant, written commun., 1999) and accounted for in the estimation of ground-water discharge to the streams. An error of ±5 percent was assumed for all streamflow measurements, thus, providing minimum and maximum estimates of streamflow and calculated ground-water discharge to streams. Similar error was assumed by Arihood and Cohen (1998) in their study of comparable northern Midwest streams.

The estimates of ground-water discharge to selected stream sections during 1999 were used to calibrate the ground-water-flow model, as were ground-water levels measured during July 19–27, 1993. To assess possible differences in the ground-water discharge to streams during late July 1993 (which followed an unusually wet period) and September 1999 (a typical dry period), surface-water levels were measured at five sites on or near the Kishwaukee River and ground-water levels were measured in eight wells near the Kishwaukee River (appendix 1, excluding wells PCHG115BD and PCHG127SP; fig. 1C). Precipitation and ground-water conditions during July 1993 are discussed, in detail, in the section “Precipitation and Streamflow” and in Mills and others (1999a).

Table 1. Description of selected wells and borings and types of water-quality data collected in the vicinity of Belvidere, Illinois, 1998–99

Hydrologic unit: GP, Galena-Platteville aquifer; CO, Cambrian-Ordovician aquifer system (Galena-Platteville, St. Peter, Ironton-Galesville, and(or) Mt. Simon aquifers); OR, Ordovician aquifer system (Galena-Platteville and St. Peter aquifers); GD, glacial drift aquifer; SP, St. Peter aquifer

Depth to water: Water levels measured July 19–27, 1993, and September 10, 1999, unless otherwise noted; --, depth not measured

Sampled for volatile organic compounds: Y, yes; N, no

Sampled for metals and cyanide: Y, yes; N, no

Sampled for tritium: Y, yes; N, no

Type of well: P, private water supply; T, test boring; M, monitoring; B, Belvidere, Illinois, municipal water supply

Well designation	Latitude	Longitude	Hydro-geologic unit	Open or screened interval of well (feet below land surface)	Depth to water, July 1993 (feet below and surface)	Depth to water, September 1999 (feet below land surface)	Sampled for volatile organic compounds	Sampled for metals and cyanide	Sampled for tritium	Type of well
00264	42°12′54″	88°52′49″	GP	200–220	--	--	N	N	N	P
00294	42°15′43″	88°50′04″	CO	239–868	--	--	N	N	N	P
00295	42°15′43″	88°49′44″	CO	62.8–627	--	--	N	N	N	P
00296	42°15′42″	88°49′52″	OR	55–550	--	--	N	N	N	P
00305	42°15′08″	88°51′16″	GP	33.1–605	--	--	N	N	N	T
00436	42°15′48″	88°50′18″	GP	27.5–215	18.80	--	N	N	N	P
00552	42°13′32″	88°47′52″	GP	117–312	--	--	N	N	N	P
20804	42°18′48″	88°52′24″	GP	236–249	50.39	--	N	N	N	P
20950	42°15′22″	88°47′23″	GP	57–150	--	--	N	N	N	P
21090	42°12′53″	88°47′02″	GP	159–210	90.96	--	N	N	N	P
21169	42°17′45″	88°48′13″	GP	60–165	13.42	--	N	N	N	P
21408	42°14′59″	88°54′50″	GD	148–150	--	--	N	N	N	P
21568	42°13′23″	88°52′52″	GP	40–155	--	--	N	N	N	P
21656	42°18′24″	88°54′42″	GP	42–148	20.43	--	N	N	N	P
21699	42°15′41″	88°49′35″	GP	61–145	26.19	--	N	N	N	P
21710	42°15′14″	88°53′48″	OR	266–420	35.83	--	N	N	N	P
21713	42°19′38″	88°47′02″	GP	205–230	--	--	N	N	N	P
21974	42°14′47″	88°49′17″	GP	132–209	--	--	N	N	N	P
22154	42°18′00″	88°53′49″	GP	117–250	89.81	--	N	N	N	P
22228	42°17′36″	88°48′59″	GP	82–168	17.99	--	N	N	N	P
22369	42°19′15″	88°55′07″	GP	48–265	27.54	--	N	N	N	P
421755	42°17′59″	88°52′21″	SP	352–398	52.04	--	N	N	N	P
AGTG305GPS	42°15′08″	88°51′16″	GP	110.0–115.0	[1]30.10	--	Y	Y	Y	M
AGTG305GPD	42°15′08″	88°51′16″	GP	246.4–251.4	[1]49.86	--	Y	Y	Y	M
AGTG305SP	42°15′08″	88°51′16″	SP	352.8–357.8	[1]63.41	--	Y	Y	Y	M
BL1MW15	42°15′50″	88°52′16″	GD	20.6–37.1	--	--	N	N	N	M
BL1MW26	42°15′47″	88°52′28″	GP	137–142.5	--	--	N	N	N	M
BL1PW10	42°15′49″	88°51′53″	GP	56–66	23.30	--	N	N	N	P
BL2RW1	42°17′31″	88°51′07″	OR	287.5–520	35.84	--	N	N	N	P
BMW2	42°15′34″	88°50′19″	CO	50–1,860	2.62	--	Y	Y	Y	B
BMW3	42°15′30″	88°50′25″	CO	55–1,800	--	--	Y	Y	Y	B
BMW4	42°15′47″	88°50′36″	CO	152–1,800	52.41	--	Y	Y	Y	B
BMW5	42°14′58″	88°50′34″	OR	151.8–610	--	--	Y	Y	Y	B
BMW6	42°16′15″	88°50′28″	CO	110–868	43.69	--	Y	N	Y	B
BMW7	42°15′06″	88°49′33″	CO	192–969	--	--	Y	N	Y	B

Table 1. Description of selected wells and borings and types of water-quality data collected in the vicinity of Belvidere, Illinois, 1998–99—Continued

Well designation	Latitude	Longitude	Hydro-geologic unit	Open or screened interval of well (feet below land surface)	Depth to water, July 1993 (feet below and surface)	Depth to water, September 1999 (feet below land surface)	Sampled for volatile organic compounds	Sampled for metals and cyanide	Sampled for tritium	Type of well
BMW8	42°14′27″	88°51′58″	CO	362–875; 995–1,390	--	--	Y	N	Y	B
BMW9	42°16′49″	88°51′39″	GD	70–90; 115–120	--	--	Y	N	Y	B
BMWR2-4	42°15′54″	88°51′17″	GP	40–96.5	--	--	N	N	N	P
CMCB700	42°14′20″	88°51′54″	GP	9–324	--	--	N	N	N	T
CMCB710	42°14′21″	88°52′19″	GP	19–354	--	--	N	N	N	T
CMCB720	42°14′21″	88°52′10″	GP	19–344	--	--	N	N	N	T
CMCB730	42°14′04″	88°52′05″	GP	22–354	--	--	N	N	N	T
MIGMW04D	42°15′18″	88°48′16″	GD	25.0–30.0	--	--	N	N	N	M
MIGMW09D	42°15′36″	88°48′27″	GD	56.0–61.0	--	--	N	N	N	M
MMSMW01	42°15′17″	88°50′25″	GP	25.9–30.9	--	--	N	N	N	M
NSMG101	42°15′34″	88°50′16″	GD	32.9–37.9	6.39	9.42	Y	N	N	M
NSMG102	42°15′28″	88°50′24″	GD	44.6–49.6	15.62	18.43	Y	N	N	M
NSMG103	42°15′32″	88°50′22″	GD	49.9–54.9	6.29	8.96	Y	Y	N	M
NSMG104	42°15′36″	88°50′21″	GD	54.1–59.0	3.7	6.63	Y	Y	N	M
NSMG105	42°15′30″	88°50′27″	GD	42.8–47.8	5.54	8.12	Y	Y	N	M
PCHT1	42°16′08″	88°50′11″	GP	49–215	--	--	N	N	N	T
PCHT2	42°16′08″	88°50′11″	GP	48–215	--	--	N	N	N	T
PCHT3	42°16′08″	88°50′11″	GP	50–215	--	--	N	N	N	T
PCHG115B	42°16′07″	88°50′11″	GP	43.6–48.6	14.30	18.33	N	N	N	M
PCHG115BD	42°16′07″	88°50′11″	GP	140.6–151.5	25.46	31.10	Y	Y	N	M
PCHG115D	42°16′07″	88°50′11″	GD	32.8–37.8	14.09	18.51	N	N	N	M
PCHG115S	42°16′07″	88°50′11″	GD	9.6–20.1	12.17	14.37	N	N	N	M
PCHG116D	42°16′09″	88°50′12″	GD	28.6–33.6	16.12	--	Y	Y	N	M
PCHG119D	42°16′03″	88°50′10″	GD	31.5–36.5	15.90	--	Y	Y	N	M
PCHG124GP	42°16′11″	88°50′13″	GP	35–267	--	--	N	N	N	T
PCHG125B	42°16′08″	88°50′15″	GP	31.2–36.2	14.31	--	Y	Y	N	M
PCHG125BD	42°16′08″	88°50′15″	GP	137.4–147.7	18.27	--	N	N	N	M
PCHG125D	42°16′08″	88°50′15″	GD	23.4–28.4	13.72	--	Y	Y	N	M
PCHG126BD	42°16′10″	88°50′13″	GP	141.0–151.3	20.09	--	N	N	N	M
PCHG127GP	42°16′08″	88°50′13″	GP	41.0–301.0	--	--	N	N	N	T
PCHG127GP	42°16′08″	88°50′13″	GP	288.9–293.9	47.04	--	Y	Y	Y	M
PCHG127SP	42°16′08″	88°50′13″	SP	370.7–375.7	57.80	66.23	Y	Y	Y	M
PCHG128GP	42°16′15″	88°50′27″	GP	30.0–310.0	--	--	N	N	N	T
PCHG128GPS	42°16′15″	88°50′27″	GP	16.0–121.0	[1]48.89	--	Y	Y	Y	M
PCHG128GPD	42°16′15″	88°50′27″	GP	253.5–258.5	[1]49.07	--	Y	Y	Y	M
PCHG130GP	42°16′12″	88°49′57″	GP	41–230	--	--	N	N	N	T
PCHG133D	42°15′54″	88°50′09″	GD	40.0–44.7	--	--	Y	Y	N	M
PCHG133GP	42°15′54″	88°50′09″	GP	45–268	--	--	N	N	N	T
PCHG134D	42°15′58″	88°50′01″	GD	38.8–43.8	--	--	Y	Y	N	M
PCHG134GP	42°15′59″	88°50′03″	GP	55–267	--	--	N	N	N	T
PCHG135D	52°16′09″	88°50′22″	GD	21.6–26.6	--	--	Y	Y	N	M
PCHG136GP	42°16′01″	88°50′18″	GP	28–283	--	--	N	N	N	T
PCHP436B	42°15′48″	88°50′18″	GP	30.0–35.0	[2]11.20	11.29	Y	N	N	M
PCHG436GPS	42°15′48″	88°50′18″	GP	102.3–107.3	[2]12.20	12.25	Y	N	N	M

[1] Water level was measured May 31–June 1, 1995.
[2] Water level was measured August 27, 1996.

In April 1998, samples were collected from 22 monitoring wells and 4 municipal wells for analysis of VOC's, metals, and cyanide. In March 1999, samples were collected from seven monitoring wells and eight municipal wells for analysis of tritium. The wells were open to various depths in the glacial drift and bedrock aquifers underlying Belvidere. Samples from the 15 wells, as well as from 3 other monitoring wells also were collected for analysis of VOC's.

VOC analyses were by either a laboratory managed under the USEPA Contract Laboratory Program or by the USEPA Region 5 Central Regional Laboratory, Chicago, Illinois. Metals and cyanide analyses were by a laboratory managed under the USEPA Contract Laboratory Program. Tritium analyses were by a USGS laboratory in Menlo Park, California.

Acknowledgments

Many people are acknowledged for their contribution to the study. Jim Grimes, Superintendent of the Belvidere Water and Sewer Department, and Craig Lawler, Director of the Belvidere Public Works Department, authorized the use of municipal wells for sampling and measurement of water levels and municipal facilities as staging sites during field studies. They also provided well-construction, hydrogeologic, water-quality, and withdrawal data for the municipal wells. Terry Wickler, Director of the Belvidere Waste Water Treatment Plant, provided discharge data from the plant and assistance in managing water disposal during drilling and aquifer testing. The citizens of Belvidere generously granted access to their wells and properties for ground-water-data collection. Dennis Kolata and Mike Sargent of the Illinois State Geological Survey (ISGS) assisted in delineation of bedrock stratigraphy. John Lane, Jr., and Peter Joesten of the USGS, Branch of Geophysical Applications and Support (Connecticut District); Fred Paillet of the Branch of Regional Research, Central Region; and James Ursic, Technical Support Section, Region 5, USEPA (Chicago), assisted in the collection and analysis of geophysical data. Leslie Arihood of the USGS (Indiana District) provided programs that facilitated the use of GIS for visualizing and analyzing hydrogeologic data and processing the data for the ground-water-flow model. Yanqing Lian, a Doctoral student at the University of Illinois at Champaign-Urbana and previous student employee at the USGS (Illinois District) and Timothy Brown of the USGS (Illinois District) assisted in the initial preparation of the input data for the flow model.

HYDROGEOLOGY

The following sections of this report describe the hydrogeologic setting of the study area. The descriptions include the physiography and principal surface-water drainages of the study area: stratigraphy, composition, and texture of the lithologic units and regional structure; hydrogeologic units (aquifers and confining units) and hydraulic properties; and the ground-water-flow system, including hydrologic inputs, losses, and boundaries to the system.

Physiography and Drainage

The study area is in the Rock River Hill Country subdivision of the Till Plains Section of the Central Lowlands Physiographic Province (Leighton and others, 1948). The area is characterized by an undulating topography (fig. 3) sculpted by fewer glacial advances and more erosion than adjacent physiographic regions to the north, east, and south.

The city of Belvidere is in a broad lowland valley (fig. 3) that generally overlies the buried ancestral Troy Bedrock Valley (figs. 4A–4C). The axis of the Troy Bedrock Valley is about 1.5 mi west of the city. Surface-water runoff in the area discharges to the Kishwaukee River and its principal tributaries: Piscasaw, Beaver, and Coon Creeks (fig. 1). Minor drainages include three small creeks or ditches that are confined approximately to the study area and scattered depressions that intermittently convey surface-water runoff or ground-water discharge. The Kishwaukee River flows westward for about 10 mi through the central part of the study area, including the city of Belvidere. Where the river traverses the western part of the city, a low-head dam affects streamflow locally (fig. 1). Uplands that flank the Kishwaukee River valley to the north and south have a maximum altitude of about 900 ft (fig. 3).

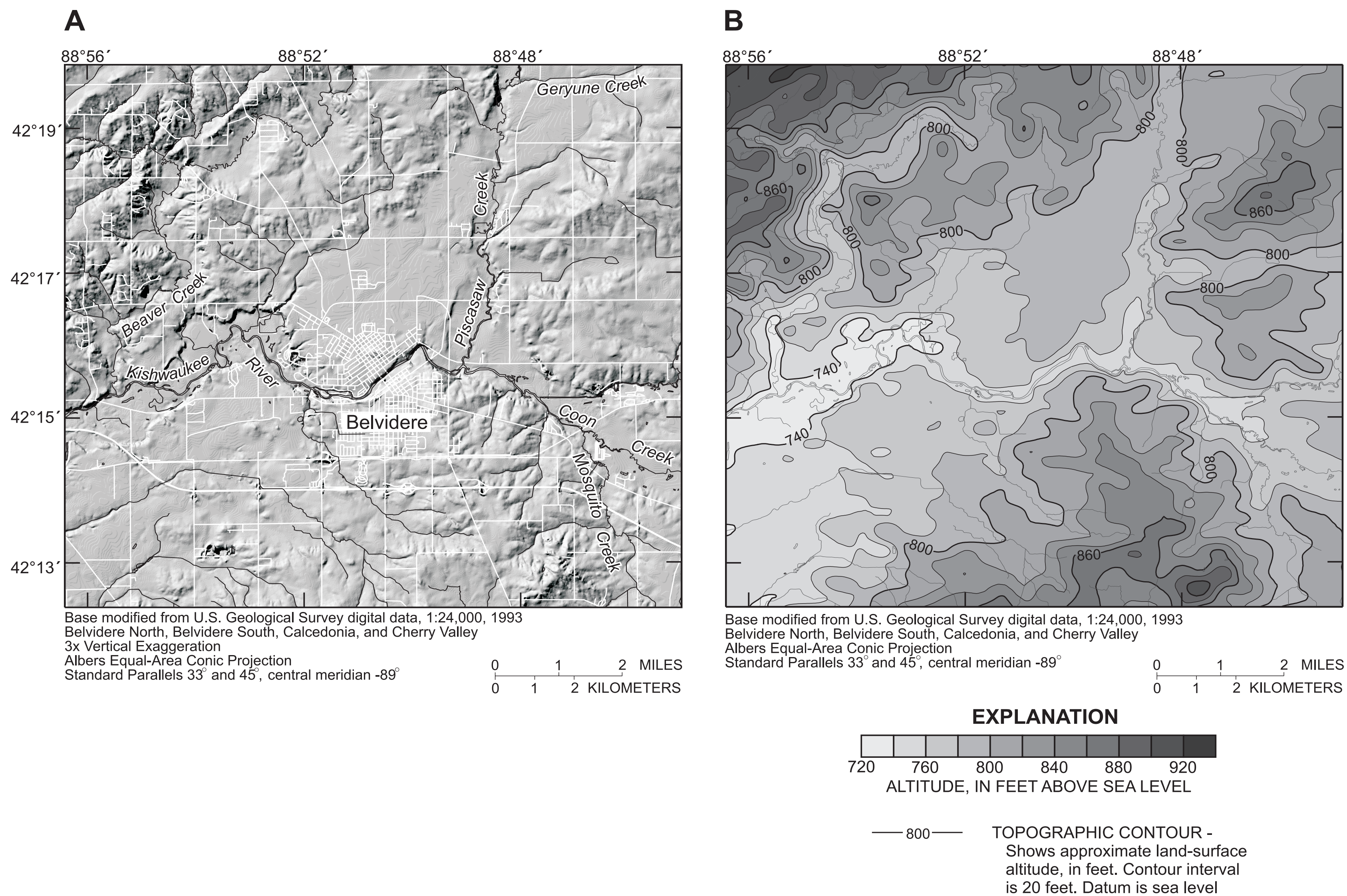


Figure 3. Shaded relief (A) and contours (B) of land-surface topography in the vicinity of Belvidere, Illinois.

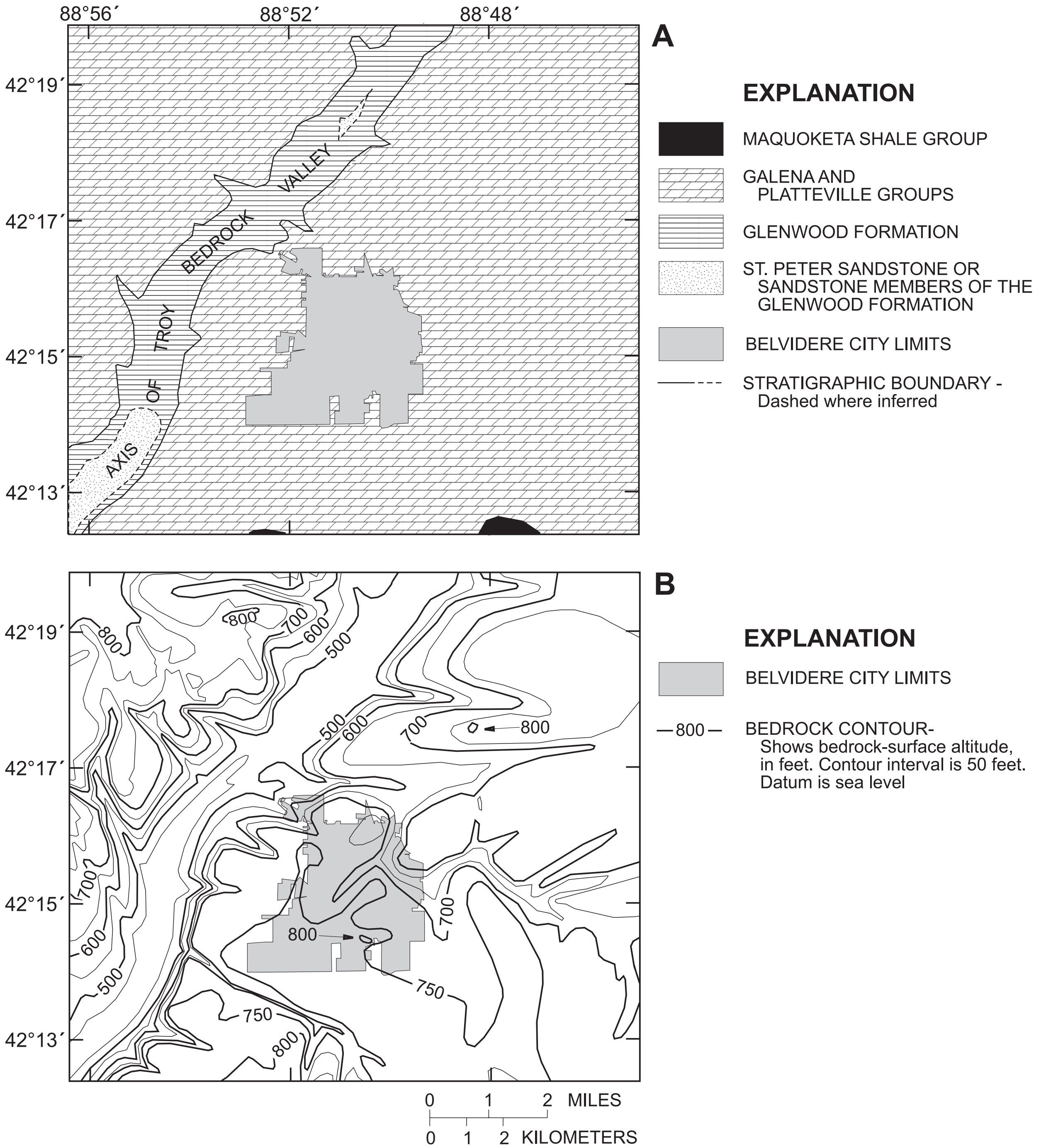


Figure 4. Geology and topography at the surface of selected bedrock units: (A) stratigraphic units that compose the bedrock surface, (B) topography of the bedrock surface, (C) shaded relief of the bedrock surface, and (D) topography of the St. Peter Sandstone surface in the vicinity of Belvidere, Illinois.

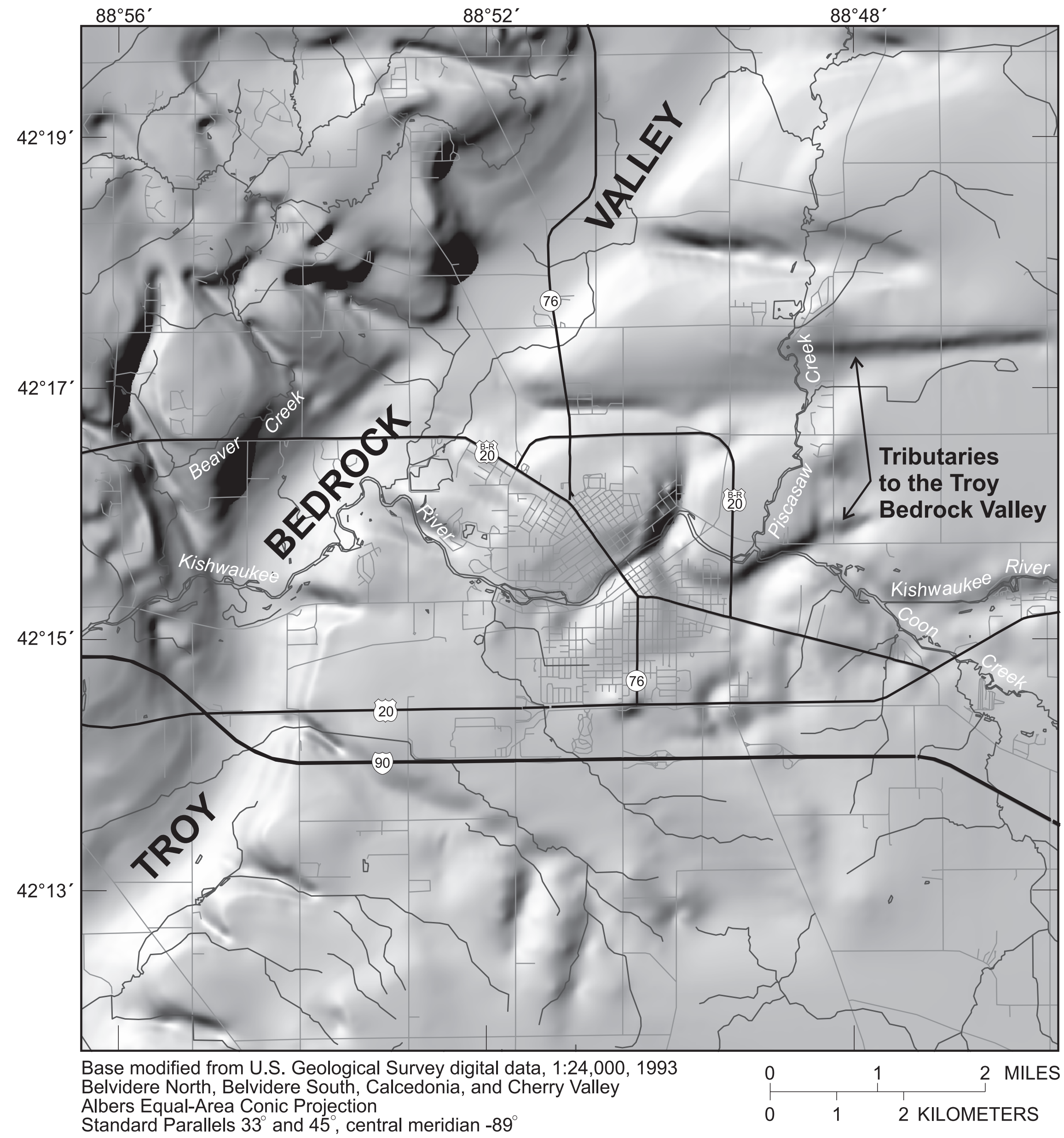


Figure 4. Geology and topography at the surface of selected bedrock units: (A) stratigraphic units that compose the bedrock surface, (B) topography of the bedrock surface, (C) shaded relief of the bedrock surface, and (D) topography of the St. Peter Sandstone surface in the vicinity of Belvidere, Illinois–Continued.

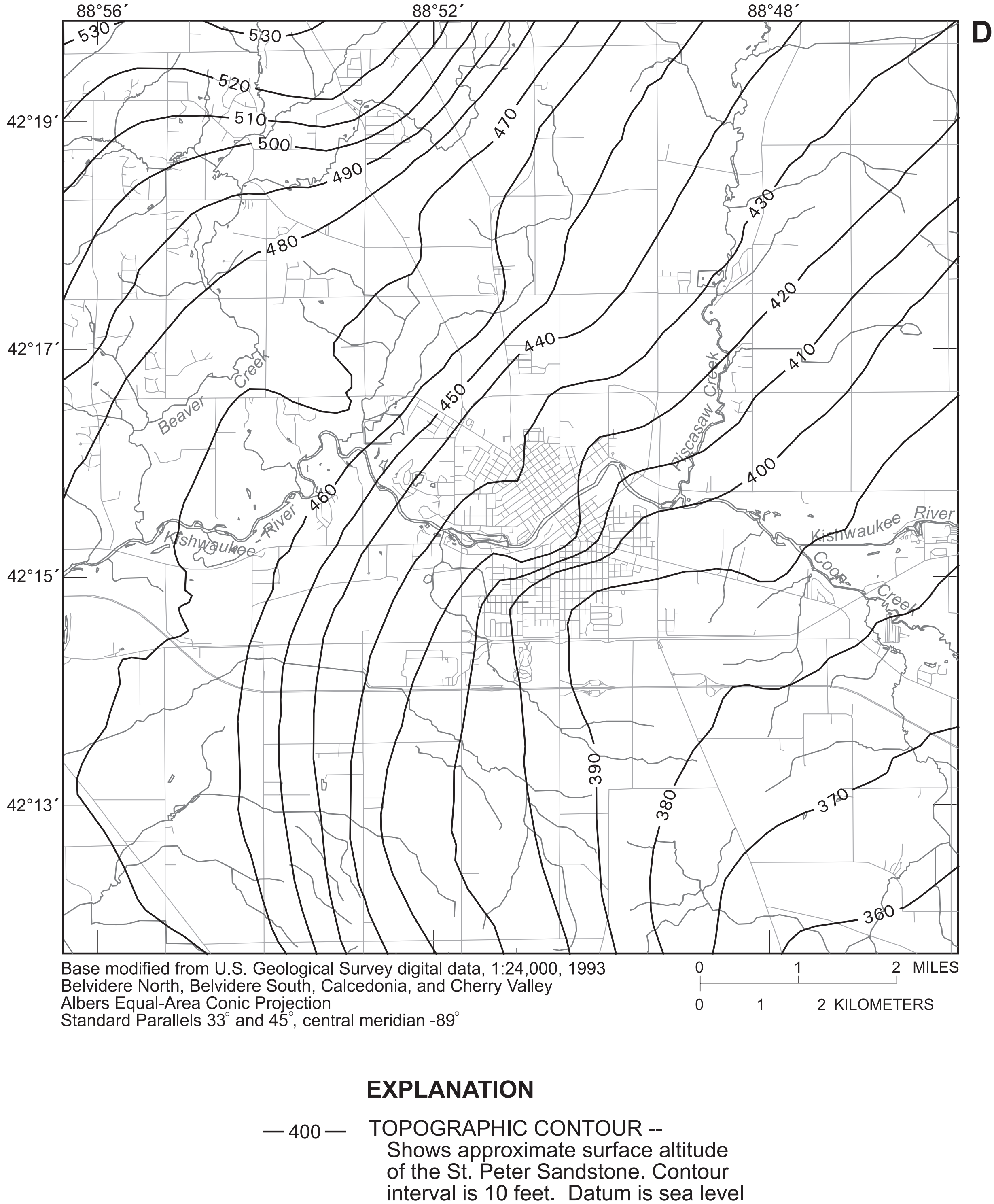


Figure 4. Geology and topography at the surface of selected bedrock units: (A) stratigraphic units that compose the bedrock surface, (B) topography of the bedrock surface, (C) shaded relief of the bedrock surface, and (D) topography of the St. Peter Sandstone surface in the vicinity of Belvidere, Illinois–Continued.

Geology

On the basis of data collected for this and previous investigations, the geologic framework of the ground-water system underlying Belvidere and vicinity is described below. Stratigraphic descriptions based on units encountered during drilling of six Belvidere municipal wells (Woller and Sanderson, 1974) were useful particularly in delineating the bedrock stratigraphy. Classification of the rock-stratigraphic units is shown in figure 2. The rock-stratigraphic nomenclature used in this report is that of the ISGS (Willman and others, 1975) and does not necessarily follow usage of the USGS.

Lithology and Stratigraphy

In order of decreasing age, the bedrock units in the study area are the Mt. Simon Sandstone, Eau Claire Formation, Galesville and Ironton Sandstones, Franconia Formation, and Potosi Dolomite of Cambrian age and the Ancell, Platteville, and Galena Groups of Ordovician age. These units are overlain by sand and gravel units of Quaternary age.

Hydrogeologic sections through the study area are shown in figures 5–9 (lines of section are shown in figs. 1A, 1B). Summarized lithologic descriptions and the depth from land surface of the shallow (less than 400 ft below land surface) bedrock units underlying Belvidere are given in table 2. Geophysical data used, in part, to delineate rock-stratigraphic units are shown in figure 10.

The Mt. Simon Sandstone is about 1,600 ft thick (fig. 2A) (Berg and others, 1984). Seven members primarily consisting of very fine- to very coarse-grained, friable, white, quartz sand have been identified in north-central Illinois. Basal deposits may include as much as 350 ft of arkosic (containing more than 25 percent feldspar and mica), silty sand. Beds of red to light-greenish gray shale up to 15 ft thick may be present in the upper 300 ft and the lower 600 ft of the formation. At a test hole north of Chicago, the upper 140 ft of the sandstone formation is underlain by about 500 ft of sandstone interbedded with red shale; more than 1,000 ft of sandstone underlie the shaley interval (Nicholas and others, 1987). A similar shaley interval may be present in the vicinity of Belvidere, as indicated by drill cuttings from Belvidere municipal wells BMW3 and BMW4. The Mt. Simon Sandstone is underlain by granitic rocks of Precambrian age (fig. 2A).

The Mt. Simon Sandstone is overlain by the Eau Claire Formation (fig. 2A). The approximately 350- to 450-ft-thick formation consists of a medium- to coarse-grained lower part (the Elmhurst Sandstone Member) and a fine-grained upper part. The lower part is gray sandstone; the upper part is sandy dolomite, shale, and dolomitic siltstone. The thickness of each part is not well determined in the study area. As indicated by the geophysical log of Belvidere municipal well BMW8 (GZA GeoEnvironmental, Inc., 1994a), the upper part may be about 220 ft thick and the lower Elmhurst Sandstone Member about 150 ft thick at that location.

The Galesville Sandstone overlies the Eau Claire Formation; the Ironton Sandstone overlies the Galesville Sandstone (fig. 2A). In borings, the separate units are not easily distinguished. Collectively, the formations range in thickness from about 115 to 160 ft. A thickness of about 150 ft is indicated by the geophysical log of Belvidere municipal well BMW2 (Mills and others, 1998). Locally, the sandstones of the lower unit are white, friable, and fine to medium grained; the sandstones of the upper unit generally are white, partly dolomitic, and relatively coarse grained (Woller and Sanderson, 1974; Berg and others, 1984).

The Franconia Formation and Potosi Dolomite are reported to separate the Galesville and Ironton Sandstones from the St. Peter Sandstone of the Ancell Group (fig. 2A) (Berg and others, 1984). The Franconia Formation is composed of primarily sandstone, interbedded siltstone and shale, and some dolomite. The Potosi Dolomite is composed of primarily fine-crystalline dolomite. Collectively, the formations range in thickness from about 100 to 220 ft; a thickness of about 110 ft is indicated by the geophysical log of well BMW2 and 150 ft by the geophysical log of well BMW8.

The St. Peter Sandstone of the Ancell Group is from about 180 to 290 ft thick. The upper part, that includes the fine-grained Tonti Sandstone Member and the medium-grained Starved Rock Sandstone Member, is composed of friable, well-rounded, well-sorted, quartz sand. The lowermost part, the approximately 45-ft-thick Kress Member, contains some red shale and chert that may occur as a conglomerate. Regional mapping (T.A. Brown, U.S. Geological Survey, written commun., 1995), including stratigraphic data from about 30 wells clustered in and near Belvidere, indicates the surface of the St. Peter Sandstone dips gently to the southeast at about 14 ft/mi (fig. 4D).

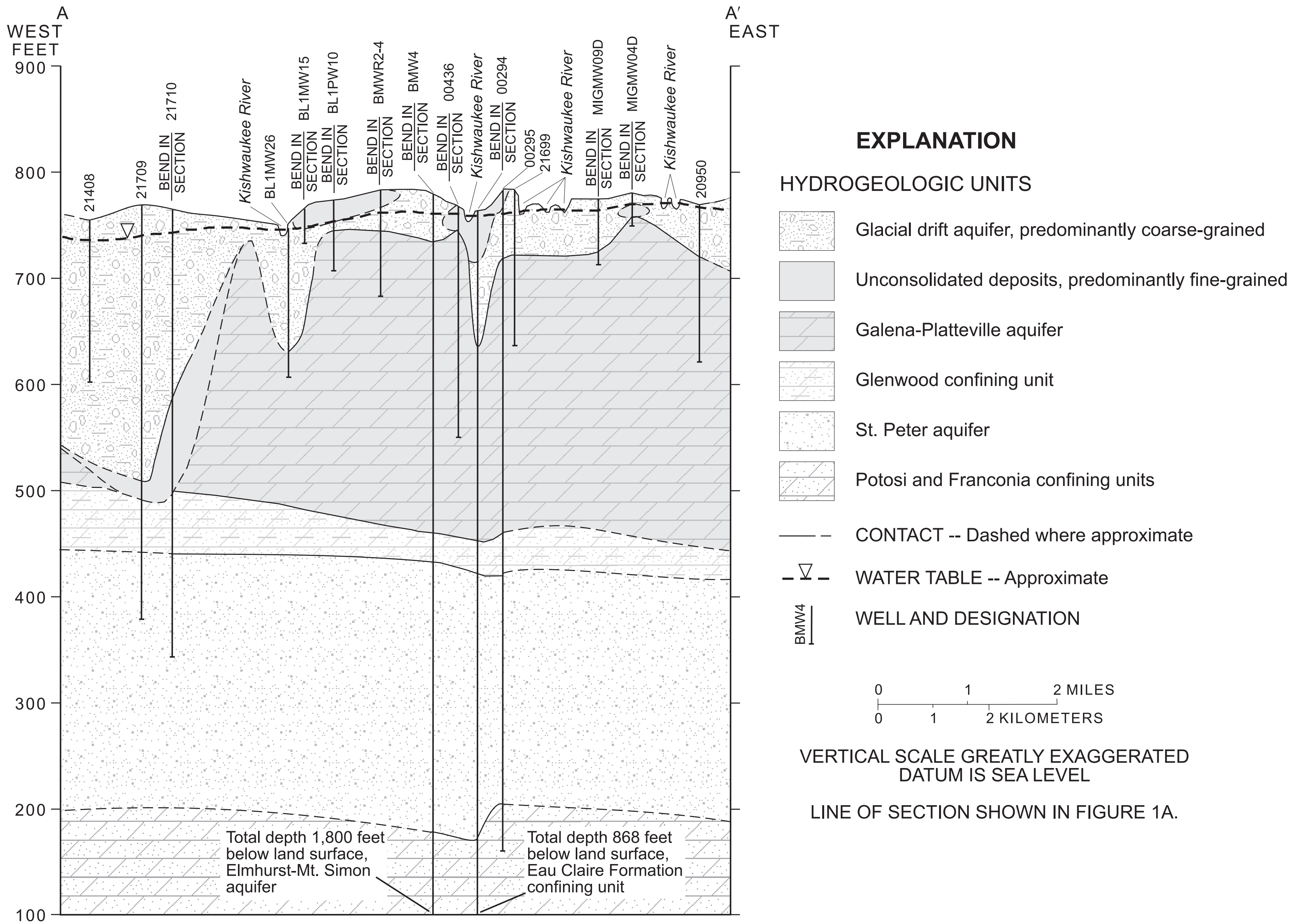


Figure 5. Hydrogeologic section A-A′ through the vicinity of Belvidere, Illinois.

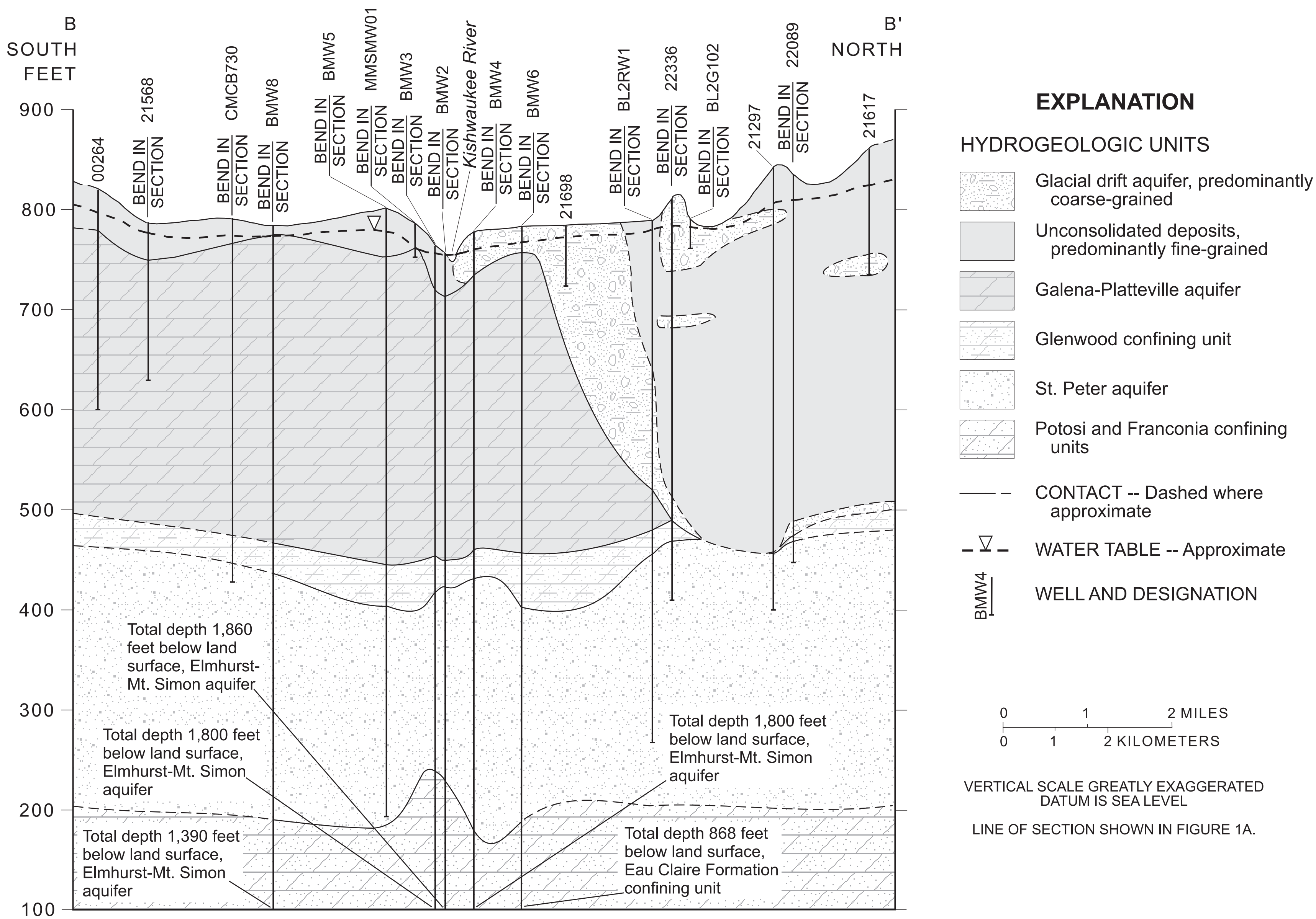


Figure 6. Hydrogeologic section B-B´ through the vicinity of Belvidere, Illinois.

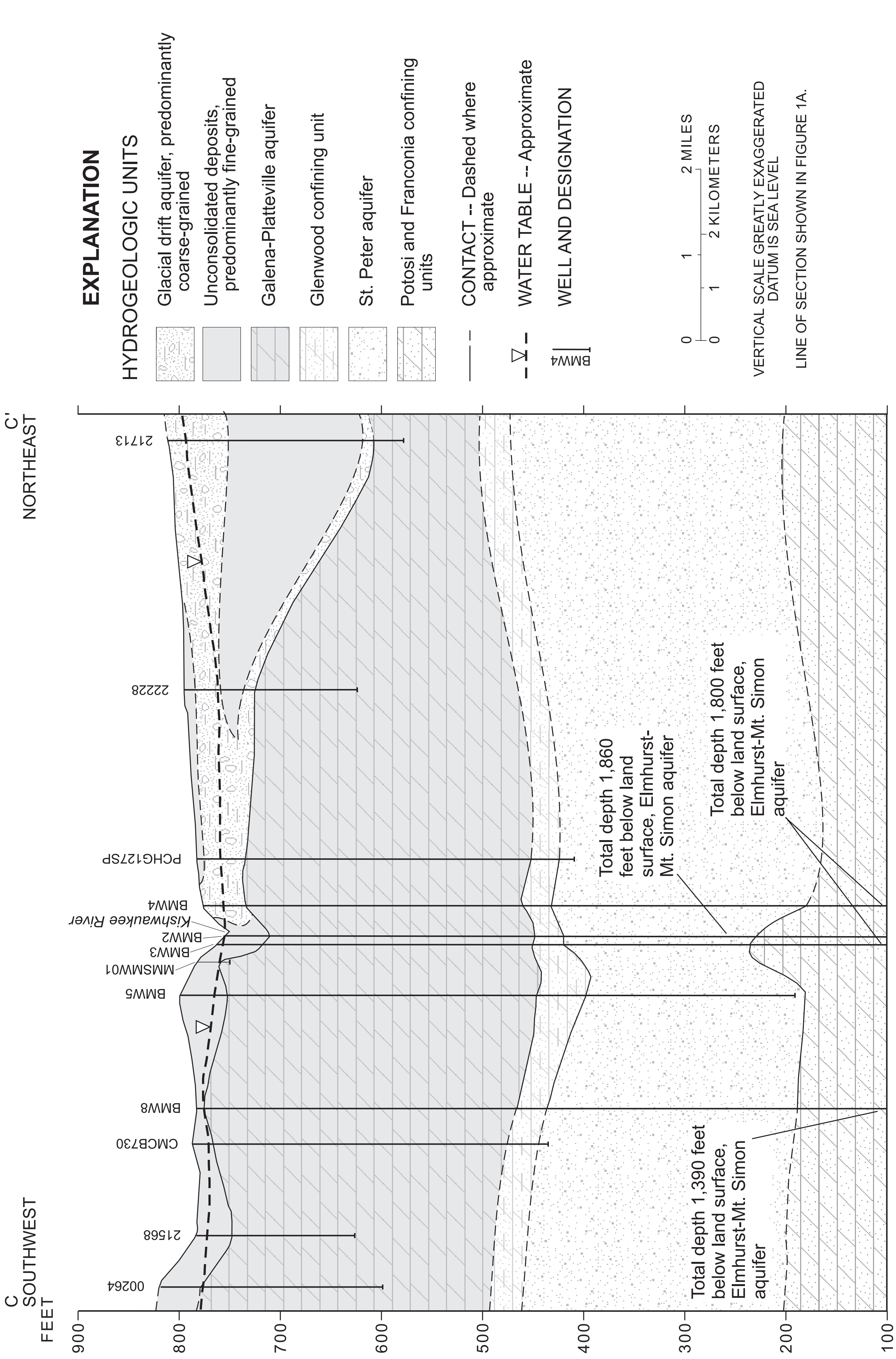


Figure 7. Hydrogeologic section C-C′ through the vicinity of Belvidere, Illinois.

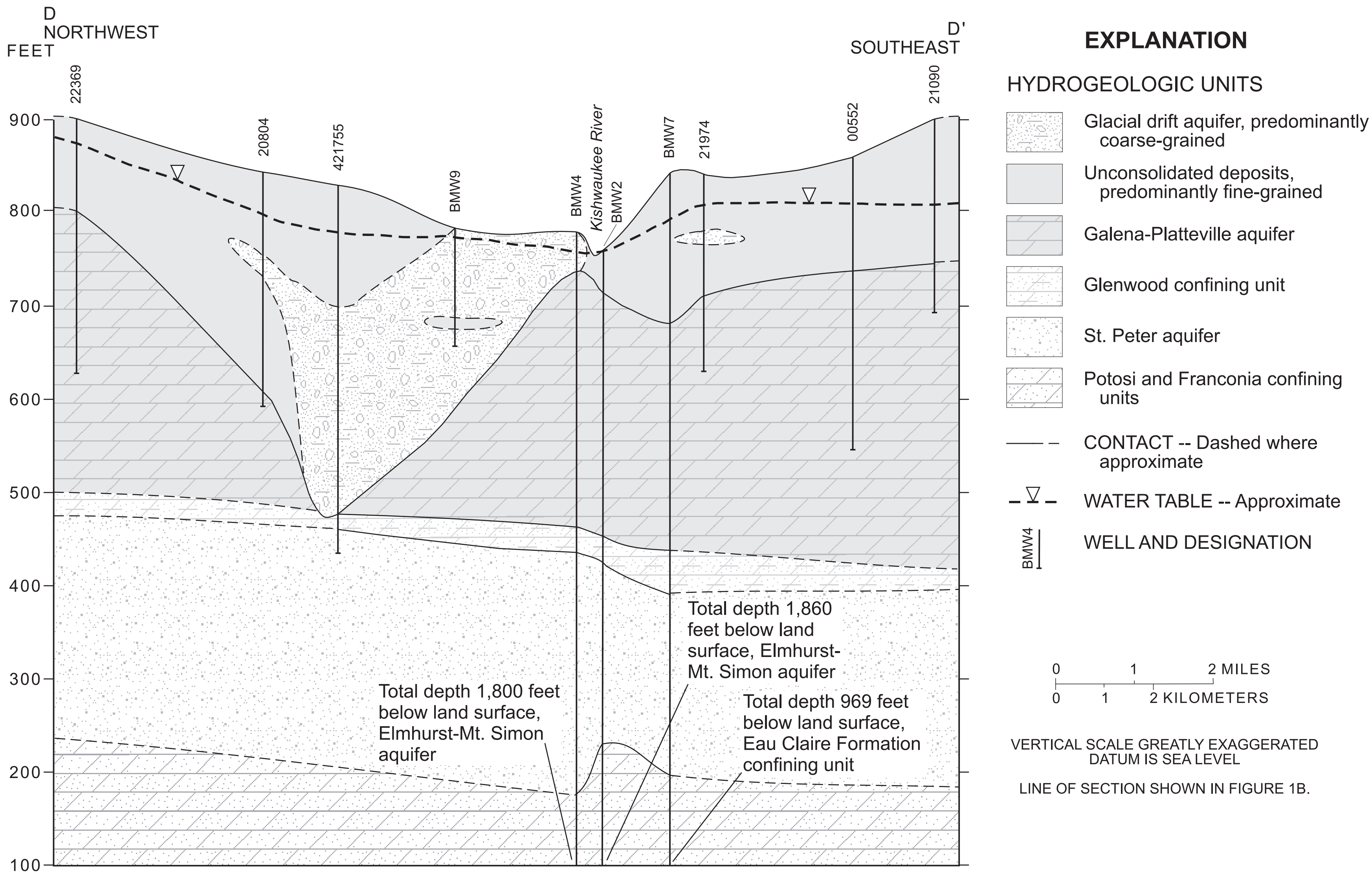


Figure 8. Hydrogeologic section D-D´ through the vicinity of Belvidere, Illinois.

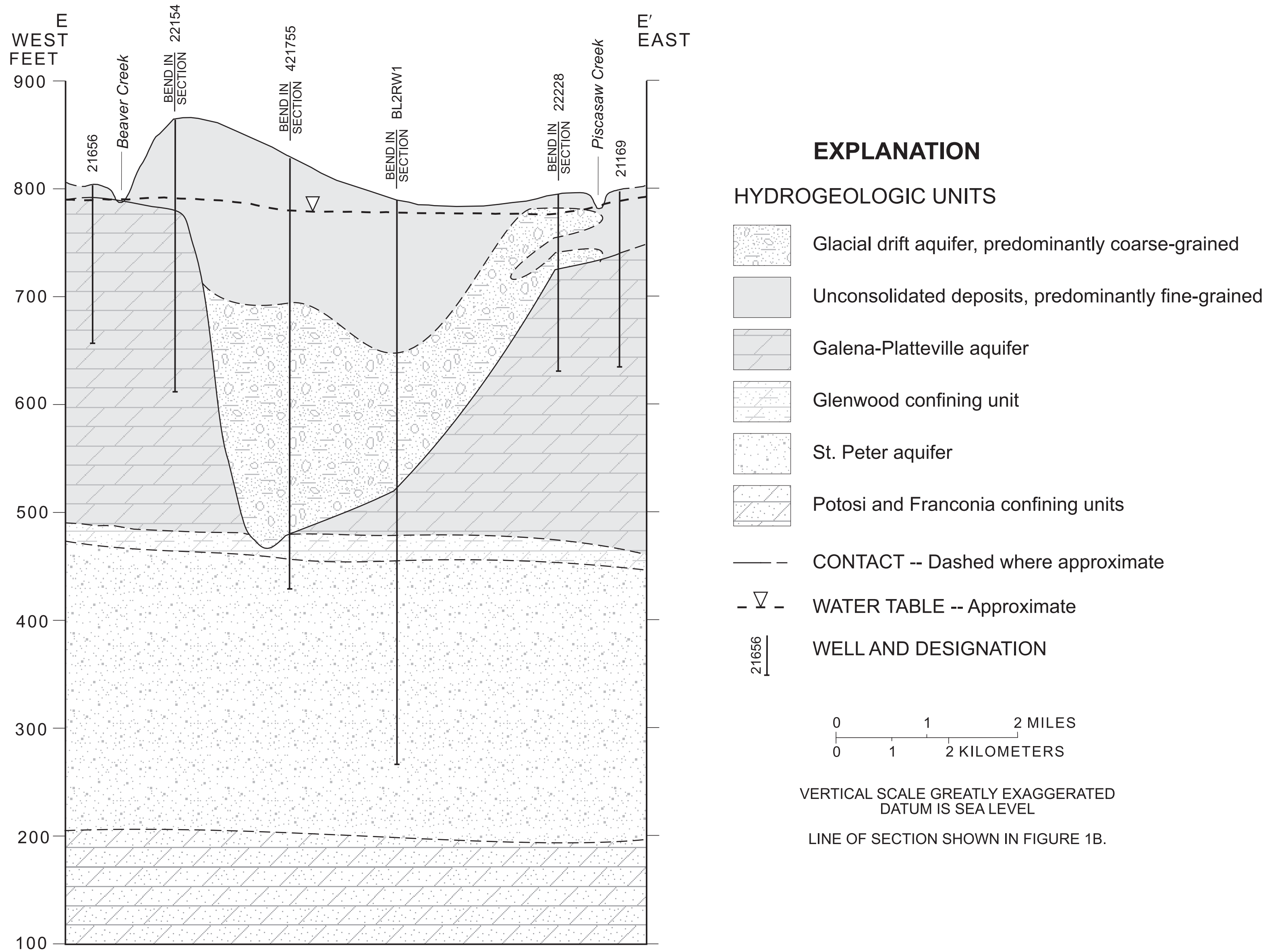


Figure 9. Hydrogeologic section E-E´ through the vicinity of Belvidere, Illinois.

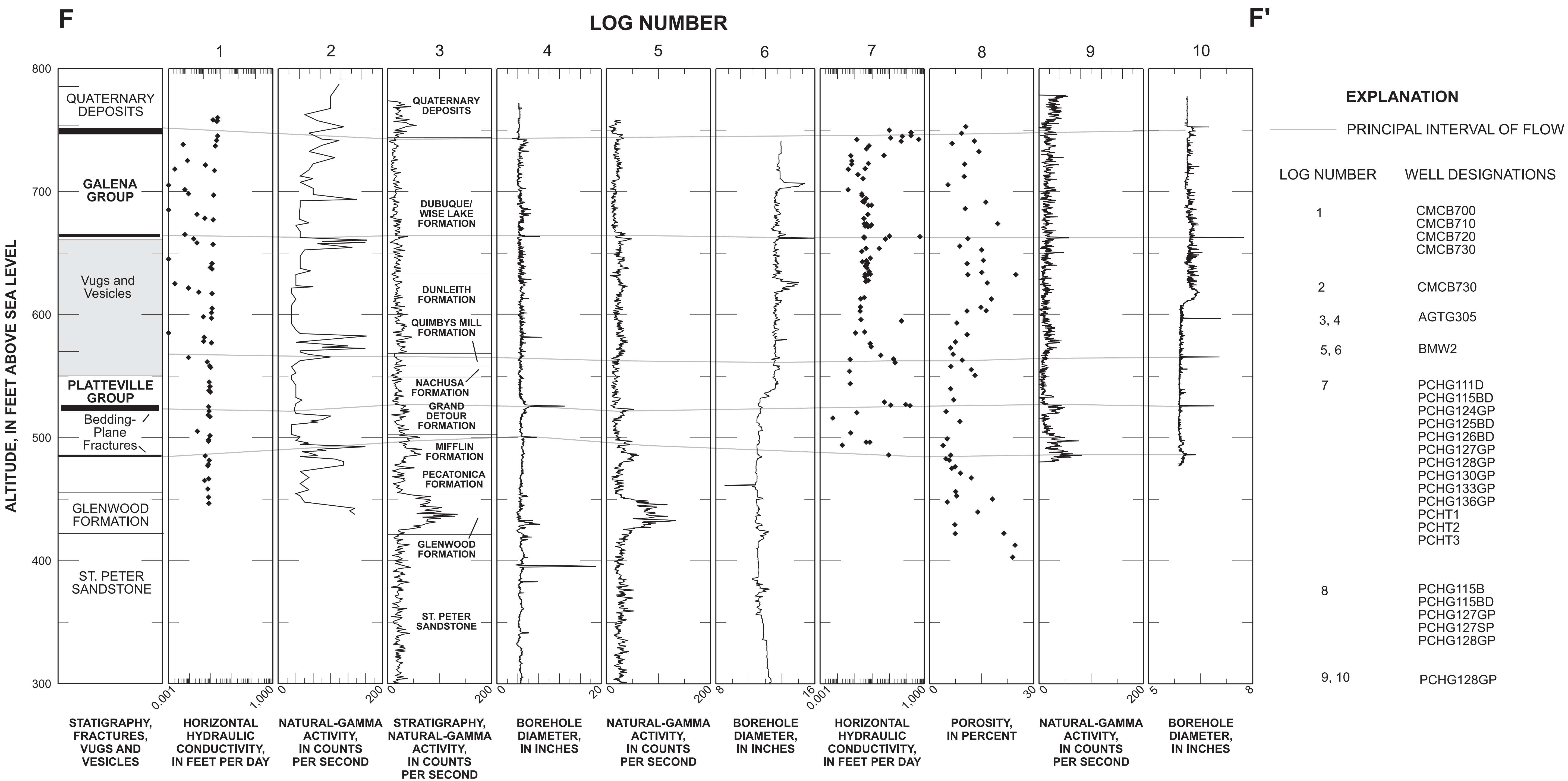


Figure 10. Hydrogeologic section F-F′ through Belvidere, Ill., showing rock-stratigraphic units and principal intervals of ground-water flow in the Galena-Platteville aquifer as indicated by vertical distribution of horizontal hydraulic conductivity, natural-gamma activity, and secondary porosity. (Natural-gamma data for well CMCB730 modified from GZA GeoEnvironmental, Inc., 1993, fig. 3B. Hydraulic-conductivity data for wells CMCB700–CMCB740 from GZA GeoEnvironmental, Inc., 1993, figs. C1–F1.) (Line of section and location of boreholes are shown in figure 1B.)

Table 2. Lithology and rock-stratigraphic units determined from cores of selected boreholes in Belvidere, Illinois

Depth, in feet below land surface	Borehole designation	Rock-stratigraphic unit and lithology
		GALENA GROUP
		Dubuque/Wise Lake Formations
30.0–150	PCHG125B PCHG115BD	Dolomite; light brown to light gray; locally mottled; fine to medium crystalline; slightly vesicular to vuggy; thin shaley partings; slightly fossiliferous, bioturbated
		Dunleith Formation
150–213.9	PCHG127GP PCHG128GP	Dolomite; locally argillaceous; light brown, orange, or gray to medium gray; locally mottled; medium to coarse crystalline; vesicular and vuggy; thin shaley partings; local chert, white to brown; slightly pyritic; very slightly to very fossiliferous, bioturbated
		PLATTEVILLE GROUP
		Quimbys Mill Formation
213.9–225.9	PCHG128GP	Dolomite; light brown to light gray; locally weakly mottled; very fine to fine crystalline; few vugs, thin shaley partings; few chert nodules; very slightly fossiliferous
		Nachusa Formation
225.9–235.1	PCHG128GP	Dolomite; grayish orange; mottled; fine to medium crystalline; large (up to 1 in.) interconnected vugs; chert, light gray; fossiliferous, bioturbated
		Grand Detour Formation
235.1–280.7	PCHG128GP	Dolomite; light orange to medium light gray; locally mottled; very fine to medium crystalline; locally shaley partings; very slightly fossiliferous, bioturbated
		Mifflin Formation
280.7–306	PCHG128GP PCHG127SP	Dolomite with interbedded shales (15 percent of section); light gray with light brown and gray interbeds; thin shales dark gray to black, red, yellowish brown; very fine to fine crystalline with interbeds of coarse crystalline calcarenite; few vugs; locally fossiliferous
		Pecatonica Formation
306–332.3	PCHG128GP PCHG127SP	Dolomite; gray to brown; mottled, light orange, gray; fine to medium crystalline; vesicular, vuggy; shaley partings; rare pyrite; slightly fossiliferous, bioturbated
		ANCELL GROUP
		Glenwood Formation
332.3–361.5	PCHG127SP	Sandstone, dolomite; argillaceous, silty; light gray to brown, locally greenish; sandstone fine to coarse, angular to rounded; dolomite fine crystalline, few vugs; locally pyritic, phosphatic; brecciated; slightly fossiliferous
		St. Peter Sandstone
361.5–394	PCHG127GP	Sandstone; light gray to white, locally greenish; fine to medium; subrounded to well rounded; quartzose, locally pyritic; friable, 25 percent intergranular porosity

The Glenwood Formation of the Ancell Group overlies the St. Peter Sandstone (fig. 2A; table 2). The Glenwood Formation consists of the basal Kingdom Sandstone Member, the medial Daysville Dolomite Member, and the upper Harmony Hill Shale Member. Each member is argillaceous (contain abundant clay and silt), which is indicated by a pronounced increase in natural-gamma activity (fig. 10). Locally, the Harmony Hill Shale Member is sandstone; at most other locations it is a green or black finely laminated shale. The sandstone members are poorly sorted; the dolomite member is dense and fine grained. The dolomite member and lower sandstone member may have a greenish tint associated with glauconite.

The Glenwood Formation may be as thick as 55 ft, which is indicated by the driller's log of Belvidere municipal well BMW6 (figs. 1, 6). Information from logs of six water-supply wells and one test core (Berg and others, 1984) indicate that some or all of the formation may be absent in the erosional Troy Bedrock Valley (figs. 4A, 6). Regional mapping (T.A. Brown, U.S. Geological Survey, written commun., 1995), including stratigraphic data from about 30 wells clustered in and near Belvidere, indicate the minimum thickness of the formation may be about 12 ft outside the Troy Bedrock Valley. Based on a core collected at the Parson's Casket Hardware site (fig. 1A), thicknesses for the Kingdom Sandstone, Daysville Dolomite, and Harmony Hill Shale Members are 1.3, 26.0, and 1.9 ft, respectively (Mills and others, 1998).

Regional characterization of the Harmony Hill Shale Member (Mills and others, 1994, 1999b; Willman and others, 1975) indicates the unit generally is absent east of the study area and thickens to the west. Typically 1–5 ft thick, the unit reaches a maximum thickness of 27 ft in Ogle County (about 40 mi southwest of the study area).

The extent to which the Glenwood Formation has been eroded within the Troy Bedrock Valley is difficult to determine because the few available water-supply wells and test core (Berg and others, 1984) seem to miss the deepest part of the valley. Most wells and the core seem to terminate near or slightly above the contact between glacial drift and bedrock. Additionally, in drill cuttings the sandstones of the Glenwood Formation and of the uppermost part of the St. Peter Sandstone can be difficult to distinguish from one another. Available data indicate the Glenwood Formation may be entirely eroded in only a very small area in the northern part and possibly the southernmost part of the Troy Bedrock Valley (figs. 4A, 6). As interpreted by others, the Glenwood Formation is eroded entirely within large parts of the Troy Bedrock Valley, including within the study area (Berg and others, 1984). In this report, only partial erosion of the Glenwood Formation in most parts of the valley is assumed.

Where the Glenwood Formation is considered partially eroded, it seems, for most areas, about 15 ft or less of the unit has been removed. The erosional loss represents about one-half of the thickness of the formation and includes the Harmony Hill Shale Member and part of the Daysville Dolomite Member. Where eroded, fine-grained till deposits seem to infill the eroded area (figs. 5, 6) (Berg and others, 1984). In a small area in the northwestern part of the valley, sand and gravel may directly overlie the partially eroded Glenwood Formation (figs. 8, 9).

The Platteville Group overlies the Glenwood Formation throughout the study area, except where eroded along the axis of the Troy Bedrock Valley (figs. 2, 4A, 5–9; table 2). Locally, five formations compose the Platteville Group: the Pecatonica, Mifflin, Grand Detour, Nachusa, and Quimbys Mill Formations (fig. 10).

The Platteville Group is composed of primarily fine- to medium-crystalline dolomite. In general, a slightly higher clay content in the dolomite of the Platteville Group distinguishes this unit from the overlying Galena Group. This differentiation is evident in the increased natural-gamma activity on the geophysical log of a borehole open to the Platteville Group (fig. 10). Although limestone and shale units and at least one clay bed also may be present (Willman and Kolata, 1978), only a few shale beds less than 2 in. thick and possibly the remnant of one clay bed were detected in cores collected within Belvidere (Mills and others, 1998). The clay beds were deposited as volcanic ash and altered to potassium-rich bentonite (Willman and Kolata, 1978). Where identified outside of the study area, the beds are less than 1 in. thick, with most less than 0.25 in. thick. The lithology and thickness of the formations that compose the Platteville Group are summarized in table 2.

As determined from cores (Mills and others, 1998), the composite thickness of the Platteville Group is about 118 ft. This thickness is consistent with thicknesses determined from rock cuttings collected in Belvidere (Woller and Sanderson, 1974) and near the study area (M.L. Sargent, Illinois State

Geological Survey, written commun., 1995). Except where eroded within the Troy Bedrock Valley, the thickness of the Platteville Group and the formations that compose the group are not expected to vary substantially within the study area.

The Galena Group overlies the Platteville Group, except where eroded in the Troy Bedrock Valley (figs. 2A, 4A; table 2). Three formations compose the Galena Group within the study area: the Dunleith, Wise Lake, and Dubuque Formations (fig. 10; table 2). The Dunleith and Wise Lake Formations are identified in cores from Belvidere (Mills and others, 1998) and at a quarry about 2.5 mi southwest of Belvidere (Willman and Kolata, 1978). The Dubuque Formation may be present only in part of the study area; the unit could not be identified reliably in the cores (Mills and others, 1998).

Differentiation of stratigraphic units of the Galena and Platteville Groups from the cores proved difficult because traditional differentiation is made primarily on the basis of the weathering signature of exposed units. Use of natural-gamma logs (fig. 10) assists differentiation of the units by allowing identification of variations in clay content (which affects weathering). However, delineation on this basis may be inconsistent with that made on the basis of the weathering signature. The difficulty in delineating stratigraphy of the formations that compose the Galena Group is compounded by apparent erosion or removal during drilling or coring of bentonite marker beds. In particular, what has been identified as the Dygerts bentonite bed (Willman and Kolata, 1978; McGarry, 2000) at the quarry in the southwestern part of the study area (fig. 1A) does not seem to be present in northern Belvidere.

The Galena Group is composed of primarily fine- to medium-crystalline dolomite. Locally, the dolomite is vesicular (visible openings less than 0.25 in. in diameter) or vuggy (openings equal to or greater than 0.25 in. in diameter) and may contain chert (figs. 2A, 11; table 2). Although limestone, shale units, and 10 bentonite beds also may be present (Willman and Kolata, 1978), only thin shaley partings were detected in cores (Mills and others, 1998). The lithology and thickness of the formations that compose the Galena Group are summarized in table 2. Natural-gamma logs indicate a few beds have a relatively high percentage of clay (fig. 10).

As determined from cores (Mills and others, 1998), composite thickness of the Galena Group is about 184 ft. This thickness is consistent with thicknesses determined from rock cuttings collected in Belvidere (Woller and Sanderson, 1974) and near the study area (M.L. Sargent, Illinois State Geological Survey, written commun., 1995). Thicknesses of the Galena Group and the formations that compose the group are assumed to vary little across the study area, except where eroded in and near the Troy Bedrock Valley and, to a lesser extent, in association with regional uplift along the Wisconsin Arch.

The Galena and Platteville Groups are the uppermost bedrock units in north-central Illinois because of uplift associated with the Wisconsin Arch; units of Silurian age present to the east and west have been eroded. This generally northwest-southeast trending structure extends southward into north-central Illinois, with the highest part of the arch in Illinois about 20 mi west of Rockford. East of the high, the bedrock units dip gently to the east at an average of about 20 ft/mi (Willman and Kolata, 1978); within Boone County, about 40 mi east of the high, the dip seems considerably less than 20 ft/mi.

Bedding-plane partings and other secondary-porosity features are present within the dolomites of the Galena and Platteville Groups. Secondary-porosity features in these units are discussed, in detail, in the section “Porosity and Fractures.” Mapping of these features provides information about the regional structure of the dolomite units. Within an area of about 1.5 mi^2 that includes Belvidere, bedding-plane partings and increased natural-gamma activity can be traced intermittently among 22 wells using geophysical logs (fig. 10). Over this area, the vertical position of these features vary less than 5 ft; on this basis, essentially flat-lying beds can be assumed.

In a few isolated locations in the southern part of the study area, the Maquoketa Shale Group overlies the Galena Group (figs. 2A, 4A). The shale deposits of this unit, sometimes described as “blue clay” in drillers' logs, may be as thick as 30 ft. Berg and others (1984) report that this shale may contain stringers of dolomite locally.

Unconsolidated deposits in the study area consist of glacial deposits of Quaternary age, as well as recent alluvial deposits (fig. 2A). The generalized distribution of the unconsolidated deposits is given in figure 12 and table 3. A brief summary of the stratigraphy of unconsolidated units is presented in this report. Berg and others (1984) provide a detailed discussion of these units and the depositional environment in Boone County.

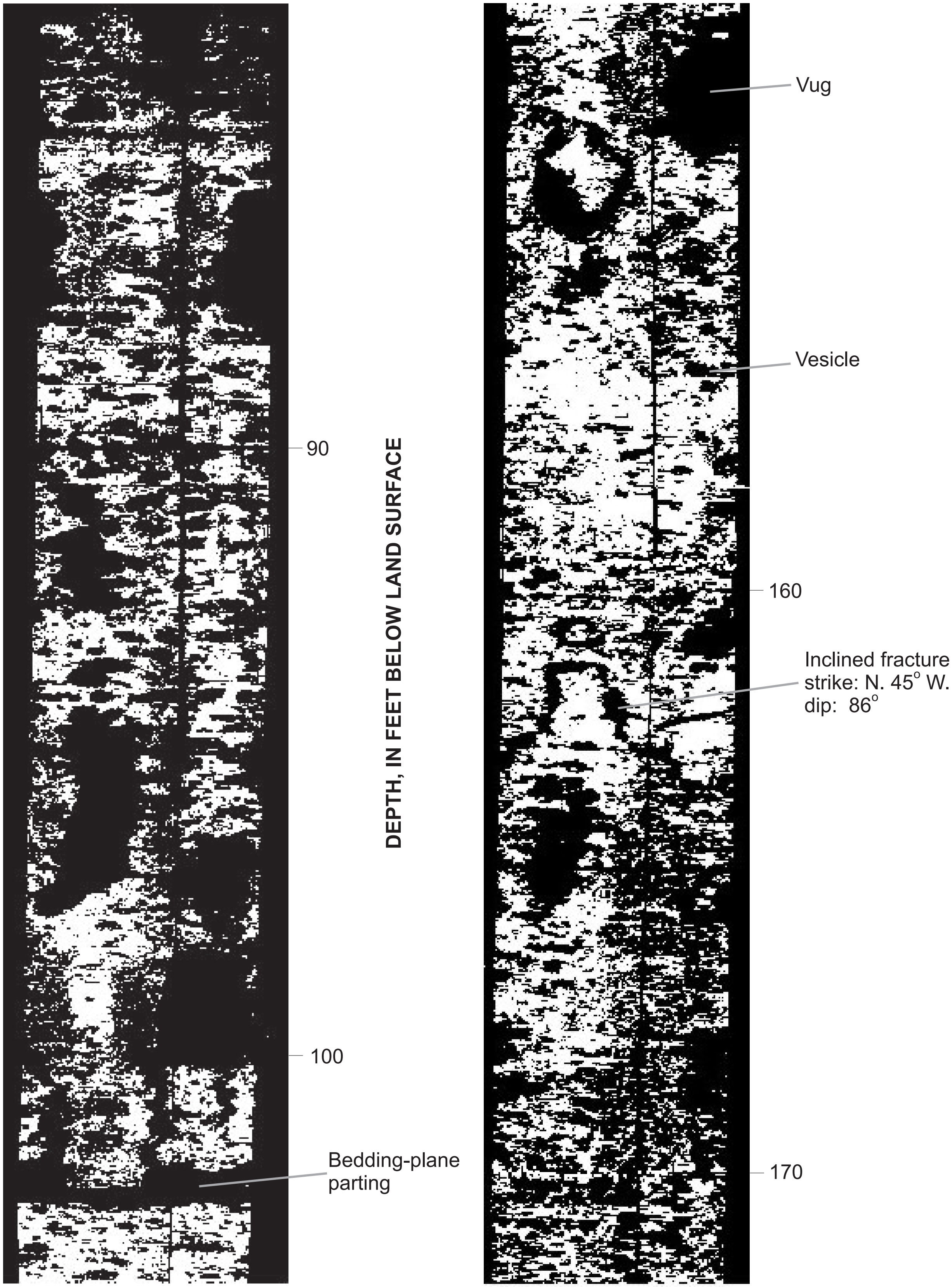


Figure 11. Acoustic-televiewer log showing secondary-porosity features in municipal well BMW2, Belvidere, Illinois.

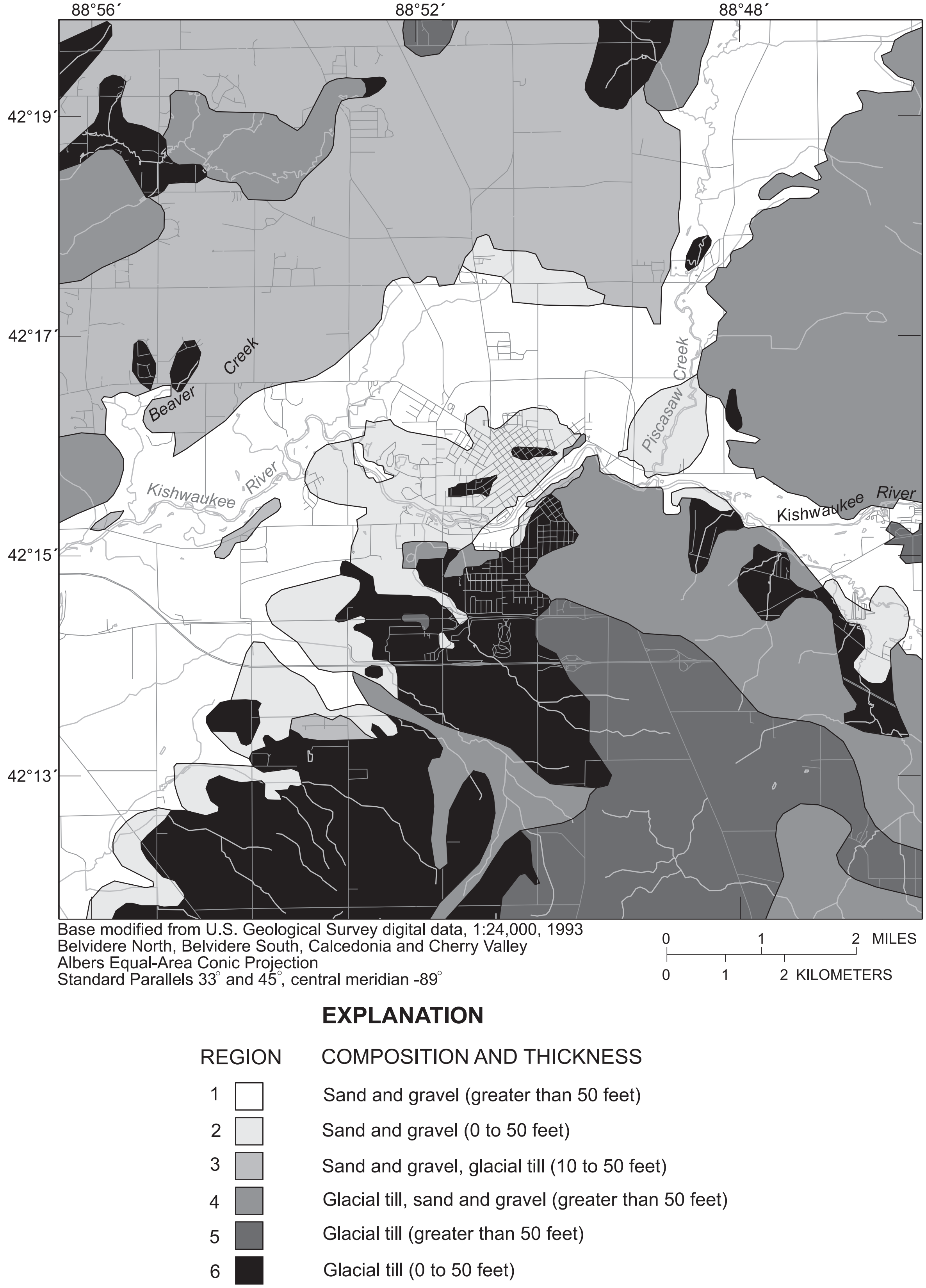


Figure 12. Generalized distribution of unconsolidated deposits in the vicinity of Belvidere, Illinois (modified from Berg and others, 1984, fig. 19).

Table 3. Generalized distribution of unconsolidated deposits in the vicinity of Belvidere, Illinois (modified from Berg and others, 1984, fig. 19)

Region[1]	Description
1	Surficial sand and gravel is at least 50 feet thick and as much as 100 feet or more locally; part of a relatively widespread sand-and-gravel deposit; fine-grained deposits possible in the upper 40 feet; includes areas of older valley-fill outwash containing interbedded fine-grained deposits
2	Surficial sand and gravel is less than 50 feet thick near valley walls or over bedrock or till highs; locally very thin
3	Sand and gravel is at least 10 feet thick locally; interbedded with glacial till or other fine-grained deposits
4	Glacial till is greater than 50 feet thick; sand-and-gravel deposits present below or within glacial till or other fine-grained deposits locally
5	Glacial till is greater than 50 feet thick; few interbedded sand-and-gravel deposits
6	Glacial till is less than 50 feet thick; very few thin interbedded sand-and-gravel deposits

[1] Regions are shown approximately in figure 12.

Quaternary-age formations present in the study area include the Glasford, Winnebago, Henry, and Equality Formations and the Cahokia Alluvium (fig. 2B). Stratigraphic subunits of these formations range in composition from fine-grained tills to coarse-grained sands and gravels.

The thick outwash sand-and-gravel deposits that compose much of the Troy Bedrock Valley and parts of the Kishwaukee River and Piscasaw Creek valleys (figs. 5–9, 12) are the Mackinaw Member of the Henry Formation (Berg and others, 1984). To a lesser extent, sand-and-gravel deposits in these areas consist of an unnamed outwash deposit of the Glasford Formation and the Wasco Member of the Henry Formation. Narrowly distributed deposits of sand of the Cahokia Alluvium flank major streams; these deposits often include silt and clay. In parts of the study area, the coarse-grained deposits are exposed at land surface, particularly along the lower reaches of Beaver Creek, near the confluence of Piscasaw Creek and Kishwaukee River, and near the northwest side of Belvidere. Scattered quarries have been operated in these areas; the largest is an approximately 50-acre site northwest of Belvidere (fig. 1).

Beyond the bedrock and stream valleys, interbedded outwash sand deposits locally are associated with till members of the Winnebago and Glasford Formation. The most extensive sand deposits, which are distributed variably across most of the study area, are assigned to the Oregon and Kellerville Till Members of the Glasford Formation (fig. 2B). Silty-to-coarse lacustrine sand deposits of the Dolton Member of the Equality Formation also are present locally in the southeastern part of the study area.

Till members of the Glasford and Winnebago Formations are primarily sandy. However, a silty clay till, the Esmond Till Member of the Glasford Formation, covers much of the south-central part of the study area. These till units constitute more than 50 percent of the surficial deposits in the study area. Outwash sand-and-gravel deposits following the northeast to southwest trend of the Troy Bedrock Valley and major streams constitute the remaining surficial deposits (fig. 12).

Unconsolidated deposits are as thick as 385 ft in the deepest part of the Troy Bedrock Valley (figs. 4C, 5, 6, 8, 9); sand-and-gravel deposits are as much as 260 ft thick. Unconsolidated deposits are absent locally where the underlying Galena Group dolomite outcrops at a bedrock high on the southwest edge of Belvidere. In Belvidere, sand-and-gravel deposits as much as 45 ft thick infill an ancestral tributary to the valley (figs. 4C, 5). At most locations, including within the Troy Bedrock Valley, sand-and-gravel deposits are interbedded with various thicknesses of fine-grained deposits. Till of the Glasford Formation underlies the sand-and-gravel deposits throughout most of the deepest part of the valley (figs. 5, 6) (Berg and others, 1984).

On the basis of the distribution and thickness of the unconsolidated deposits, Berg and others (1984) identified six principal regions (fig. 12; table 3). Four areas with notable sand-and-gravel deposits are (1) the Troy Bedrock Valley and Piscasaw Creek valley, where thick sand-and-gravel deposits predominate; (2) the areas that immediately flank the Troy Bedrock Valley and major streams, where thinner sand-and-gravel deposits predominate; (3) the northwestern part of the study area, where sand-and-gravel deposits with interbedded sandy till predominate; and (4) the northeastern part of the study area, where till with locally interbedded sand-and-gravel deposits predominate. Till predominates in the south-central and southeastern parts of the study area.

Fractures and Porosity

Dolomite of the Galena and Platteville Groups typically has considerable secondary porosity. This porosity is associated with near-horizontal bedding-plane partings; inclined fractures (joints); and dissolutional enlargement of the fractures, partings, and dolomite matrix.

At least five laterally persistent bedding-plane partings have been identified in two or more geophysical logs of 22 wells within Belvidere (fig. 10; table 4) (Mills and others, 1998; Kay and others, 2000; GZA GeoEnvironmental, Inc., 1993). None of the partings have been detected in every logged well. In some cases, the partings have not been identified by logging because (1) the surface casings of the wells are installed too deep into bedrock and prevent access to the partings, (2) the wells are not deep enough to intercept the partings, or (3) the partings possibly are obscured by increases in well diameter.

A cluster of partings, typically about 5 ft thick, is associated with the irregular weathered surface of the Galena and Platteville Groups (fig. 4A). The other easily identified partings seem to occur as individual features. With consideration of the monitoring radius of the caliper tools (8–12 in.), apertures of most partings seem to be less than 3 in. The aperture of one parting, at about 525 ft above sea level (about 260 ft below land surface[1]; hereafter referred to as the 260-ft parting), may be as large as 1 ft. The intermittent detection of the partings in the geophysically logged wells and the variable hydraulic properties of the partings indicate dissolutional enlargement and subsequent infilling of the partings (and, thus, the aperture size) are variable spatially.

Limited information is available regarding the noted bedding-plane partings (table 4) in parts of the study area outside the approximate 1.5-mi^2 area where wells were logged. The parting at about 660 ft above sea level (about 125 ft below land surface; hereafter referred to as the 125-ft parting) is reported to be present in the vicinity of Belvidere municipal well BMW8 and at the quarry southwest of Belvidere (D.H. Fischer, Quality Aggregates of Illinois, Inc., oral commun., 1999) (fig. 1). The partings and their general characteristics would be expected to persist throughout most of the study area because of the consistency of the carbonate-bedrock geology within the vicinity of the study area. Modeling results indicate this assumption may not be valid, possibly because the hydrogeologic controls on carbonate dissolution do not persist (see "Model Calibration").

Inclined fractures are present throughout the study area, as they are throughout northern Illinois. Surface- and borehole-geophysical logs (Mills and others, 1998; Kay and others, 2000) indicate some fractures may penetrate deeper than 300 ft; thus,

[1]Depths below land surface here and elsewhere in the report are referenced to an approximate land surface of 785 feet above sea level at the Parson's Casket Hardware site in Belvidere.

Table 4. Principal bedding-plane partings identified in the rock-stratigraphic units that compose the Galena and Platteville Groups underlying Belvidere, Illinois

Approximate altitude of parting, in feet above sea level	Approximate depth of parting, in feet below land surface	Rock-stratigraphic unit where fracture was identified	Well where fracture was identified
[1]740	[1]45	Dubuque/Wise Lake[1]	BMW2, PCHG115BD, PCHG125BD, PCHG126BD, PCHG128GPD, PCHG127SP(?)
660	125	Dubuque/Wise Lake	AGTG305SP, BMW2, PCHG128GP, PCHG436BD, PCHG126BD(?)
590	195	Dunleith	AGTG305SP, BMW2, PCHG128GPD(?)
560	220	Quimbys Mill	PCHG128GP, G124GP[2], G130GP[2]
525	260	Grand Detour	AGTG305SP, PCHG127GP, PCHG128GP, PCHG127SP(?)
485	300	Mifflin	PCHG128GP, BMW2

[1] Altitude, depth, and rock-stratigraphic unit are for the clustered bedding-plane partings associated with the weathered surface of the Galena Group. The position and rock-stratigraphic unit with which the weathered surface is associated may vary within the study area. The information provided is for the area near the Parson's Casket Hardware Superfund site (fig. 1).

[2] From Kay (2001).

cross-cutting bedding-plane partings are distributed throughout the thickness of the aquifer and, possibly, the underlying Glenwood confining unit. Orthogonal fractures, as mapped by Foote (1982) at quarries and outcrops in and near the study area, have primary and secondary orientations of about N. 60° W. and N. 30° E., respectively. McGarry (2000) mapped similar fracture sets in the area, with approximate orientations of N. 75° W. and N. 30° E. As part of the present study, orientations of N. 80° W. and N. 10° E. were mapped at a small quarry in the northwestern part of the study area (fig. 1A). At two sites near Belvidere (fig. 1B), surface-geophysical surveys (square-array resistivity) tentatively identified deeply penetrating high-angle fractures (interpreted as extending to about 220 ft below land surface) (Mills and others, 1998). Primary orientations of the fractures seem to be about N. 30° W. and N. 45° W., with a secondary orientation of about N. 60° E. Borehole-geophysical logs of three wells in Belvidere indicate fracture orientations range from about N. 90° W. to N. 50° E. but typically fall in the range from about N. 45° W. to N. 60° W. (Mills and others, 1998; F.L. Paillet, U.S. Geological Survey, written commun., 1992 and 1995).

Where visible in quarries and outcrops, the spacing between the majority of inclined fractures is less than about 100 ft. At the quarry in the southwestern part of the study area (fig. 1A), spacing between about 70 percent of the 49 mapped fractures is less than about 80 ft (McGarry, 2000). Median spacings between the northwest and northeast trending fractures in the quarry are about 48 ft and 62 ft, respectively. From eight boreholes installed within less than 50 ft from each other at the Parson's Casket Hardware site, the spacing between fractures is estimated to be 30 ft (Kay and others, 2000). Dip angles of the fractures measured at the three wells logged in Belvidere are about 35–85° (Mills and others, 1998; J.W. Lane, Jr., U.S. Geological Survey, written commun., 1993). Mean fracture lengths measured at quarries in and near the study area are about 300 ft for fractures in the Galena Group and 750 ft for fractures in the Platteville Group (McGarry, 2000). Interpretation of resistivity data from one surface-geophysical site indicates porosity of about 32 percent for the deepest penetrating fracture (Mills and others, 1998; P.K. Joesten and J.W. Lane, Jr., U.S. Geological Survey, written commun., 1996).

Core and geophysical (ground-penetrating radar, acoustic televiewer, and caliper) data indicate a fairly even distribution of bedding-plane partings and inclined fractures throughout the thickness of the Galena and Platteville Groups. Furthermore, as many as four fracture traces identified in ground-penetrating-radar logs at the Parson's Casket Hardware site (at well PCHG127GP) (Mills and others, 1998) (fig. 1A) have been interpreted as intercepting the well trace just above (within 30 ft) or below (about 300 ft) the Glenwood Formation. Such fractures, if present, could penetrate the formation. If partings and fractures extend to the lower part of the Galena and Platteville Groups in relatively consistent density, the pattern would be contrary to that indicated in the carbonate units of Silurian age in northeastern Illinois. In that area, parting and fracture density (and associated transmissivity) are greatest in the upper part of the units (Csallany and Walton, 1963).

Primary bedding-plane partings enlarged extensively by secondary dissolution may have developed above stratigraphic horizons of low hydraulic conductivity, such as the bentonite beds. Restricted downward flow and substantial seepage have been observed in the sidewalls of area quarries above thin bentonite-clay beds (D.R. Kolata, Illinois State Geological Survey, oral commun., 1999). Peaks in natural-gamma activity often are associated with the partings. Inspection of a core collected at well PCHG128GPD (fig. 1A) indicated a gravelly mud, possibly bentonite, at the depth of the prominent 260-ft parting (Mills and others, 1998). A relatively high concentration of fluoride (1.8 mg/L) was detected in a water sample from a packed interval at well PCHG127GP (fig. 1A) that included the 260-ft parting (Mills, 1993c). Bentonite is a natural source of fluoride in ground water (Hem, 1985). In a study of the Galena and Platteville Groups about 40 mi southwest of Belvidere, some of the clays associated with the partings were determined to have the radioactive signature of potassium (others had the signature of uranium and thorium) (F.L. Paillet, U.S. Geological Survey, written commun., 1991). As previously indicated, potassium is a principal constituent of bentonite. The evidence of bentonite from the geophysical logs and cores may support the suggested origin of the dissolutionally enlarged partings.

Dissolution openings in the dolomite matrix, vesicles and vugs (hereafter referred to collectively as vugs) (fig. 11), are concentrated primarily in the Dubuque/Wise Lake and Dunleith Formations of the Galena Group and the Nachusa Formation of the Platteville Group (fig. 10). Vugs generally are prevalent in units with low clay content. At the Parson's Casket Hardware site (fig. 1), vugs that enhance permeability are concentrated in two intervals that are from about 660 to 570 ft above sea level (about 125 to 215 ft below land surface) and about 560 to 550 ft above sea level (about 225 to 235 ft below land surface). Less than 0.25 mi from the site, the vugs also are present throughout the upper part of the Dubuque/Wise Lake Formation, above about 660 ft above sea level (Kay, 2001).

Effective porosity (excluding fracture porosity) of each of the three above-noted vuggy units of the Galena and Platteville Groups averages about 12.5 percent (table 5; fig. 10) (Mills and others, 1998). Porosity of other rock-stratigraphic units that compose the Platteville Group averages from about 5 to 8 percent. In contrast to the Galena and Platteville Groups, porosity of the three rock-stratigraphic units that compose the underlying Glenwood Formation averages about 12 percent. Porosity of the Daysville Dolomite Member, which composes about 90 percent of the thickness of the formation, averages about 8 percent. Porosity of the uppermost Starved Rock Member of the St. Peter Sandstone averages about 24 percent. In some cases, effective porosity can be associated positively with the capacity of an aquifer to transmit water.

Hydrology

On the basis of data collected for this and previous investigations, the hydrology of the ground-water system underlying Belvidere and vicinity is described. The ground-water system includes the principal unconsolidated and bedrock aquifers, subunits within the aquifers, and confining units. Hydraulic properties (horizontal hydraulic conductivity (K_h) and transmissivity) of the aquifers and confining units are discussed, as are gains (precipitation/recharge), losses (well withdrawals and discharge to streams), and boundaries to the flow system; ground-water levels and directions of flow; and water quality.

Classification of hydrogeologic units for Belvidere and vicinity is shown in figure 2A. Hydrogeologic sections are shown in figures 5–9 (lines of section are shown in figs. 1A, 1B). The nomenclature is slightly modified from that of the Illinois State Water Survey (Woller and Sanderson, 1974); modifications accommodate the scale, water-quality, and flow-simulation aspects of this study.

Precipitation and Streamflow

Long-term (1961–90) annual precipitation at the National Weather Service (NWS) station in Rockford (Rockford WSO AP, about 15 mi west of Belvidere)

Table 5. Average matrix porosity of the rock-stratigraphic units that compose the Galena and Platteville Groups, Glenwood Formation, and St. Peter Sandstone underlying Belvidere, Illinois

[--, information not applicable]

Rock-stratigraphic unit			Porosity[1] (percent)
Group	**Formation**	**Member**	
Galena	Dubuque/Wise Lake	--	12.3
Galena	Dunleith	--	12.1
Platteville	Quimbys Mill	--	7.4
Platteville	Nachusa	--	12.6
Platteville	Grand Detour	--	6.6
Platteville	Mifflin	--	5.1
Platteville	Pecatonica	--	8.3
Ancell	Glenwood	Harmony Hill Shale	18.1
Ancell	Glenwood	Daysville Dolomite	8.2
Ancell	Glenwood	Kingdom Sandstone	14.4
Ancell	St. Peter Sandstone	Starved Rock	24.2

[1] Porosity data are presented in full in Mills and others (1998). Porosity of the tested cores represents effective porosity, which is presumed to approximate the total porosity of most cores.

averages 36 in/yr (U.S. Department of Commerce, 1961–90). During 1961–90, annual precipitation ranged from 23 in/yr, in 1976 to 56 in/yr, in 1973. During 1990–95, when most water-level data were collected for this study, annual precipitation ranged from 32 to 45 in. (measured at the NWS station in Belvidere (fig. 1C)) (Clayton Environmental Consultants, Inc., 1996).

During spring and summer of 1993, precipitation was more than 150 percent of average in much of the upper Mississippi River Valley region, including the vicinity of Belvidere (D.W. Kolpin, U.S. Geological Survey, written commun., 1993). In June 1993, 14.1 in. of precipitation fell in the vicinity of Belvidere. Long-term (1961–90) average precipitation in June is about 4 in.

Since 1939, streamflow in the Kishwaukee River has been gaged at the USGS streamflow-gaging station Kishwaukee River at Belvidere (fig. 1). The study area represents about 7 percent of the 538-mi^2 drainage area monitored at the station. Annual mean ([2]1940–99) streamflow at the station is 376 ft^3/s. The highest annual mean on record, 992 ft^3/s, was measured in water year 1993 (LaTour and others, 2000).The highest mean for July on record, 1,815 ft^3/s, also was measured in 1993. The lowest annual mean on record, 112 ft^3/s, was measured in water year 1963. In water year 1993, the instantaneous low-flow rate was 128 ft^3/s (October 31) and the annual 7-day minimum flow rate was 142 ft^3/s (October 25) (Maurer and others, 1994).

In 1981, estimates of 7-day, 2-year (Q7,2) and 7-day, 10-year (Q7,10) low flow were made at the Kishwaukee River at Belvidere station and at five partial-record stations in and near the study area (Allen and Cowan, 1985). The Q7 low flow is the minimum 7-day mean streamflow with a 2- or 10-year recurrence interval and is calculated from the frequency of annual values of the lowest mean flow for 7 consecutive days. Estimates of Q7,2 and Q7,10 low flow ranged from respective rates of 2.4 and 1.3 ft^3/s at a partial-record station on Beaver Creek (drainage area of 26.1 mi^2) to 62 and 33 ft^3/s at the Kishwaukee River at Belvidere station.

Streamflow measurements made during September 8–10, 1999, are given in table 6 (measurement sites are shown in fig. 1C). In the Kishwaukee River, streamflow rates ranged from 43.2 ft^3/s, on the eastern edge of the study area (site S01), to 143 ft^3/s, on the western edge (site S09). The highest flow rate for tributaries to the Kankakee River was 33 ft^3/s, in Piscasaw Creek at its confluence with the Kishwaukee River (site S05). Streamflow at other locations ranged from 0.44 to 18 ft^3/s. Low-flow conditions, which generally indicate that most streamflow is represented by ground-water discharge to the streams, can be demonstrated by comparison of discharge measurements at the Kishwaukee River at Belvidere station (site S12) to an annual hydrograph (water year 1999) and flow-duration curve for the station (fig. 13). Discharge at the station, as measured in September 1999, is exceeded at least 80 percent of the time (fig. 13B).

[2] Period represents water years. The water year is the 12-month period from October 1 through September 30. The water year is designated by the calendar year in which it ends and which includes 9 of the 12 months.

Aquifers and Confining Units

In order of increasing age, the aquifers in the study area are the glacial drift aquifer of Quaternary age and the following bedrock aquifers: the Galena-Platteville and St. Peter aquifers of Ordovician age, and the Ironton-Galesville and Elmhurst-Mt. Simon aquifers of Cambrian age (figs. 2, 5–9). In this report, the nomenclature Cambrian-Ordovician aquifer represents the system that includes the above-listed bedrock aquifers; this nomenclature generally conforms to prevailing usage (Woller and Sanderson, 1974; Young, 1992). A well that is designated as open to the Cambrian-Ordovician aquifer is open to one or more of the aquifers of Ordovician age and one or more of the aquifers of Cambrian age. For convenience, the nomenclature Ordovician aquifer represents the system that includes the Galena-Platteville and St. Peter aquifers. A well that is designated as open to the Ordovician aquifer is open to the Galena-Platteville and St. Peter aquifers.

Sand-and-gravel deposits compose the glacial drift aquifer. On a local scale, specific sand-and-gravel deposits may compose units that are hydraulically isolated by interbedded fine-grained deposits. However, for the purposes of this study, all sand-and-gravel deposits are assumed to be a single glacial drift aquifer. When considering flow on a regional scale, this assumption is reasonable.

The glacial drift aquifer is distributed throughout much of the study area, particularly the Troy Bedrock Valley (figs. 4, 5, 6, 8, 9), its ancestral tributaries, and the present-day drainages of the Kishwaukee River and

Table 6. Measured streamflow on selected streams in the vicinity of Belvidere, Illinois, September 8–10, 1999

[ft^3/s, cubic feet per second]

Measurement site	Site number[1]	Measurement date	Measured streamflow[2] (ft^3/s)
Kishwaukee River at Newburg Road	(S02)	09-08-99	143
Kishwaukee River at Belvidere, Illinois[3]	(S12)	09-10-99	97.8
Belvidere Waste Water Treatment Plant[4]	(S12W)	09-08-99	5.4
Kishwaukee River near Belvidere, Illinois	(S09)	09-09-99	43.2
Beaver Creek at Kishwaukee River	(S01)	09-08-99	17.2
Beaver Creek at Orth Road	(S03)	09-08-99	8.96
Unnamed creek below Candlewick Lake	(S04)	09-08-99	.44
Piscasaw Creek at Lawrenceville Road	(S05)	09-09-99	32.8
Piscasaw Creek at Russellville Road	(S08)	09-09-99	18.0
Geryune Creek at Wolf Road	(S07)	09-09-99	2.59
Coon Creek at Kishwaukee River	(S06)	09-09-99	16.0
Coon Creek near Garden Prairie, Illinois	(S10)	09-09-99	13.8
Mosquito Creek at Coon Creek	(S13)	09-09-99	1.02
Mosquito Creek at Huber Road	(S11)	09-09-99	.55

[1] Locations of measurement sites are shown in figure 1C.
[2] A 5-percent measurement error is assumed for the streamflow measurements.
[3] Measurement site for U.S. Geological Survey streamflow-gaging station Kishwaukee River at Belvidere, Illinois (05438500).
[4] The plant is about 500 feet west of Stone Quarry Road, adjacent to the U.S. Geological Survey streamflow-gaging station Kishwaukee River at Belvidere, Illinois.

its tributaries (fig. 12; table 3). The aquifer also is present in the northern parts of the study area. Elsewhere, coarse-grained deposits that may be present are considered too thin or narrowly distributed to be considered aquifers, particularly in the southern part of the study area. The glacial-drift deposits are unsaturated in two general bands in the western part of the study area (fig. 14A). The deposits that compose the aquifer are thickest (up to 260 ft) within the Troy Bedrock Valley. Locally, the aquifer is near or at land surface, particularly where the valley is overlain by the Kishwaukee River. Sand-and-gravel deposits compose a substantial part of most major streambeds.

The compositionally and hydraulically similar dolomites of the Galena and Platteville Groups compose the Galena-Platteville aquifer. The aquifer is absent where eroded in the deepest parts of the Troy Bedrock Valley, but is as thick as about 300 ft outside the valley (figs. 4A–4C, 5–9). The network of secondary openings in the dolomite matrix account for the usually dependable supply of moderate quantities (up to 40 gal/min) of water to wells (Berg and others, 1978).

The St. Peter aquifer ranges in thickness from about 180 to 290 ft. The compositionally and hydraulically similar deposits of the Ironton and Galesville Groups compose the Ironton-Galesville aquifer; thickness of the aquifer ranges from about 115 to 160 ft. The compositionally and hydraulically similar Elmhurst Sandstone Member of the Eau Claire Formation and the upper part of the Mt. Simon Sandstone compose the Elmhurst-Mt. Simon aquifer. The aquifer is about 1,600 ft thick. The sandstone aquifers are present throughout northern Illinois and are the primary source of water to high-capacity wells. The Ironton-Galesville aquifer is considered the most productive unit in this region (Visocky, 1993).

The individual aquifers are separated by confining units. In order of increasing age, are the fine-grained deposits locally interbedded within the glacial drift aquifer, and the Maquoketa, Glenwood, Potosi-Franconia, Eau Claire, and Mt. Simon confining units (figs. 2, 5–9).

The Maquoketa confining unit may be present locally in the far southern parts of the study area (fig. 4A). However, because its presence is restricted and it is overlain by fine-grained unconsolidated deposits, the unit is not considered further in this report.

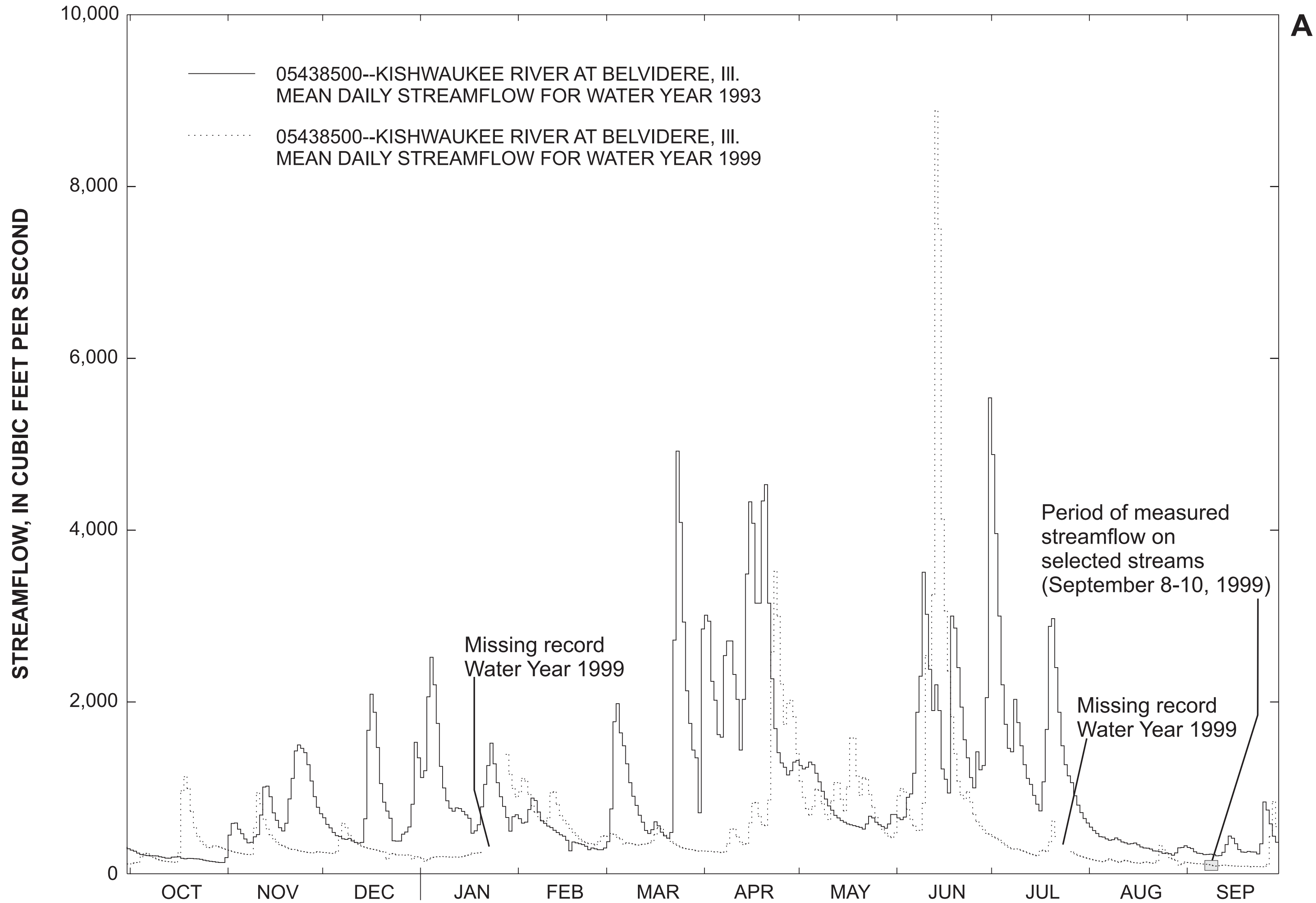


Figure 13. Streamflow in the Kishwaukee River at Belvidere, Illinois: (A) hydrographs for water years 1993 and 1999, and (B) flow duration for water years 1940–2000.

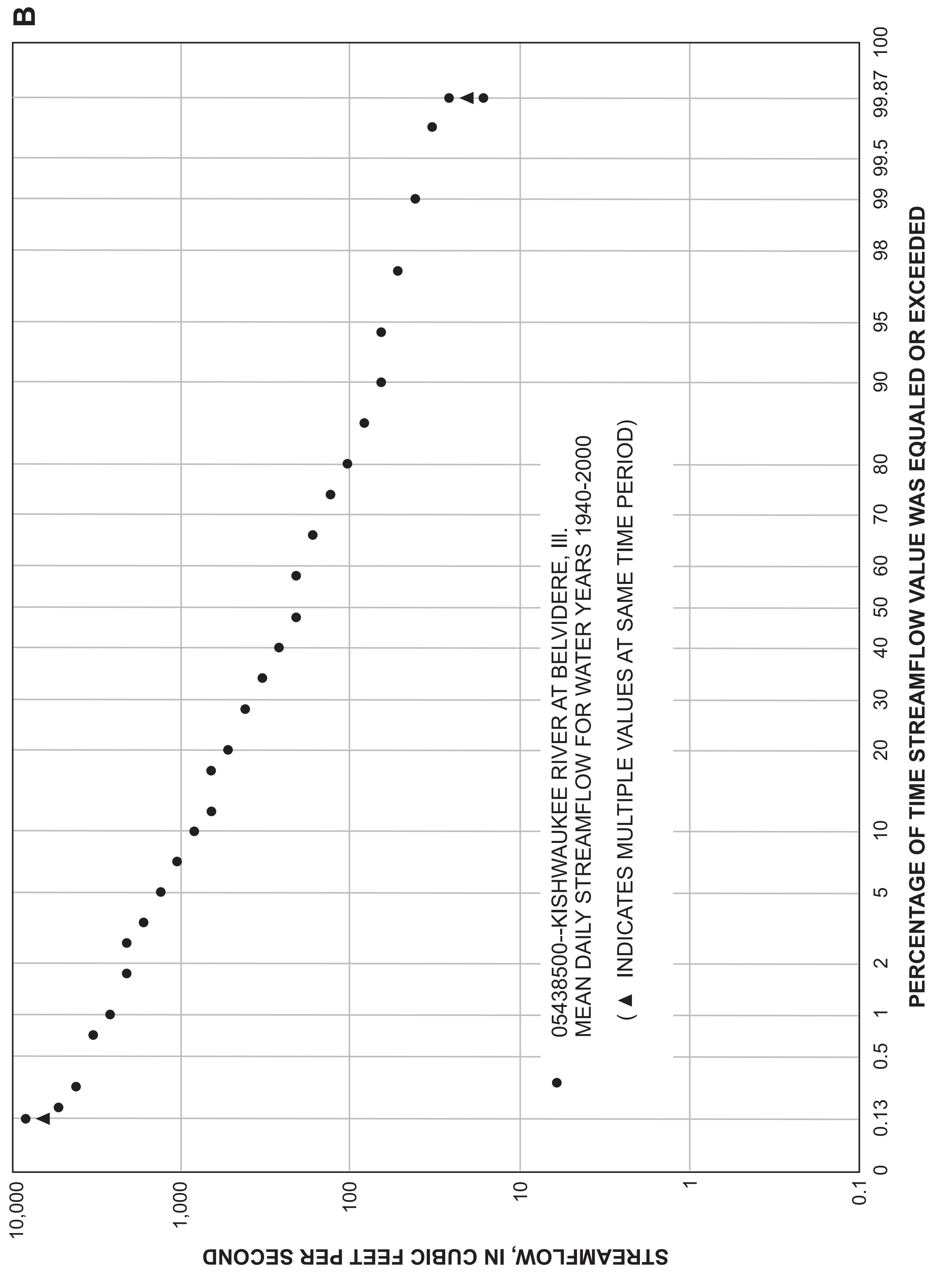
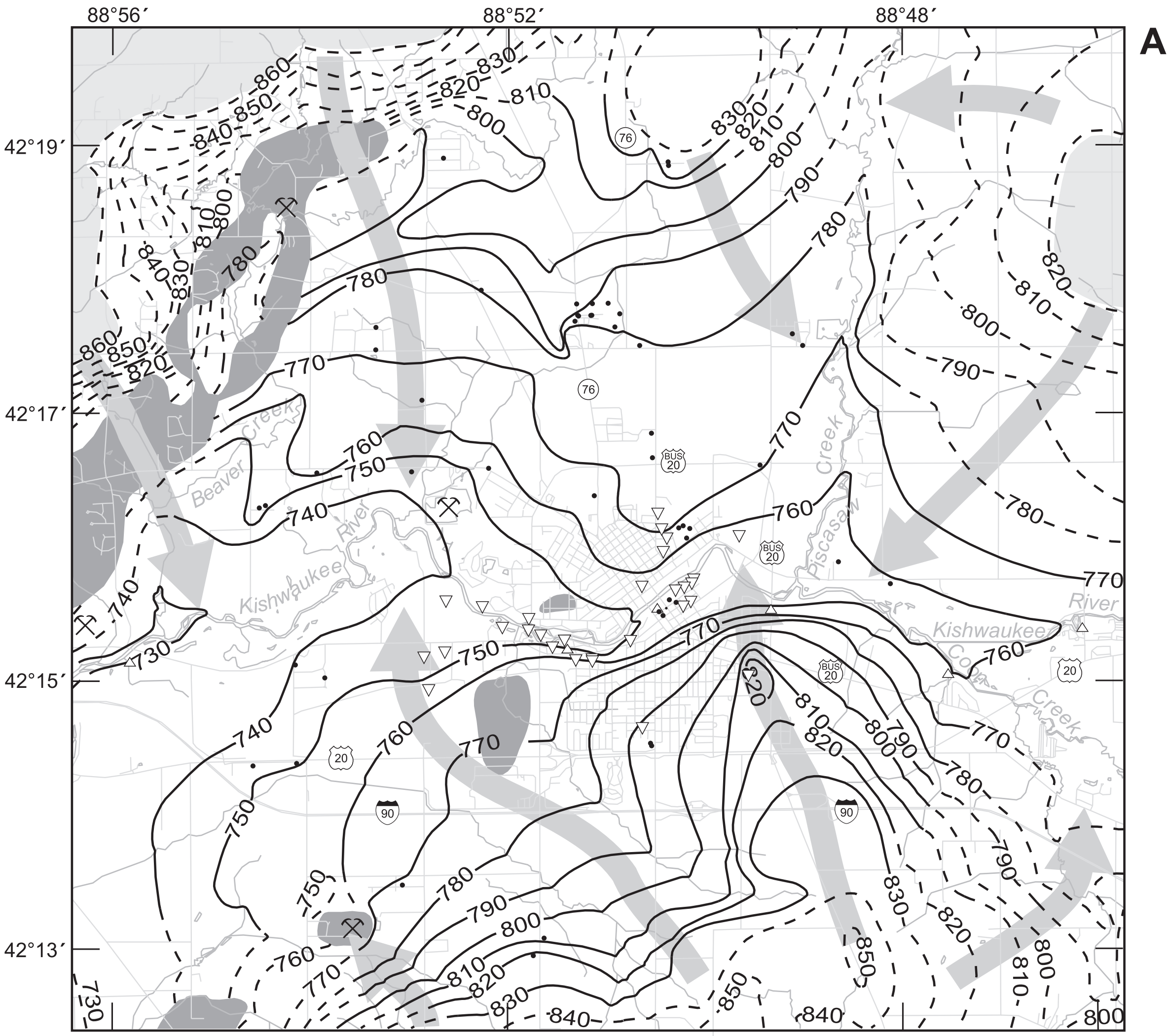


Figure 13. Streamflow in the Kishwaukee River at Belvidere, Illinois: (A) hydrographs for water years 1993 and 1999, and (B) flow duration for water years 1940–2000—Continued.



Base modified from U.S. Geological Survey digital data, 1:24,000, 1993
Belvidere North, Belvidere South, Calcedonia, and Cherry Valley
Albers Equal-Area Conic Projection
Standard Parallels 33° and 45°, central meridian -89°

0 1 2 MILES
0 1 2 KILOMETERS

EXPLANATION

APPROXIMATE AREA WHERE GLACIAL DRIFT IS UNSATURATED

NOT CONTOURED BECAUSE OF LIMITED WATER-LEVEL-CONTROL DATA

GENERALIZED DIRECTION OF GROUND-WATER FLOW

—750– – POTENTIOMETRIC CONTOUR – Shows altitude at which water would have stood in tightly cased wells. Dashed where inferred. Contour interval is 10 feet. Datum is sea level

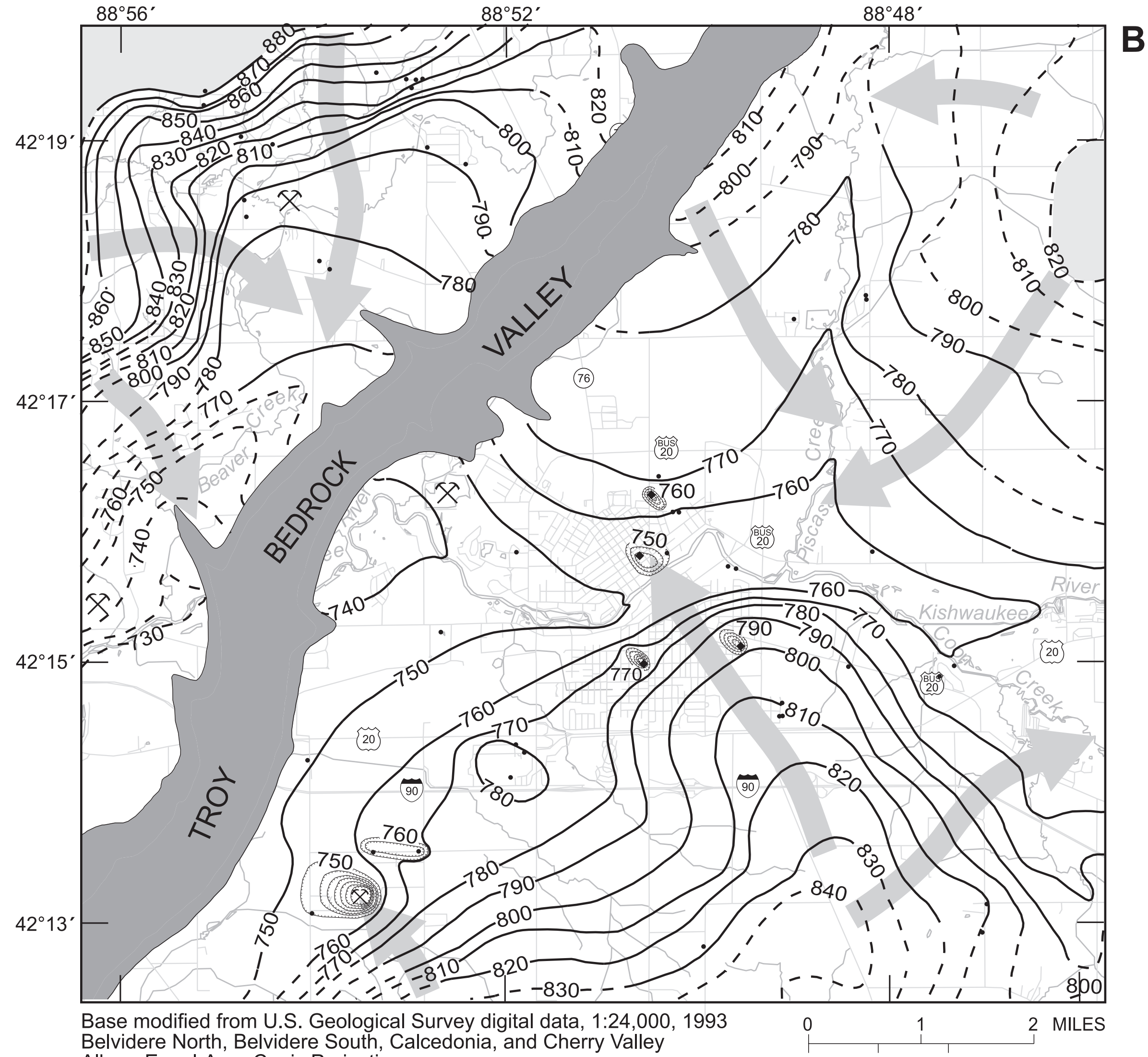
• MONITORING OR WATER-SUPPLY WELL

▽ TEMPORARY WELL

△ SITE OF SURFACE-WATER MEASUREMENT

⚒ QUARRY

Figure 14. Potentiometric levels and horizontal-flow directions in the (A) glacial drift and (B) Galena-Platteville aquifers underlying Belvidere, Illinois, July 1993.



Base modified from U.S. Geological Survey digital data, 1:24,000, 1993
Belvidere North, Belvidere South, Calcedonia, and Cherry Valley
Albers Equal-Area Conic Projection
Standard Parallels 33° and 45°, central meridian -89°

EXPLANATION

APPROXIMATE LOCATION WHERE THE GALENA-PLATTEVILLE AQUIFER IS ABSENT IN THE TROY BEDROCK VALLEY

NOT CONTOURED BECAUSE OF LIMITED WATER-LEVEL-CONTROL DATA

GENERALIZED DIRECTION OF GROUND-WATER FLOW

—750— — POTENTIOMETRIC CONTOUR – Shows altitude at which water would have stood in tightly cased wells. Dashed where inferred. Contour interval is 10 feet. Datum is sea level

MONITORING OR WATER-SUPPLY WELL

BELVIDERE MUNCIPAL WATER-SUPPLY WELL – Open to the Galena-Platteville aquifer and deeper bedrock aquifers

QUARRY

Figure 14. Potentiometric levels and horizontal-flow directions in the (A) glacial drift and (B) Galena-Platteville aquifers underlying Belvidere, Illinois, July 1993–Continued.

The Glenwood confining unit is recognized throughout north-central to northwestern Illinois (Kay and others, 1989, 1994, 1997). The extent to which the unit confines the underlying St. Peter aquifer may vary locally. At a Superfund site about 15 mi south of Rockford, low vertical hydraulic gradients recorded across the unit indicate that there may be downward leakage (Harding-Lawson Associates, 1990). Regionally, the Harmony Hill Shale Member at the top of the Glenwood confining unit is the principal confining bed within the unit (Kay and others, 1989, 1994, 1997). The shale beds that compose the member typically are 1–5 ft thick, but may reach 27 ft. This member likely provides limited confining capacity in the vicinity of Belvidere, where core data indicate that the member only is about 2 ft thick and is argillaceous sandstone (Mills and others, 1998; 1999b). In the vicinity of Belvidere, the Daysville Dolomite Member, about 25 ft thick, likely represents most of the confining capacity of the unit.

The Potosi-Franconia confining unit is composed primarily of dolomite with some shale in the lower 60–100 ft of the 100–220-ft thick unit. The unit provides small to moderate quantities of water to deep wells, but in a relative sense, substantially restricts flow between the overlying St. Peter aquifer and the underlying Ironton-Galesville aquifer (Woller and Sanderson, 1974).

The Eau Claire confining unit is composed primarily of shale. The 115–380-ft thick unit separates the Ironton-Galesville aquifer and the approximately 1,600-ft thick Elmhurst-Mt. Simon aquifer (fig. 2A).

Although not specifically identified in drillers' logs, the lower and upper parts of the Elmhurst-Mt. Simon aquifer are assumed to be separated by a shale-dominant confining unit. As identified in the vicinity of Chicago (Nicholas and others, 1987), the 400-ft thick unit separates the saline water-bearing lower part of the aquifer from the freshwater upper part. Wells in the vicinity of Belvidere are limited to a depth of 1,800 ft and seem to be too shallow to intersect the confining unit. On the basis of the assumption that the confining unit is present, the unit is considered the base of the Cambrian-Ordovician aquifer.

Hydraulic Properties

Horizontal hydraulic conductivities of the materials that compose the glacial drift, Galena-Platteville, and St. Peter aquifers have been estimated from almost 200 aquifer tests at 11 sites within the study area. The sites primarily include the Parson's Casket Hardware site (Mills and others, 1998, 1999a), National Sewing Machine facility (Mills and others, 1999a), MIG/DeWane Landfill site (Clayton Environmental Consultants, Inc., 1996), Chrysler Motors Assembly plant (GZA GeoEnvironmental, Inc., 1993), Belvidere Landfill No. 1 site (Roy F. Weston, Inc., 1988), and three vertically nested well sites (AGTG305, PCHG128, PCHG436) (Mills and others, 1998) (figs. 1A, 1B). All of the sites are within about 1 mi of Belvidere. Hydraulic-property data for the Glenwood confining unit and the Ironton-Galesville and Elmhurst-Mt. Simon aquifers are not available. With the exception of one multiple-well aquifer test of the Galena-Platteville aquifer at the Parson's Casket Hardware site (Mills, 1993c) and two single-well drawdown tests of the glacial drift aquifer (K.J. Hlinka, Illinois State Water Survey, written commun., 1995), all tests in the study area are single-well slug tests. Many of the slug tests were done in packed intervals of boreholes to obtain vertical profiles of K_h (fig. 10) (Mills and others, 1998; Kay, 2001).

Statistical results of the aquifer tests are presented in table 7. The geometric mean is considered to provide the best indicator of K_h. For the Galena-Platteville aquifer, this value of 0.59 ft/d agrees well with the K_h of 0.82 ft/d estimated from the multiple-well aquifer test (Mills, 1993c). Data from the Ironton-Galesville and Elmhurst-Mt. Simon aquifers are reported from discrete-interval drawdown tests in a single well in Rockford (Visocky and others, 1985) and near Chicago (Nicholas and others, 1987). The estimates are considered reasonable for the study area, because the distance between the location of the tests (less than 50 mi) and the study area is small relative to the large distribution of the aquifers across the northern Midwest (hundreds of miles) (Young, 1992). The K_h of the Glenwood confining unit is considered to be equal to or less than the lowest K_h estimated for the Galena-Platteville aquifer (0.005 ft/d). Natural-gamma logs indicate a substantially larger percentage of clay within the Glenwood confining unit than within the Galena-Platteville aquifer (fig. 10); thus, a substantially lower K_h would be expected for the Glenwood confining unit. On the basis of these estimates of K_h, it is apparent that the glacial drift aquifer and the St. Peter, Ironton-Galesville, and Mt. Simon aquifers have a substantially greater capacity to transmit water than does the Galena-Platteville aquifer. The Glenwood confining unit and parts of the lower Galena-Platteville aquifer (fig. 10)

Table 7. Horizontal hydraulic conductivity of the aquifers and hydrogeologic subunits underlying Belvidere, Illinois

[ft/d, feet per day; --, data not available]

Aquifer or hydrogeologic subunit	Arithmetic mean (ft/d)	Geometric mean (ft/d)	Median (ft/d)	Standard deviation (ft/d)	Range (ft/d)	Number of measure-ments
Glacial drift aquifer	54.6	6.5	2.5	98.6	0.13–280	35
Galena-Platteville aquifer	29.6	.59	.47	204	.005–2,467	161
Weathered surficial unit	45.5	5.0	4.7	110	.15–471	21
Upper confining unit	.19	.08	.07	.30	.01–1.3	23
Zone above 260-foot parting[1]	36.9	.51	.44	264	.01–2,467	92
260-foot parting	43.6	5.8	3.0	64.9	.13–175	9
Zone below 260-foot parting	1.1	.41	.79	2.1	.005–9	16
St. Peter aquifer	11.1	9.1	11.1	9.1	4.7–17.5	2
Ironton-Galesville aquifer[2]	11.8	11.7	--	2.6	10.0–13.6	2
Elmhurst-Mt. Simon aquifer[2]	2.6	2.4	--	1.6	1.5–3.8	2

[1] Reference depth of the bedding-plane parting that generally is at about 525 feet above sea level.

[2] Values are derived from estimates of transmissivity by Visocky and others (1985), and Nicholas and others (1987). Estimates are from discrete-interval drawdown tests in a municipal well in Rockford, Illinois, and test hole near Chicago, Illinois, respectively.

seem to restrict water movement between the Galena-Platteville aquifer and St. Peter aquifer.

Data indicate that the K_h of the glacial drift aquifer varies substantially across the study area, with depth and lateral position. This variability is related to the complex glacial and alluvial depositional environment. For the bedrock aquifers, bulk K_h would be expected to vary little at the scale of the study area. However, data are insufficient to verify this assumption. On the basis of vertical variations in K_h, the Galena-Platteville aquifer does seem to be partitioned vertically into hydrogeologic subunits and simulation results indicate that the K_h may vary laterally within the Galena-Platteville aquifer (see “Model Calibration”). At the Parson’s Casket Hardware site (fig. 1), five hydrogeologic subunits are recognized: a weathered surficial unit (about 5 ft thick), an upper confining unit (about 40 ft thick), an intermediate unit between the upper confining unit and the 260-ft bedding-plane parting (about 180 ft thick), the 260-ft bedding-plane parting (about 1 ft thick), and an intermediate unit below the 260-ft bedding-plane parting (about 70 ft thick). Elsewhere, the subunits may differ. An upper confining unit also was identified in the area of an automobile assembly plant on the southwest side of Belvidere (fig. 1) (GZA GeoEnvironmental, Inc., 1993); however, data inspection indicate that the confining unit referred to in the site report may be the clay-dominant interval associated with the 125-ft bedding-plane parting. A recent study within about 0.25 mi of the Parson’s Casket Hardware site indicates that the upper confining unit may not be present (Kay, 2001). In four of five boreholes, ground-water flow was measured within the porous matrix of this part of the aquifer.

In addition to the five hydrogeologic subunits described above, the 125-ft bedding-plane parting locally may be considered a hydrogeologic subunit. The presence of the parting as a subunit may be more variable than the 260-ft parting, but where present the 125-ft parting may have a greater effect on flow. A hydraulic conductivity of 2,500 ft/d has been estimated at one test location near the Parson’s Casket Hardware site (Mills and others, 1998) and substantial seepage associated with the parting at the quarry southwest of Belvidere (D.H. Fischer, Quality Aggregates of Illinois, Inc., oral commun., 1999).

The investigations by Mills (1993b, c, d), Mills and others (1998), Kay and others (2000), and Kay (2001) indicate that the Galena-Platteville aquifer in the vicinity of Belvidere is a dual-porosity aquifer. Water flows through the conductive (vuggy) intervals of the matrix and through discrete fractures and bedding-plane partings (figs. 10, 11, 15). The multiple-well aquifer test completed during the investigation (Mills, 1993c) supports, but because of the insufficient duration of the test for proper analysis, does not confirm dual porosity.

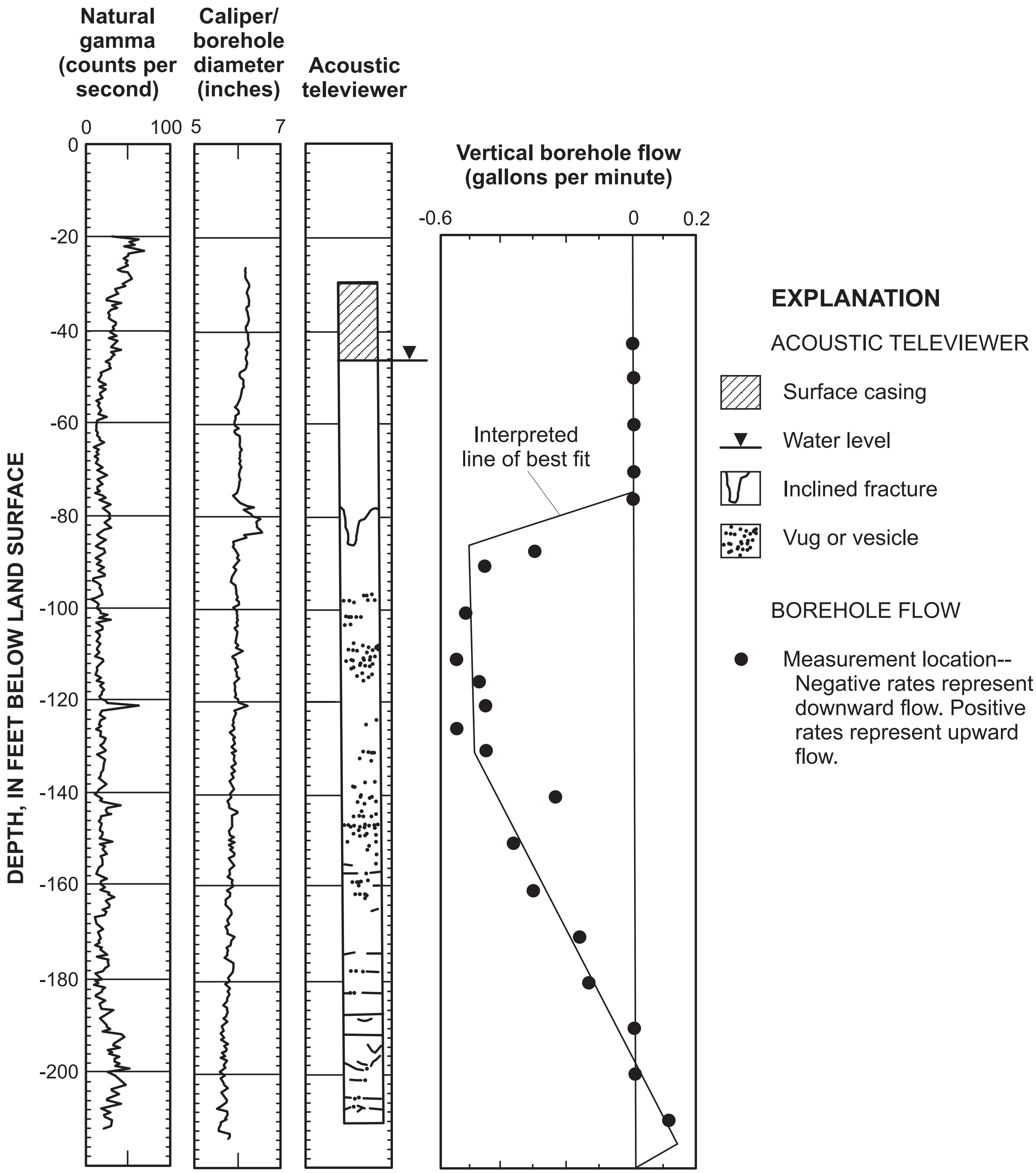


Figure 15. Ground-water flow in boreholes, as affected by fractures and matrix porosity, Belvidere, Illinois.

However, the aquifer-test results clearly indicate that the aquifer is anisotropic and heterogeneous. Dual porosity is indicated best by the geophysical data, including borehole flow measurements.

Geophysical and hydraulic data collected from the aquifer at Superfund sites in Rockford and Byron, Illinois (Kay and others, 1989, 1994, 1997) indicate that characteristics of dual porosity are present elsewhere in north-central Illinois. Much of the heterogeneity of the Galena-Platteville aquifer results from the subtle variations in the composition of the dolomite formations that compose the aquifer. The effects of heterogeneity in hydraulic properties, particularly fracture porosity, on ground-water flow and contaminant distribution are scale dependent, and are most evident at local scales of investigation.

Aquifer tests indicate that specific hydraulic properties may be associated with individual rock-stratigraphic units that compose the Galena-Platteville aquifer (fig. 16). As such, identification of the units that may underlie a study site could be useful in initial conceptualization of the local potential for water and contaminant movement within the Galena-Platteville aquifer. Aquifer-test results indicate that the highest mean (geometric) and greatest range of K_h are associated with the Dubuque/Wise Lake Formations of the Galena Group and the Grand Detour Formation of the Platteville Group. Hydraulic conductivities also are reported to be highest in the Grand Detour Formation at the Superfund site in Byron, Illinois, located about 20 mi southwest of Belvidere (Kay and others 1989, 1997).

On the basis of the estimated K_h and range of thicknesses (b) of the aquifers and hydrogeologic subunits in the study area, their transmissivities can be approximated ($K_h \times b$) (table 8). The transmissivities are highly dependent on whether they represent areas within or outside the Troy Bedrock Valley (thus, affecting unit thicknesses). Additionally, most estimates of K_h are of hydrogeologic subunits that were identified in a relatively small part of the study area outside the valley and that may not persist throughout the study area. As such, only approximations of transmissivity are provided here. The approximations are intended to show the relative differences in transmissivity among aquifers and hydrogeologic subunits. Transmissivity also can be estimated from specific-discharge data (that generally are available from drawdown tests conducted on newly completed water-supply wells). However, these estimates were determined to be only marginally better than those provided here and, therefore, provide no substantial benefit to the effort of simulating ground-water flow.

Recharge and Ground-Water Withdrawals

Ground-water recharge in the vicinity of Belvidere is estimated using a method based on streamflow-hydrograph separation (Rutledge, 1993). Ground-water recharge is considered to be water made available to the saturated zone at the water table and water made available to hydrogeologic units below the water table. The following is assumed with the hydrograph-separation method: (1) the hydraulic properties of the contributing hydrogeologic units (recession index) can be estimated from streamflow records; (2) periods of exclusive ground-water discharge can be identified reliably; and (3) streamflow peaks approximate the magnitude and timing of recharge events. To provide an initial estimation of recharge, these assumptions are considered to be met or approximated for the vicinity of Belvidere.

For the estimate of ground-water recharge, streamflow records (fig. 13) from the streamflow-gaging station Kishwaukee River at Belvidere (fig. 1) were used. The gaged drainage area of 538 mi^2 includes about half (40 mi^2) of the study area and consists of similar coarse- and fine-grained unconsolidated surficial deposits. Unlike the study area, most of the uppermost bedrock underlying the Kishwaukee River Basin (at least 75 percent of the area) consists of shale (Maquoketa Group). The extensive shale is expected to limit recharge to deeper dolomite units and increase discharge to area streams through unconsolidated deposits. Thus, shallow recharge in the study area, as derived by the hydrograph-separation method, may be overestimated. For the 1993 water year, 17.8 in. of recharge were estimated. For water years 1980–93, 10.3 in/yr of recharge were estimated. The estimate for water year 1993 is indicative of the substantial amount of precipitation during that period.

Mills (1993a) estimated 3.0 in/yr of recharge to the unconsolidated deposits at a site about 80 mi southwest of Belvidere. Cravens and others (1990) estimated soil-moisture surplus (approximating ground-water recharge) that ranged from 9.7 in/yr in silt/clay loam to 19.3 in/yr in fine sand for agricultural areas of Kankakee and Iroquois Counties (south of Chicago). Beaty (1987) estimated 3.7–10.6 in/yr of recharge to glacial drift aquifers in northern Indiana.

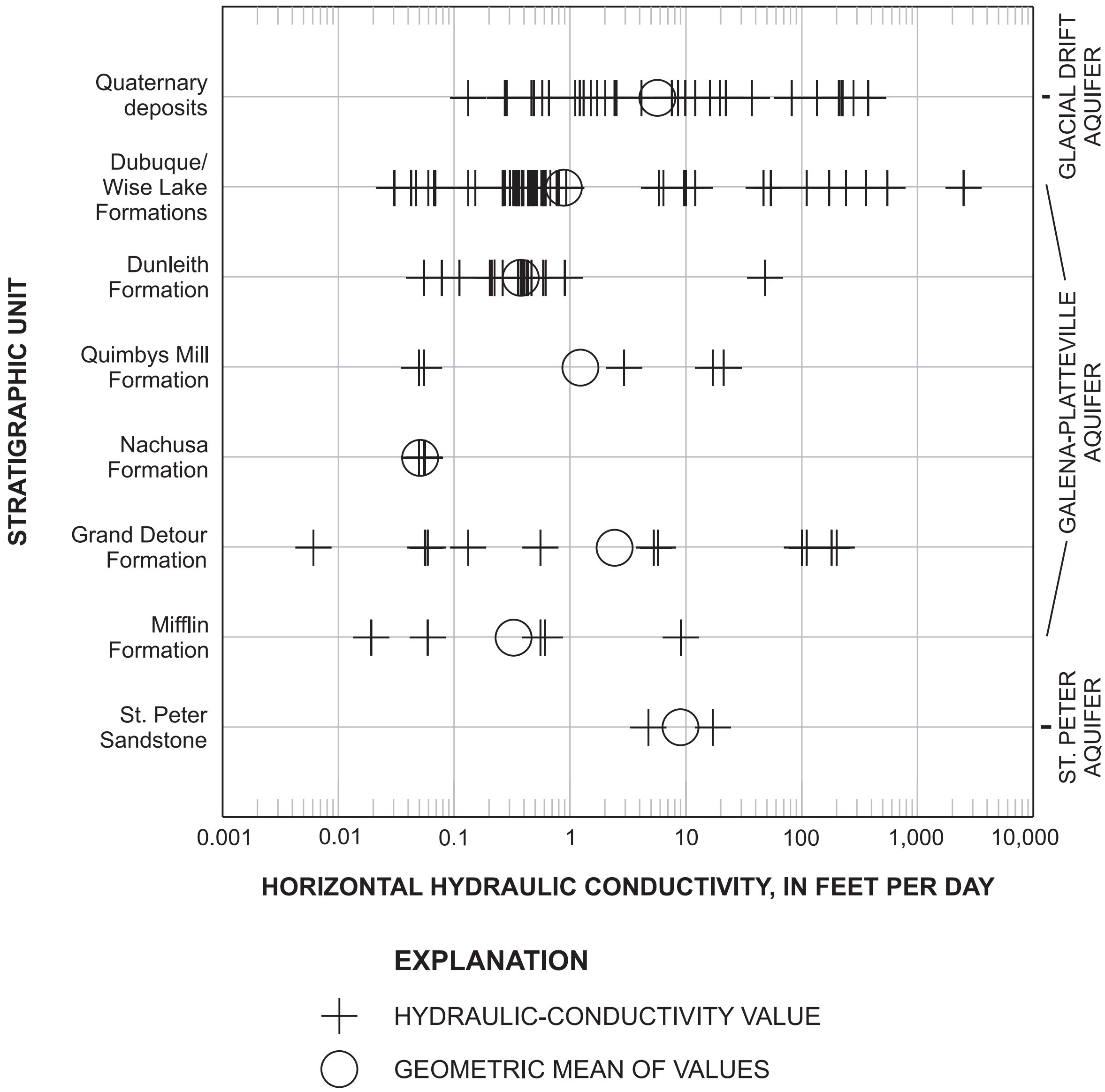


Figure 16. Distribution of horizontal hydraulic conductivity within the rock-stratigraphic units that compose the glacial drift, Galena-Platteville, and St. Peter aquifers underlying Belvidere, Illinois (modified from Mills and others, 1998, fig. 16).

Table 8. Approximate transmissivity of the aquifers and hydrogeologic subunits underlying Belvidere, Illinois

[ft, feet; ft^2/d, feet squared per day; <, less than]

Aquifer or hydrogeologic subunit	Approximate mean transmissivity[1] (ft^2/d)	Approximate minimum transmissivity (ft^2/d)	Approximate maximum transmissivity (ft^2/d)
Glacial drift aquifer	[2]125–1,500	5	[3]15,000–50,000
Galena-Platteville aquifer	[4]200	<1	1,300
Weathered surficial unit	15	<1	700
Upper confining unit	<5	<1	50
Zone above 260-foot parting[5]	85	<1	1,300
260-foot parting	<5	<1	150
Zone below 260-foot parting	30	<1	650
St. Peter aquifer	2,000	1,050	4,000
Ironton-Galesville aquifer	[6]1,750	[7]1,100	[7]2,000
Elmhurst-Mt. Simon aquifer	[6]1,900	[7]600	[7]1,500

[1] Transmissivities are derived using the geometric mean of horizontal hydraulic conductivity, as estimated from individual slug tests, unless noted. Mean and maximum transmissivities are derived using the approximate thicknesses of the aquifers and hydrogeologic subunits in the vicinity of the Parson's Casket Hardware Superfund site (fig. 1), unless noted. At this location, the Galena-Platteville aquifer is near its maximum thickness and all identified hydrogeologic subunits of the aquifer are present. Minimum transmissivities represent locations where the units are thin to not present (by erosion or hydraulic property).

[2] Minimum value represents the vicinity of the Parson's Casket Hardware Superfund site, where the aquifer is about 20 feet thick; maximum value represents the axis of the Troy Bedrock Valley, where the aquifer is about 260 feet thick.

[3] Minimum value represents the estimate from an aquifer test in the Troy Bedrock Valley (K.J. Hlinka, Illinois State Water Survey, written commun., 1995); maximum value represents the axis of the Troy Bedrock Valley, where the aquifer is about 260 feet thick.

[4] Value is from a multiple-well aquifer test conducted at the Parson's Casket Hardware Superfund site (Mills, 1993c).

[5] Bedding-plane parting at 525 feet above sea level.

[6] Transmissivity is derived using the geometric mean of horizontal hydraulic conductivity, estimated from discrete-interval drawdown tests in a municipal well in Rockford, Illinois (Visocky and others, 1985) and a test hole near Chicago, Illinois (Nicholas and others, 1987), respectively. The derived transmissivity is based on the estimated thickness of the aquifer in the vicinity of the Parson's Casket Hardware Superfund site.

[7] Transmissivity is estimated from discrete-interval drawdown tests in a municipal well in Rockford, Illinois (Visocky and others, 1985) and a test hole near Chicago, Illinois (Nicholas and others, 1987), respectively. As such the maximum transmissivity of the Elmhurst-Mt. Simon aquifer is less than the mean transmissivity derived for the aquifer underlying the study area.

Southeast of the study area (southwest to southeast of Chicago), the uppermost bedrock deposits are dolomites of Silurian age similar in hydraulic property to that of the Ordovician-age dolomites of the Galena Group (Csallany and Walton, 1963). Estimates of recharge to the Silurian dolomite aquifer range from about 1.8 to 4.7 in/yr, where the aquifer is overlain predominantly by till; rates of 5.1 to 6.0 in/yr are estimated for areas overlain primarily by coarse-grained deposits (Cravens and others, 1990). Walton (1962, 1964), Hoover and Schicht (1967), and Visocky and others (1985) estimated rates from 0.43 to 0.88 in/yr to the Cambrian-Ordovician aquifer in areas within 40 mi of Belvidere. The areas are characterized by the presence of the Galena or Platteville Groups as the uppermost bedrock formations. In parts of the area, these units have been substantially thinned or entirely eroded, thus, enhancing recharge through the locally thick, coarse-grained glacial deposits to the St. Peter and deeper aquifers. Computer simulation by Burch (1991) has shown that the deeply entrenched bedrock valleys in northern Illinois are recharge areas for the underlying St. Peter and deeper aquifers.

Ground water is the sole source for public- and private-water supply in the study area. Ground-water withdrawals reportedly exceed 1,000,000 gal/yr at only 11 industrial or public-supply wells and one quarry (figs. 1, 4; table 9). The largest withdrawals are by the eight Belvidere municipal wells, that typically exceed 0.3 Mgal/d per well (J.A. Grimes, Belvidere Water and Sewer Department, written commun., 1999). About 80 percent of wells with withdrawals that exceed 1,000,000 gal/yr are located in Belvidere.

Table 9. Reported annual (August 1992–July 1993) and average annual (1989–93) ground-water withdrawals in the vicinity of Belvidere, Illinois, and simulated withdrawals distributed by hydrogeologic unit (July 1993)

[Withdrawals for Belvidere municipal wells (BMW2–BMW9) and wells pumping more than 1,000,000 gallons per year; Mgal/d, million gallons per day; --, no data or not simulated]

Hydrogeologic unit: GP, Galena-Platteville aquifer; GF, Glenwood confining unit; CO, sandstone aquifers of the Cambrian-Ordovician aquifer system; ALL, all bedrock hydrogeologic units; GD, glacial drift aquifer

Well designation	Hydrogeologic unit	Annual withdrawal (Mgal/d)	Average annual withdrawal (Mgal/d)	Simulated withdrawal (Mgal/d)
[1]BMW2	GP	--	--	--
do.	GF	--	--	--
do.	CO	--	--	--
do.	ALL	0.000	0.045	--
[2]BMW3	GP	--	--	0.0011
do.	GF	--	--	0
do.	CO	--	--	.0029
do.	ALL	.004	.034	--
BMW4	GP	--	--	.0022
do.	GF	--	--	.000003
do.	CO	--	--	.32
do.	ALL	.32	.35	--
BMW5	GP	--	--	.0048
do.	GF	--	--	.000009
do.	CO	--	--	.32
do.	ALL	.32	.42	--
BMW6	GP	--	--	.0029
do.	GF	--	--	.000005
do.	CO	--	--	.43
do.	ALL	.43	.28	--
BMW7	GP	--	--	.0059
do.	GF	--	--	.00001
do.	CO	--	--	.54
do.	ALL	.55	.59	--
BMW8	CO	.57	.70	.57
BMW9	GD	.57	.77	.57
[3]00294	GP	--	--	.0012
do.	GF	--	--	.000003
do.	CO	--	--	.17
do.	ALL	.17	.17	--
[3]00295	GP	--	--	.0011
do.	GF	--	--	.000002
do.	CO	--	--	.015
do.	ALL	.016	.016	--
[3]BL2RW1	GP	--	--	.00011
do.	GF	--	--	.000004
do.	CO	--	--	.012
do.	ALL	.012	.012	--
[4]Quarry	GP	.022	.022	.022
TOTAL	--	2.98	3.41	2.98

[1] Withdrawal data for the municipal wells were provided by the city of Belvidere (J.A. Grimes, Belvidere Water and Sewer Department, written commun., 1999).

[2] Well BMW2 was not used during 1991–96; well BMW3 was not used during 1994–96.

[3] Withdrawal data are from the Illinois Water Inventory Program (K.J. Hlinka, Illinois State Water Survey, written commun., 1995). Data for well 00294 are from 1994; data for well 00295 are from 1986; data for well BL2RW1 are from 1994.

[4] Withdrawal data are estimated from information provided by quarry personnel (D.H. Fischer, Rockford Sand and Gravel, Inc., oral commun., 1995).

Daily withdrawals from individual municipal wells, calculated on the basis of annual withdrawals during August 1992–July 1993, ranged from 0 to 0.57 Mgal/d (total of 2.77 Mgal/d for all wells). Daily withdrawals from individual municipal wells, calculated on the basis of annual withdrawals during 1989–93, ranged from 0.34 to 0.77 Mgal/d (total of 3.21 Mgal/d for all wells). During 1989–93, total withdrawals per day from the municipal wells declined from 3.59 Mgal/d to 2.76 Mgal/d. During 1994–98, total withdrawals per day averaged about 3.1 Mgal/d. Withdrawals by a municipal-well system vary temporally, as necessitated by seasonal demand and equipment-maintenance requirements. The recent (1989–98) trend in decreasing withdrawals is counter to the trend of increasing population in Belvidere.

More than 550 private water-supply wells also are located in the study area (Brown and Mills, 1995), about 4 percent of which are within Belvidere. Approximately 50 percent of these wells are clustered in about 10 subdivisions distributed throughout the study area (Brown and Mills, 1995, pl. 1). Total withdrawal from these wells is unknown, but is assumed to be small relative to withdrawal from the identified high-capacity wells. Withdrawal data for Boone County from 1970 indicated that private-well withdrawals accounted for about 20 percent of total withdrawals (Sasman and others, 1974). Most of the water withdrawn from these rural wells is returned to the ground-water system through septic fields and lawn watering; withdrawal rates are low and the wells are used intermittently. About 30 percent of the wells are open to the glacial drift aquifer, 65 percent to the Galena-Platteville aquifer, and 5 percent to the St. Peter aquifer (Brown and Mills, 1995).

Ground-Water Levels and Response to Withdrawals

Ground-water levels were measured in monitoring or water-supply wells open to the various aquifers underlying the study area (Mills and others, 1999). Water levels are assumed to represent potentiometric levels in all aquifers. The St. Peter and deeper aquifers are confined; the glacial drift and Galena-Platteville aquifers are unconfined or confined depending on local hydrogeologic conditions.

During July 1993, depth to water in wells open to the glacial drift aquifer ranged from about 2 to 50 ft below land surface. Shallowest depths generally were along stream banks. Deepest depths to water generally were in wells open to the sand-and-gravel deposits in the Troy Bedrock Valley. Most of the wells where depths to water were greater than 30 ft are in the upland areas north of the valley and where the wells are completed at depths greater than 100 ft.

Potentiometric levels in the glacial drift aquifer range from about 900 ft above sea level in the southern and northwestern uplands to about 740 ft above sea level along the Kishwaukee River in the western part of the study area (fig. 14A). The potentiometric surface of the aquifer generally mimics the land-surface configuration; thus, the surface is considered a regional approximation of the water table (fig. 14A).

The glacial-drift deposits are unsaturated in two general areas (fig. 14A). Locally thin glacial deposits that trend northeast to southwest overlie the dolomite bedrock in the northwestern uplands. Unsaturated glacial deposits are observed in the immediate vicinity of two dolomite quarries in this area (fig. 1A). Also trending northeast to southwest, unsaturated glacial drift overlies local highs in the bedrock in the southwestern part of the study area. Dewatering at the dolomite quarry in this area may account partly for the unsaturated drift.

During July 1993, depth to water in wells open to the Galena-Platteville aquifer ranged from about 2 to 91 ft below land surface. Shallowest depths generally were in wells near the Kishwaukee River and its principal tributaries. Deepest depths to water generally were in the upland areas.

Potentiometric levels in the Galena-Platteville aquifer range from about 900 ft above sea level in the southern and northwestern uplands to about 740 ft above sea level along the Kishwaukee River (fig. 14B). The potentiometric levels are similar to the levels in the overlying glacial drift aquifer; although to a lesser extent than the glacial drift aquifer, the potentiometric surface generally mimics the land-surface configuration.

Bedrock highs are present in the southwestern and northwestern parts of the study area. In these areas, Galena Group dolomites are near or at land surface, and locally, the deposits are unsaturated. Unsaturated conditions in the southwestern part of the study area can be attributed, in part, to dewatering at the dolomite quarry (fig. 1A). The approximate areas where the Galena Group dolomites are unsaturated are shown in figure 14A.

Cones of depression developed as a result of withdrawals by the Belvidere municipal wells are shown in figure 14B. The areal extent and orientation of the cones should be considered approximate, because of limited water-level data. Exemplifying the anisotropy of the aquifer, the axes of the cones are interpreted to coincide with the approximate principle orientation (N. 60° W.) of inclined fractures in the aquifer. In actuality, the principal orientation varies over a range of about 50° (Foote, 1982; Mills and others, 1998).

During July 1993, depth to water in wells open to the St. Peter aquifer ranged from about 52 to 75 ft below land surface. Potentiometric levels ranged from about 726 to 779 ft above sea level (fig. 17). The few available data indicate that potentiometric levels are about 25–50 ft higher in the northern part than in the central part of the study area. Seven municipal wells in the central part of the study area withdraw water from either the Ordovician or Cambrian-Ordovician aquifer, that include the St. Peter aquifer (fig. 1; table 1).

The scarcity of available wells precludes evaluation of water levels in the St. Peter aquifer, within and outside the Troy Bedrock Valley. Within the valley, the St. Peter aquifer is overlain by the Glenwood confining unit, the glacial drift aquifer (or fine-grained glacial drift), and (or) the substantially thinned Galena-Platteville aquifer. Outside the valley, the St. Peter aquifer is overlain by the Glenwood confining unit and the Galena-Platteville aquifer (figs. 5–9).

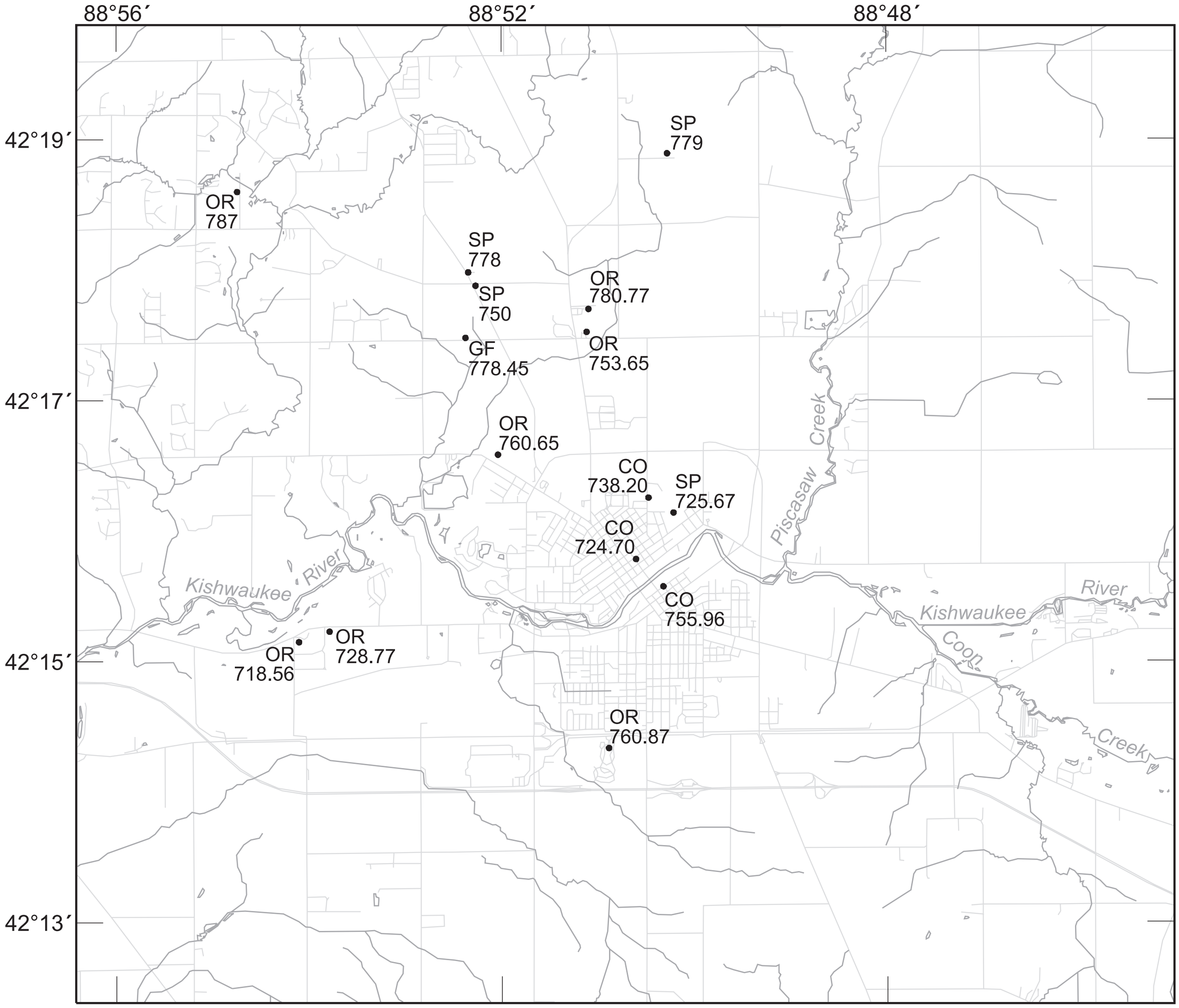
During July 1993, depth to water in wells open to the Cambrian-Ordovician aquifer ranged from about 3 to 52 ft below land surface. Potentiometric levels ranged from about 725 to 756 ft above sea level (fig. 17). In 1995, potentiometric levels that ranged from 599 to 753 ft above sea level were measured in the Belvidere municipal wells (Visocky, 1997). The deepest depth to water and lowest potentiometric level were recorded in well BMW8, open to the lower part of the Cambrian-Ordovician aquifer (St. Peter and deeper aquifers). The shallowest depth to water and highest potentiometric level were recorded in well BMW3, open to the entire thickness of the Cambrian-Ordovician aquifer (Galena-Platteville and deeper aquifers) (fig. 1). The uncharacteristically high potentiometric levels in BMW3 and nearby BMW2 were similar to the potentiometric level in the overlying glacial drift aquifer and the water level in the Kishwaukee River, about 250 ft northwest of the wells. The similarity indicates that the upper part of the Galena-Platteville aquifer is hydraulically connected to the overlying glacial drift aquifer. The wells are cased into the weathered surface of the Galena-Platteville aquifer.

In and near the study area, no wells are open exclusively to the Ironton-Galesville and (or) Elmhurst-Mt. Simon aquifers that, in part, compose the Cambrian-Ordovician aquifer. Thus, in this area, potentiometric levels in these sandstone aquifers and their vertical distribution in the lower part of the Cambrian-Ordovician aquifer are unknown. Data collected in 1980 from a municipal well in Rockford indicated that potentiometric levels are about 4 ft higher in the St. Peter aquifer than the Ironton-Galesville aquifer and about 2 ft higher in the Ironton-Galesville aquifer than the Elmhurst-Mt. Simon aquifer (Visocky and others, 1985). Data collected in 1982 from a test hole north of Chicago indicated that potentiometric levels are about 3.5 ft higher in the St. Peter than the Ironton-Galesville aquifer and about 7 ft higher in the Elmhurst-Mt. Simon than the Ironton-Galesville aquifer (Nicholas and others, 1987).

Ground-water levels are affected by substantial withdrawals in the Rockford and Chicago areas. Withdrawals from the Cambrian-Ordovician aquifer in Belvidere likely result in a vertical distribution of potentiometric levels similar to that observed in the Rockford area.

Ground-water levels fluctuate in response to recharge to the aquifers. In the study area, recharge is primarily by infiltration of precipitation. On the basis of monitoring at the Parson's Casket Hardware site (Mills and others, 1998), ground-water levels in the shallow parts (depths less than about 50 ft) of the glacial drift aquifer and Galena-Platteville aquifer seem to fluctuate seasonally by about 2–5 ft. The highest levels are usually in late fall to early summer and the lowest in early winter, as shown in the hydrographs for wells PCHG115S and PCHG115D (fig. 18A). Seasonal fluctuations in ground-water levels generally are not observed in the deeper parts of the Galena-Platteville aquifer and generally are not expected in the deepest parts of the glacial drift aquifer, particularly where interbedded fine-grained deposits are present.

Withdrawals at high-capacity wells directly affect ground-water levels in nearby monitoring wells and boreholes open to the Galena-Platteville and St. Peter aquifers (Mills, 1993c); fluctuations in water levels have been recorded up to 0.7 mi from the nearest water-supply well. Mills (1993c) monitored water levels in wells open to the top (about 40 ft below land surface) and middle (about 150 ft below land surface) parts of the Galena-Platteville aquifer at the Parson's Casket Hardware site (fig. 1). The timing and magnitude of water-level responses were correlated with withdrawals at Belvidere municipal wells BMW6 (located about 0.25 mi from the monitoring wells) and BMW4 (located about 0.5 mi from the monitoring wells). The water-level responses were greatest in the deep well (about 5 ft of change) and least in the shallow well (about 0.1 ft of change).



Base modified from U.S. Geological Survey digital data, 1:24,000, 1993
Belvidere North, Belvidere South, Calcedonia, and Cherry Valley
Albers Equal-Area Conic Projection
Standard Parallels 33° and 45°, central meridian -89°

0 1 2 MILES

0 1 2 KILOMETERS

EXPLANATION

OR 718.56 — GROUND-WATER WELL -- Hydrostratigraphic-unit designation and altitude at which water would have stood in tightly cased wells, in feet above sea level

HYDROGEOLOGIC-UNIT DESIGNATION

GF Glenwood confining unit

SP St. Peter aquifer

OR Ordovician aquifer system

CO Cambrian-Ordovician aquifer system

Figure 17. Potentiometric levels in the Glenwood confining unit, St. Peter aquifer, Ordovician aquifer system, and Cambrian-Ordovician aquifer system underlying Belvidere, Illinois, July 1993.

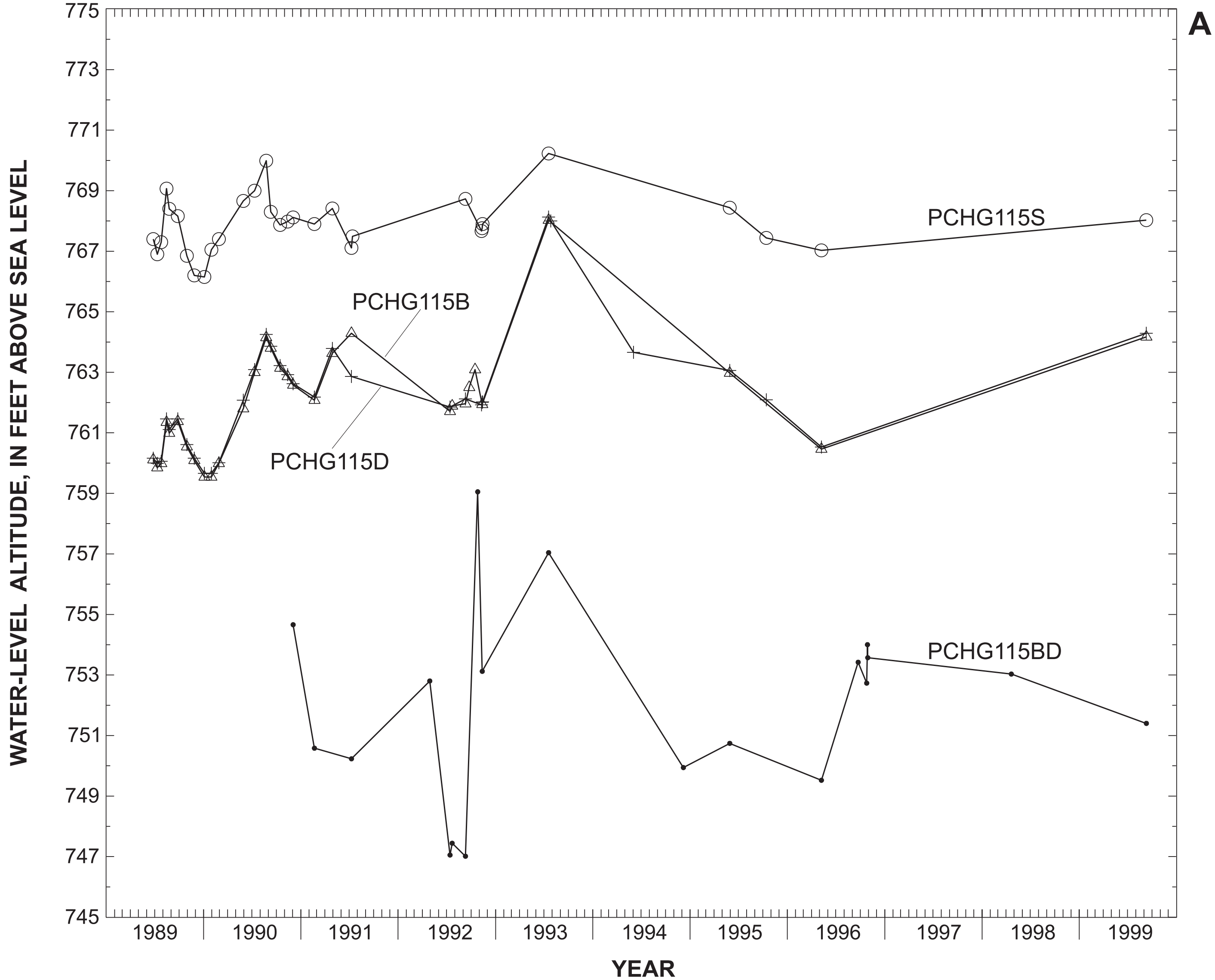


Figure 18. Hydrographs for selected wells open to the glacial drift and bedrock aquifers underlying Belvidere, Illinois: (A) multiple-year records (1989–99) showing response to precipitation and (B) short-term record (November–December 1994) showing response to withdrawals from high-capacity supply wells.

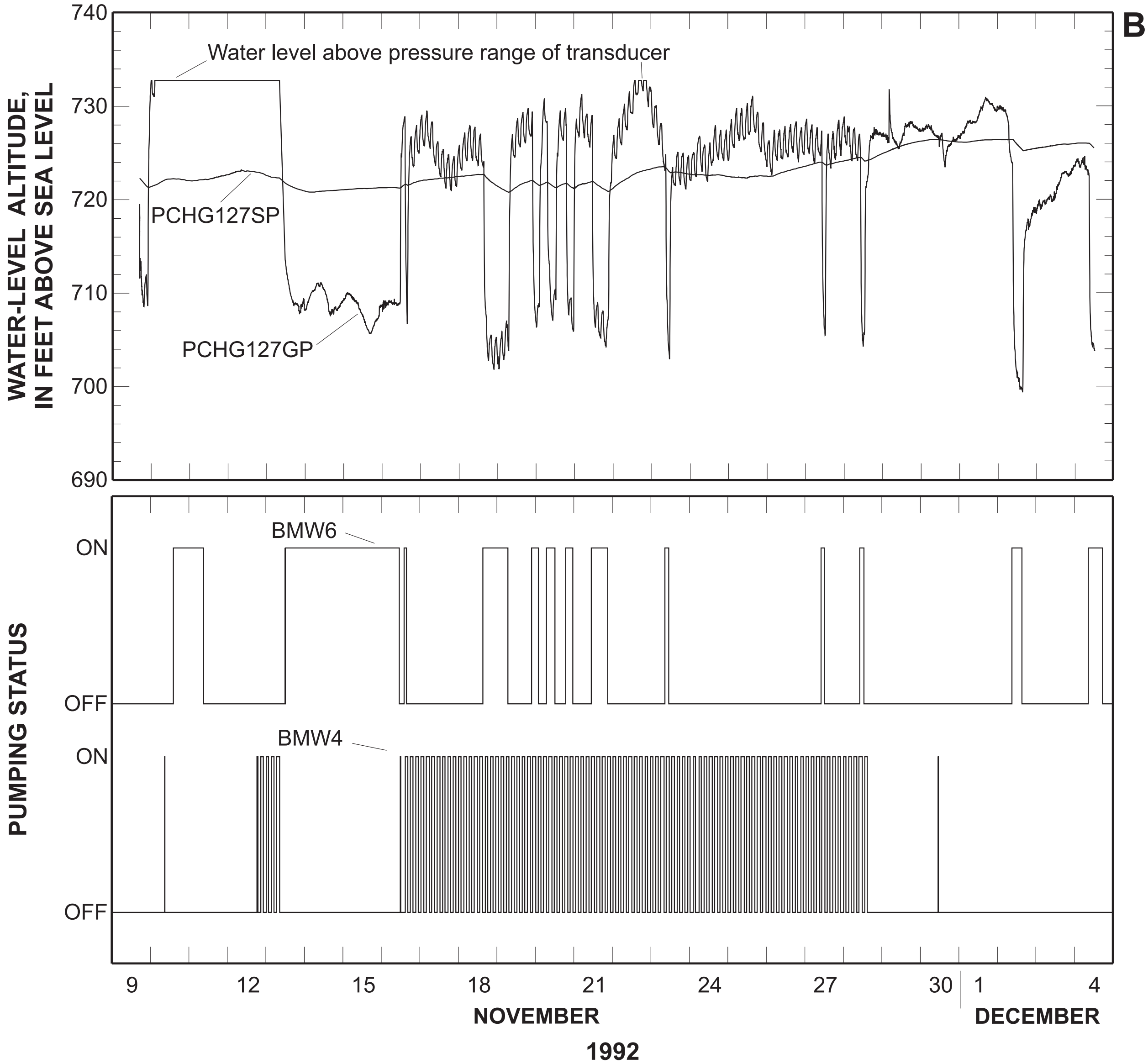


Figure 18. Hydrographs for selected wells open to the glacial drift and bedrock aquifers underlying Belvidere, Illinois: (A) multiple-year records (1989–99) showing response to precipitation and (B) short-term record (November–December 1992) showing response to withdrawals from high-capacity supply wells–Continued.

Water levels in the wells responded more to withdrawals from well BMW6 than BMW4, despite an average withdrawal rate that, for the study period, was about three times greater for well BMW4 than BMW6. The closer proximity of well BMW6 to the monitoring wells likely accounts for the greater water-level response. Well BMW6 also seems to be in more direct hydraulic connection with the monitoring wells at the Parson's Casket Hardware site. Well BMW6 has a shorter surface casing than well BMW4 (110 ft and 152 ft, respectively); thus, the well is open to the locally conductive 125-ft parting (Mills and others, 1998).

During November–December 1992, response of water levels at the Parson’s Casket Hardware site to municipal-well withdrawals again was monitored (Mills and others, 1998). In addition to monitoring the same depths in the Galena-Platteville aquifer as Mills (1993c), water levels were monitored in a well open to an interval between the conductive partings in the lower part of the aquifer (260-ft parting and a parting at about 300 ft below land surface; hereafter referred to as the 300-ft parting) and in a well open to the uppermost part of the St. Peter aquifer (at a depth of about 360 ft). At this time, withdrawal activity was monitored continuously at municipal wells BMW4 and BMW6. In the upper one-half of the aquifer, water-level response to withdrawals was similar to that previously observed (Mills, 1993c). Responses in the lower part of the Galena-Platteville aquifer were much more exaggerated than in the upper parts of the aquifer. Water levels fluctuated as much as 25 ft in an almost instantaneous response to the initiation and cessation of withdrawals (fig. 18B), indicating a direct hydraulic connection between this depth of the aquifer at this location and the high-capacity wells at distances of at least 0.25 mi. Also as previously observed, water levels responded most to withdrawals from municipal well BMW6. Additionally, at a time when the municipal wells were not in use, a slight (about 1 ft) response to withdrawals from another well(s) was indicated. The nearest high-capacity wells in the area open to the deep part of the Galena-Platteville aquifer, and that were operating at the time of the study, were industrial wells located about 0.5 mi from the study site and south of the Kishwaukee River (fig. 1).

Water levels also fluctuated (about 1–2 ft) in the St. Peter aquifer in apparent response to withdrawals from municipal well BMW6. Similar responses to withdrawals from high-capacity wells in other parts of Belvidere have been observed (Mills and others, 1998). Water levels fluctuate in vertically nested wells (AGTG305GPS, AGTG305GPD, and AGTG305SP) open to the Galena-Platteville and St. Peter aquifers in apparent response to withdrawals from the nearest (about 0.7 mi) municipal (BMW5) and industrial (00065) wells (fig. 1B).

Ground-Water Flow

Nearby hydrogeologic boundaries for flow in the glacial drift aquifer are considered to be Piscasaw Creek and Coon Creek, east of Belvidere; Beaver Creek and South Branch (not shown in fig. 1; the stream is outside the study area) west of Belvidere; and the Kishwaukee River. A ground-water divide possibly is present beneath the uplands within about 1 mi of the southern boundary of the study area. North of the study area no ground-water divide has been identified within 10 mi.

Horizontal hydraulic gradients in the glacial drift and Galena-Platteville aquifers generally are greatest in the upland areas in the northwestern and southeastern parts of the study area and least in the lowlands flanking the Kishwaukee River and Piscasaw Creek and overlying the Troy Bedrock Valley (fig. 14). Lateral ground-water flow in the aquifers is from the uplands in the northern and southern parts of the study area toward the Kishwaukee River. Ground water primarily discharges to the Kishwaukee River and its principal tributaries, and possibly to the Troy Bedrock Valley, where the Galena and Platteville Groups have been eroded. The shallowest ground water discharges to small ditches, streams, and ponds. Measured gains in streamflow to the Kishwaukee River and its tributaries, as attributed to discharge from the glacial drift and Galena-Platteville aquifers, are given in table 10. Simulated gain in streamflow is discussed in the section “Model Calibration.”

About 80 percent of the wells in which water levels were measured in the Galena-Platteville aquifer (Mills and others, 1999a) are open to the upper one-half or less of the unit. Thus, discharge outside the study area is possible in the deeper part of the aquifer, where flow is unaffected by withdrawals by municipal and industrial wells in Belvidere. The deep part of the flow system, established primarily below the Glenwood confining unit, is described in detail below. A conceptual model of the ground-water-flow system is shown in figure 19.

Table 10. Measured and simulated gains in streamflow in selected streams in the vicinity of Belvidere, Illinois

[ft^3/s, cubic feet per second; mi^2, square miles; --, streamflow or drainage area not determined]

Stream name[1]	Measured gain in streamflow[2] (ft^3/s)	Simulated gain in streamflow (ft^3/s)
Kishwaukee River, eastern section[3]	30.1–51.2	--
Kishwaukee River, western section[4]	18.6–45.3	--
Piscasaw Creek[5]	9.6–14.9	10.2
Beaver Creek[6]	6.4–9.1	7.0
Coon Creek	.07–1.9	--
Mosquito Creek	.39–.55	--
Kishwaukee River[7]	31.9–68.6	47.8

[1] Streams are shown on figure 1C.
[2] 5-percent measurement error was assumed for each streamflow measurement; thus, allowing estimation of a realistic range of flow rates. Measurements made September 8–10, 1999.
[3] From streamflow-measurement site S09 downstream to S12. Excludes inflow from Coon and Piscasaw Creeks.
[4] From streamflow-measurement site S12 downstream to S02. Excludes inflow from the Belvidere Waste Water Treatment Plant and Beaver Creek.
[5] From northern limit of model area to confluence with the Kishwaukee River.
[6] From northern limit of model area to confluence with the Kishwaukee River. Includes gains from contributing tributaries.
[7] Includes gains in streamflow for all stream sections measured within the study area.

Although the data are inconclusive, shallow ground-water discharge within the study area seems to be greater to the eastern section of the Kishwaukee River than to the western section (table 10; fig. 1C). Generally, less recharge from precipitation and stream discharge would be expected in the eastern part because the unconsolidated deposits in the eastern part of the study area are finer grained than the deposits in the western part. Possibly, in the western part the thick coarse-grained deposits that compose the Troy Bedrock Valley and the unsaturated and weathered-bedrock deposits allow for more recharge to deeper parts of the ground-water-flow system, thus, less ground water discharges to the river.

Immediately east of the study area, a ground-water divide is present in the Cambrian-Ordovician aquifer, principally the St. Peter and deeper sandstone aquifers used regionally for water supply (Visocky, 1997, fig. 8). The divide trends north to south, near the Belvidere/McHenry County line (about 2.5 mi east of the study area). With large reduction in withdrawals from the aquifer in and near Chicago beginning in about 1991, the divide has moved gradually westward toward withdrawal centers in Belvidere and Rockford (Visocky, 1993, 1997). East of the divide, ground-water flow is toward the cone of depression developed near Chicago. West of the divide, beyond the effect of withdrawals in Belvidere, flow is westward toward the cone of depression developed near Rockford (Visocky, 1993, 1997), as well as toward the Rock and Mississippi Rivers (Young, 1992). A ground-water divide may be present between the withdrawal centers in Rockford and Belvidere, however, the substantially greater rates of ground-water withdrawal in Rockford relative to those in Belvidere (about seven times greater (Kirk, 1987; Avery, 1999)) may preclude establishment of a divide. Data are not available presently (2001) to substantiate and map such a divide.

Vertical hydraulic gradient is the difference between water levels in paired wells open to different depths of an aquifer or different aquifers divided by the vertical distance between the screened or open intervals of the wells. Gradient direction identifies the vertical direction of ground-water flow (downward or upward), and, thus, recharge and discharge locations in an aquifer. The magnitude, in part, indicates the potential for vertical water movement. Vertical hydraulic gradients in and between the glacial drift, Galena-Platteville, and St. Peter aquifers have been determined in various parts of the study area, but generally are restricted to the vicinity of Belvidere (table 11).

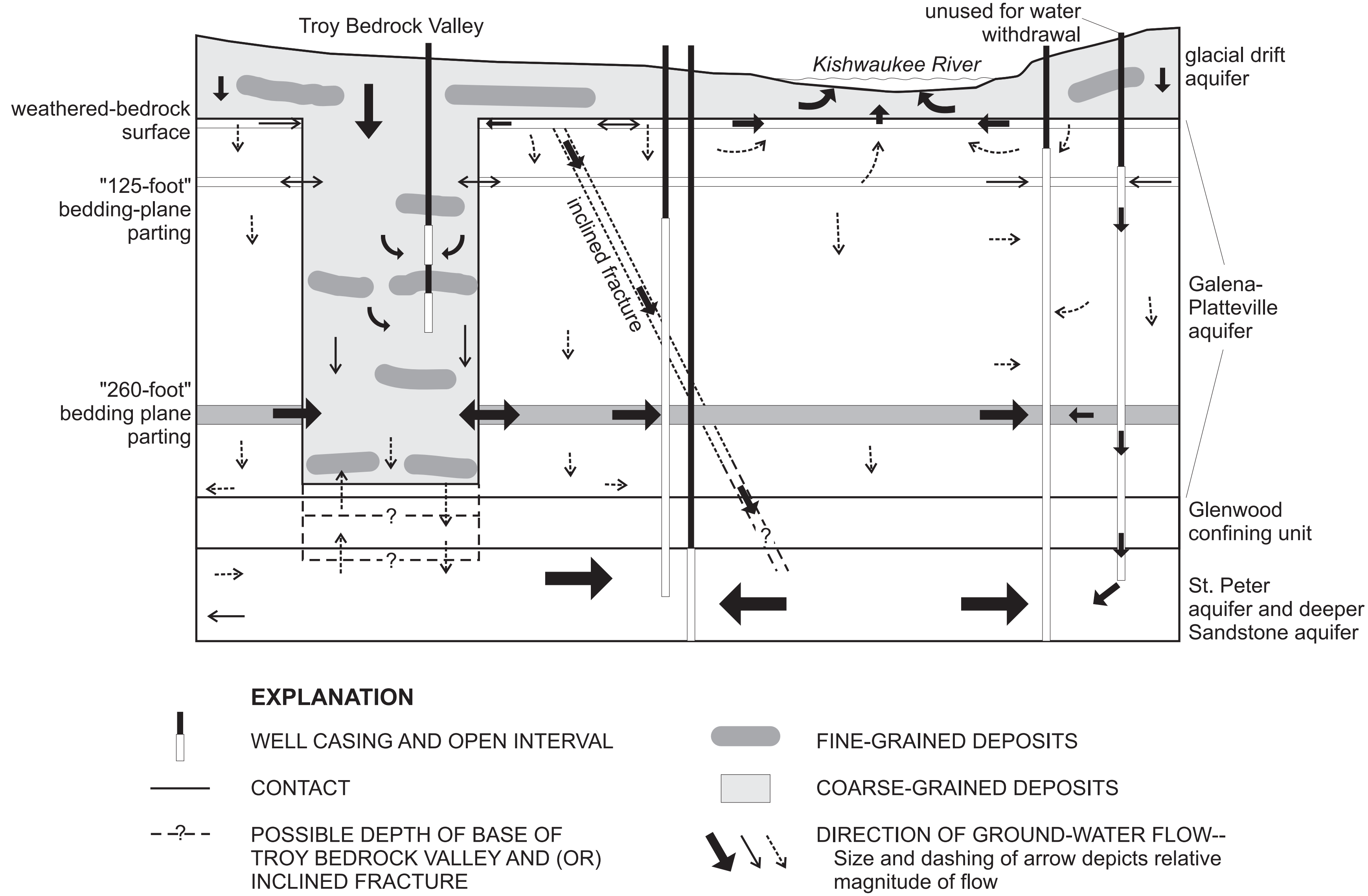


Figure 19. Conceptual movement of water in the glacial drift and bedrock aquifers underlying Belvidere, Illinois.

Table 11. Representative vertical hydraulic gradients in the aquifers underlying Belvidere, Illinois

[>, greater than; mi, mile; ft, feet; <, less than; gradients in foot per foot; values of downward gradients are positive, upward gradients are negative; --, not applicable]

Measurement sites[1]	Gradients away from Kishwaukee River (> than 2 mi)	Gradients near Kishwaukee River (100–3,500 ft)	Gradients adjacent to Kishwaukee River and other streams (< 100 ft)
	Glacial Drift Aquifer		
[2]Belvidere Landfill No. 2	-0.01 – 0.02	--	--
[3]Parson's Casket Hardware	--	-0.85 – 0.66	--
[4]Belvidere Landfill No. 1	--	-.005 – .004	-0.02
[5]MIG/DeWane Landfill	--	--	-.04 – -.03
	Glacial Drift—Galena-Platteville Aquifers[6]		
Parson's Casket Hardware	--	.02 – .09	--
Belvidere Landfill No. 1	--	--	-.01
MIG/DeWane Landfill	--	-.006 – .10	[7]-.09 – -.001
	Galena-Platteville Aquifer		
Parson's Casket Hardware	--	.004 – .37	--
MIG/DeWane Landfill	--	-.05 – .13	--
[8]AGTG305GPS/AGTG305GPD	--	.14	--
	Galena-Platteville—St. Peter Aquifers[9]		
Parson's Casket Hardware	--	-.06 – .13	--
AGTG305GPD/AGTG305SP	--	.13	--

[1] Locations of measurement sites are shown in figures 1A and 1B.
[2] RMT, Inc., 1993.
[3] Mills and others, 1998.
[4] Roy F. Weston, Inc., 1988.
[5] Clayton Environmental Consultants, Inc., 1996.
[6] Represents the uppermost 30 feet of the Galena-Platteville aquifer, including the weathered-bedrock surface.
[7] Flowing artesian well. Upward hydraulic gradient exceeds the measured value.
[8] Mills and others, 1999a.
[9] Represents the uppermost 15 feet of the St. Peter aquifer.

Within the glacial drift aquifer, vertical gradients typically are downward at locations remote from the Kishwaukee River and other streams (thus, are recharge areas); locally, upward gradients can be present where there are confining units within the sand-and-gravel deposits. Gradients are upward immediately adjacent to streams, indicating ground water discharges to the streams.

As within the glacial drift aquifer, gradients between the glacial drift aquifer and the uppermost 30 ft of the Galena-Platteville aquifer, including the weathered surface, typically are downward away from streams. Gradients typically are upward immediately adjacent to streams. At the Mig/DeWane Landfill site (fig. 1), flowing-artesian conditions have been measured periodically at a well adjacent to an intermittent stream (Clayton Environmental Consultants, Inc., 1996).

In and near Belvidere, gradients within the Galena-Platteville aquifer typically are downward away from streams. No data are available to determine gradients, and, thus, flow directions, adjacent to streams.

Gradients have been determined using 8 pairs of vertically nested wells and 18 boreholes (Mills, 1993b, c, d; Clayton Environmental Consultants, Inc., 1996; Mills and others, 1998; Kay and others, 2000; Kay, 2001). Using straddle packers in the boreholes, the entire thickness of the aquifer has been isolated into 10–20 ft intervals. All measurement locations are 300 ft or more from the Kishwaukee River or other streams.

Gradients based on water-level measurements from wells range from about 0.05 ft/ft upward to 0.15 ft/ft downward (Mills and others, 1998). Periodic upward gradients at two well locations seem to relate to local conditions associated with an adjacent landfill (Clayton Environmental Consultants, Inc., 1996).

Gradients based on water-level measurements from boreholes range from less than 0.01 to about 0.40 ft/ft downward (Mills, 1993b). Gradients in the uppermost 30 ft of the aquifer typically are 0.02 ft/ft or less and, in the upper half of the aquifer (about 150 ft below land surface), are 0.05 ft/ft or less. Gradients in the lower half of the aquifer often fluctuate in response to nearby municipal-well withdrawals. In about six test intervals in the boreholes, small upward gradients are recorded. The gradients are transient and seem to be related to nearby withdrawals.

On the basis of vertical gradients between the glacial drift aquifer and the uppermost part of the Galena-Platteville aquifer, it is assumed that adjacent to streams, including the Kishwaukee River, flow in the upper part of the Galena-Platteville aquifer is upward. In the lower part of the aquifer (greater than 150 ft below land surface), gradients may be downward adjacent to streams, and, thus, may not discharge to the streams. Water-level measurements at two borehole locations, each within about 350 ft of the Kishwaukee River (near the Parson's Casket Hardware site (fig. 1)), indicate downward gradients of about 0.10 ft/ft between the river and the bedding-plane parting at a depth of about 260 ft (Kay, 2001). The boreholes are within 2,500 ft of two municipal wells (BMW4, BMW6) that are known to depress water levels at this depth in the aquifer. In this area, flow that does not discharge to the river may discharge to these nearby municipal wells, located north of the river, or toward other municipal and (or) industrial wells located south of the river.

In Belvidere, gradients between the Galena-Platteville and St. Peter aquifers generally are downward, as affected by substantial withdrawals by high-capacity wells open to the St. Peter and deeper sandstone aquifers of the Cambrian-Ordovician aquifer. Transient upward gradients between the two aquifers are observed where there is a substantial hydraulic connection between nearby high-capacity wells and the deep bedding-plane partings. At the PCHSG127GP/PCHG127SP well pair at the Parson's Casket Hardware site (fig. 1A), gradients typically range from about 0.13 ft/ft downward to 0.06 ft/ft upward (Mills and others, 1998).

Elsewhere in the study area, gradients between the Galena-Platteville and St. Peter aquifers are considered to be downward. Water-level measurements in a municipal well in Rockford support this assumption (Visocky and others, 1985). As the partial result of substantial ground-water withdrawals in the Rockford area west of Belvidere (Visocky, 1993, 1997), most of the study area is included in a regional cone of depression (Visocky and others, 1993, 1997). The extent of the hydraulic connection between the two aquifers is not clearly indicated by available water-level data. The connection is assumed to be limited except where the dolomite deposits of the Galena and Platteville Groups and the Glenwood Formation are thin or absent or dissected by deeply penetrating inclined fractures. Available water-quality data provide insight into the extent of the connection in areas outside the Troy Bedrock Valley. Discussion of these data is provided in the section "Ground-Water Quality."

A limited number of measurements in municipal well BMW2 indicate downward flow at a rate of about 3–5 gal/min in the Galena-Platteville aquifer (Mills and others, 1998). Downward flow also was measured in the Potosi-Franconia confining unit; most of the flow exited the well in the Ironton-Galesville aquifer (fig. 2A). In 1980, downward flow was measured between the St. Peter, Ironton-Galesville, and Elmhurst-Mt. Simon aquifers in the vicinity of Rockford (Visocky and others, 1985). With the substantial amount of withdrawals from these aquifers in Rockford since 1980, flow between the Elmhurst-Mt. Simon aquifer may be upward to the most productive Ironton-Galesville aquifer. Nicholas and others (1987) have measured upward flow in the vicinity of Chicago, where the Ironton-Galesville aquifer is pumped heavily and the potentiometric level has declined below that of the underlying and overlying aquifers.

Withdrawals from municipal wells BMW2 and BMW3, located within about 500 ft of the Kishwaukee River, may contribute locally to loss of streamflow. These wells are cased 10 ft into the weathered deposits that compose the surface of the Galena-Platteville aquifer. Concentrations of trichloroethene (TCE) and tetrachloroethene (PCE) measured in the well samples (total about 10 µg/L, April 1998) are similar to the concentrations in the overlying glacial drift aquifer (total about 50 µg/L, April 1998), indicating the wells may withdraw some water from the glacial drift aquifer (or the aquifers are well connected). Water levels have been measured in five nearby monitoring wells (NSMG101-NSMG105) (fig. 1B) open to the glacial drift aquifer when the municipal wells were in use (measured in 1988), and when not in use or used sparingly (measured in 1993, 1994, 1999). When the municipal wells were in use, horizontal flow in the glacial drift aquifer seemed to be from the vicinity of the river toward the municipal wells (Illinois Environmental Protection Agency, 1988). When not in use or used sparingly, flow was towards the river (Mills and others, 1998, 1999a). Thus, the municipal wells seem to withdraw some water from the nearby river. Streamflow measurements near the municipal wells possibly could verify loss of streamflow to the bedrock wells. However, conditions (flow rate and stream depth) are not conducive to conventional methods of measurement (Rantz and others, 1982). An acoustic Doppler current profiler (ADCP) (Simpson, in press) possibly could be applied for these measurements; ADCP's allow 3-dimensional measurement of flow velocities as low as about 0.05 ft/s in depths greater than about 3 ft.

Secondary porosity contributes to the majority of ground-water flow within the Galena-Platteville aquifer. However, geophysical-log and hydraulic-test data clearly indicate that the hydraulic properties of the secondary-porosity features and the related contribution to preferential flow vary spatially. Of the five principal bedding-plane partings that have been identified, four seem to contribute to local or area-wide movement of water. Those partings include the clustered partings developed within the weathered surface of the aquifer, the 260-ft parting, and possibly, the 125- and 300-ft partings (fig. 10). Vertical flow rates up to 1.5 gal/min have been measured in tested boreholes in association with flow into and out of the partings (Mills, 1993c; Mills and others, 1998; Kay and others, 2000). Vugs represent a varied, yet consistently smaller contribution to flow in the aquifer. Vertical flow rates associated with vuggy intervals seem to be less than 0.5 gal/min, and typically are less than 0.1 gal/min.

Borehole-flow and water-level measurements indicate that the 260-ft parting within the Galena-Platteville aquifer may contribute substantially to lateral movement of water, and possibly movement of contaminants. Measurements of vertical flow at borehole PCHG128GP indicate that 65 percent of the outflow from the borehole primarily was through this parting; about 15 percent was through the 125-ft parting and about 20 percent through the 300-ft parting (the determination does not account for the possible effect of water-level (head) differences in the borehole) (Mills and others, 1998; F.L. Paillet, U.S. Geological Survey, written commun., 1993).

The large, near-instantaneous fluctuations in water level in monitoring well PCHG127GP at the Parson’s Casket Hardware site (fig. 1) indicate that one or more municipal wells (including BMW6 and BMW4) and possibly other high-capacity wells (including 00294, 00295, and 00296) intercept the 260-ft parting and (or) the 300-ft parting. Review of geophysical logs (fig. 10) and the depth of the surface casings (Woller and Sanderson, 1974) in these wells and other Belvidere municipal wells indicates that wells BMW2, BMW3, BMW5, and BMW7 also may intercept the parting(s). Casings depths of potentially affected wells range from about 50 ft below land surface (the uppermost 5 to 10 ft of the aquifer) at wells BMW2 and BMW3 to about 107 ft (about 152 ft below land surface) at well BMW4. The surface casing at well BMW7 penetrates only about 35 ft of the aquifer, but is 192 ft deep.

Water-level fluctuations in well PCHG127GP (fig. 18B) attributed to the industrial wells south of the Kishwaukee River (Mills and others, 1998) indicate that the river may not be a hydraulic barrier or discharge location for flow in the deep part of the Galena-Platteville aquifer. VOC’s detected at low concentrations (2 μg/L and lower) in samples from industrial wells 00294 and 00296 (Mills and others, 1999a) may be attributable to the Parson’s Casket Hardware site or adjacent sites by way of flow beneath the Kishwaukee River. Of the industrial wells, 00294 has the greatest potential for affecting ground-water flow beneath the river; annual withdrawals from well 00294 are about 10 times that of nearby wells 00295 and 00296 (table 9; fig. 1A).

Although the industrial wells south of the Kishwaukee River may derive some water from north of the river, there may be other sources for the VOC’s detected in samples from these wells. VOC’s have been detected in the glacial drift aquifer underlying the National Sewing Machine facility (Illinois Environmental Protection Agency, 1988; Mills and others, 1999a); that facility is south of the Kishwaukee River and about 1,000 to 2,000 ft closer to the industrial wells than the Parson’s Casket Hardware site (Mills and others, 1999a) (fig. 1). Withdrawal data from wells BMW2 and BMW3 and additional water-level and quality data could provide better understanding of the potential for lateral movement of ground water and contaminants beneath the Kishwaukee River and the source of VOC’s detected in samples from the municipal and industrial wells in the vicinity of the National Sewing Machine facility.

The hydraulic connection between the parting(s) intersected by well PCHG127GP and municipal wells

BMW2 and BMW3 is unknown. During the period that water levels were measured in well PCHG127GP and other nearby wells (Mills and others, 1998, 1999a), these municipal wells were not in use or were used sparingly. It is assumed that, although these municipal wells are about 500 to 1,000 ft farther from well PCHG127GP than the nearby industrial wells (fig. 1A), the higher withdrawal rate of the municipal wells would affect water levels and flow in the area near well PCHG127GP to an extent similar to or greater than that attributed to the industrial wells.

Whereas the 260-ft parting in the Galena-Platteville aquifer seems to be the predominant preferential pathway for ground-water flow to enter many of the high-capacity wells, this parting does not seem to be the singular, or in some cases the predominant pathway for contaminant movement to the wells. Elevated concentrations of VOC's (greater than 10 µg/L) have been measured in samples from the parting from three monitoring wells and (or) borehole test intervals. A total VOC concentration of about 50 µg/L was measured in well PCHG127GP at the Parson's Casket Hardware site and as high as 130 µg/L in a well about 1,500 ft south of the site (R.T. Kay, U.S. Geological Survey, oral commun., 2000).

Less-developed partings, inclined fractures, and vuggy intervals also contribute to water and contaminant transport through the Galena-Platteville aquifer, as indicated by the results of numerous discrete-interval (packer) tests of boreholes at the Parson's Casket Hardware site (Mills, 1993b, c, d; Mills and others, 1998; Kay and others, 2000; Kay, 2001). Water-quality sampling coordinated with tests of the hydraulic properties indicated no clear and consistent relation between the presence of bedding-plane partings and fractures with high hydraulic conductivities and elevated concentrations of VOC's. Similar concentrations of VOC's often were distributed throughout the sampled intervals of the aquifer. Although these VOC trends may have been affected by mixing in the open boreholes prior to sampling, sampling procedures were used that generally preclude that possibility.

VOC's have either not been detected or detected at low concentrations (2 µg/L or less) in samples from four monitoring wells open to the 260-ft parting and near (within 0.25 mi) sources of elevated concentrations of VOC's (greater than 100 µg/L). This result is interesting particularly in regards to well PCHG128GPD, which is within 50 ft of municipal well BMW6 (fig. 1B). Since 1985, when testing began, VOC's have been measured periodically at concentrations as high as 5 µg/L in samples from the municipal well.

Inclined fractures within the Galena-Platteville aquifer provide vertical pathways for water and contaminant transport between near-horizontal pathways (bedding-plane partings and vuggy intervals). Fewer wells are expected to penetrate the inclined fractures than the near-horizontal pathways; thus, the fractures likely provide a more indirect pathway for contaminant transport to wells than the near-horizontal pathways. As indicated by geophysical and water-quality data, some of the inclined fractures may penetrate through the entire thickness of the aquifer and underlying confining unit. These vertically connecting pathways may account for the well-distributed VOC concentrations observed in many of the boreholes open to the aquifer.

Ground-Water Quality

Water quality of the aquifers underlying Belvidere has been described previously in detail (Brown and Mills, 1995; Mills and others, 1998, 1999a). These studies describe background water quality and spatial and temporal trends in areas affected by contaminants. Findings of these studies, as well as water-quality data collected during spring 1998 and 1999, (table 1; appendixes 2–4) are summarized for the purpose of describing (1) the movement of ground water within and between aquifers, and (2) how ground-water flow likely affects contaminant distribution.

Water-quality data collected during 1970–92 were reviewed by Brown and Mills (1995). On the basis of data from 157 wells in the area, they concluded that, at most locations, inorganic constituents in ground water are present at concentrations below maximum contaminant levels (MCL's) established by the USEPA for protection of public-water supplies and that generally represent background levels. Trace-metal concentrations that have been measured above MCL's or secondary maximum contaminant levels (SMCL's) are restricted to the glacial drift aquifer in the immediate vicinity of three industrial or waste-disposal sites. During 1985–92, organic compounds were measured in samples from 99 monitoring wells at 7 industrial or waste-disposal sites, 18 private water-supply wells, and 6 of 8 municipal wells. Most of the detected compounds are VOC's used as solvents (TCE, for example); petroleum-related compounds (benzene, for example), trihalogen derivatives from well disinfection (bromodichloromethane, for example), and semivolatile compounds (SVOC's) used in disinfectants, deodorizers, and plasticizers, and as by-products of coal-tar processing (*bis* (2-ethylhexyl) phthalate, for example) also were detected. TCE and PCE were detected in samples from 111 wells located primarily at the three Superfund sites in the area (fig. 1A) and 6 Belvidere municipal wells. VOC's primarily were detected in samples from wells open to the glacial drift aquifer, but also were detected in samples from wells open in part or entirety to the Galena-Platteville, St. Peter, and Cambrian-Ordovician aquifers.

The VOC detections indicate that the glacial drift and Galena-Platteville aquifers are hydraulically connected; limited insight is provided regarding the hydraulic connection between the Galena-Platteville and underlying aquifers, and, thus, the capacity of the Glenwood confining unit to restrict vertical flow. VOC's were detected temporarily (in 1992) at elevated concentrations (TCE as high as 880 µg/L) in samples from one well open to the St. Peter aquifer; however, subsequent samplings (1993–99) measured only trace concentrations, if detected. Sampled wells open to the Cambrian-Ordovician aquifer are open, in part, to the Galena-Platteville aquifer. Movement of the VOC's to the aquifers underlying the confining unit may be limited to flow through wells or boreholes that penetrate the unit. Unused or intermittently used wells may provide the most effective preferential pathway for deep movement of water and contaminants, with downward flow induced by substantial withdrawals from the area's high-capacity wells. Municipal wells BMW2 and BMW3 (fig. 1) could have provided (and may still provide) such a temporary pathway. These wells are open through most of the Galena-Platteville aquifer to the Elmhurst-Mt. Simon aquifer (fig. 2), have elevated concentrations of VOC's in samples (total concentrations approaching 20 µg/L in 1992) and a nearby source for the VOC's (Mills and others, 1999a), and were used rarely during the early 1990's. In 1996, these wells were put back into intermittent service with an air stripper installed to remove VOC's from the water distributed to the public (J.A. Grimes, Belvidere Water and Sewer Department, oral commun., 2000).

Water samples were collected at discrete depth intervals in eight boreholes in Belvidere (Mills and others, 1998). These samples were analyzed selectively for major ions, trace metals, tritium, and VOC's. At the Parson's Casket Hardware site (fig. 1A), total concentrations of VOC's as high as 418 µg/L (at depths up to 150 ft below land surface) and 48 µg/L (at a depth of 300 ft) were measured in the Galena-Platteville aquifer. Major-ion analyses indicate that the Galena-Platteville and St. Peter aquifers have a nearly indistinguishable calcium-bicarbonate water type (fig. 20). A similar water type for the St. Peter aquifer was classified by Visocky and others (1985) from samples collected in Rockford, and Nicholas and others (1987) from samples collected near Chicago.

Water samples collected from 125 wells during 1992–99 (Mills and others, 1998; 1999a; data from 1998-99 in appendixes 2–4) and from municipal wells since 1985 (R.P. Cobb, Illinois Environmental Protection Agency, written commun., 2000) further indicate the vulnerability of the glacial and bedrock aquifers to contamination and evidence of hydraulic connections between aquifers. The samples collected during 1992–99 were analyzed selectively for major ions, trace metals, cyanide, SVOC's, and VOC's. Contamination of the aquifers consisted primarily of VOC's, as previously indicated (Brown and Mills, 1995). VOC's were detected in samples from 60 wells, with samples from 30 wells having at least one VOC at a concentration above MCL's. TCE and PCE were the most frequently detected and generally had the highest concentrations of the five VOC's with concentrations above MCL's. VOC's with concentrations above MCL's were detected in samples from 18 wells open to the glacial drift aquifer, 7 wells open to the Galena-Platteville aquifer, 2 wells open to the St. Peter aquifer, and 3 wells open to the Cambrian-Ordovician aquifer. Since 1985, petroleum-related VOC's (benzene, toluene, xylene, or methyl tertiary-butyl ether (MTBE)) have been detected periodically in samples from seven municipal wells open to the Cambrian-Ordovician aquifer; benzene concentrations have equaled or exceeded the MCL in a few samples collected from two wells (Mills and others, 1999a). MTBE first was used as a gasoline additive in the United States in 1979, indicating a travel time between the glacial drift aquifer and the uppermost part of the Galena-Platteville aquifer of about 16 years or less. VOC's generally are not detected in the glacial drift aquifer further than 1,000 ft of known or potential source areas (industrial or disposal sites), because most source areas are near the Kishwaukee River, where shallow ground water discharges. Except in the immediate vicinity of a known hazardous-waste site, possible sources of VOC's in bedrock aquifers were difficult to identify; concentrations of VOC's at most locations in these aquifers were below 5 µg/L.

Galena-Platteville aquifer:

Median Specific Conductance: 710 microsiemens/centimeter

Median pH: 7.10

St. Peter aquifer:

Median Specific Conductance: 764 microsiemens/centimeter

Median pH: 7.15

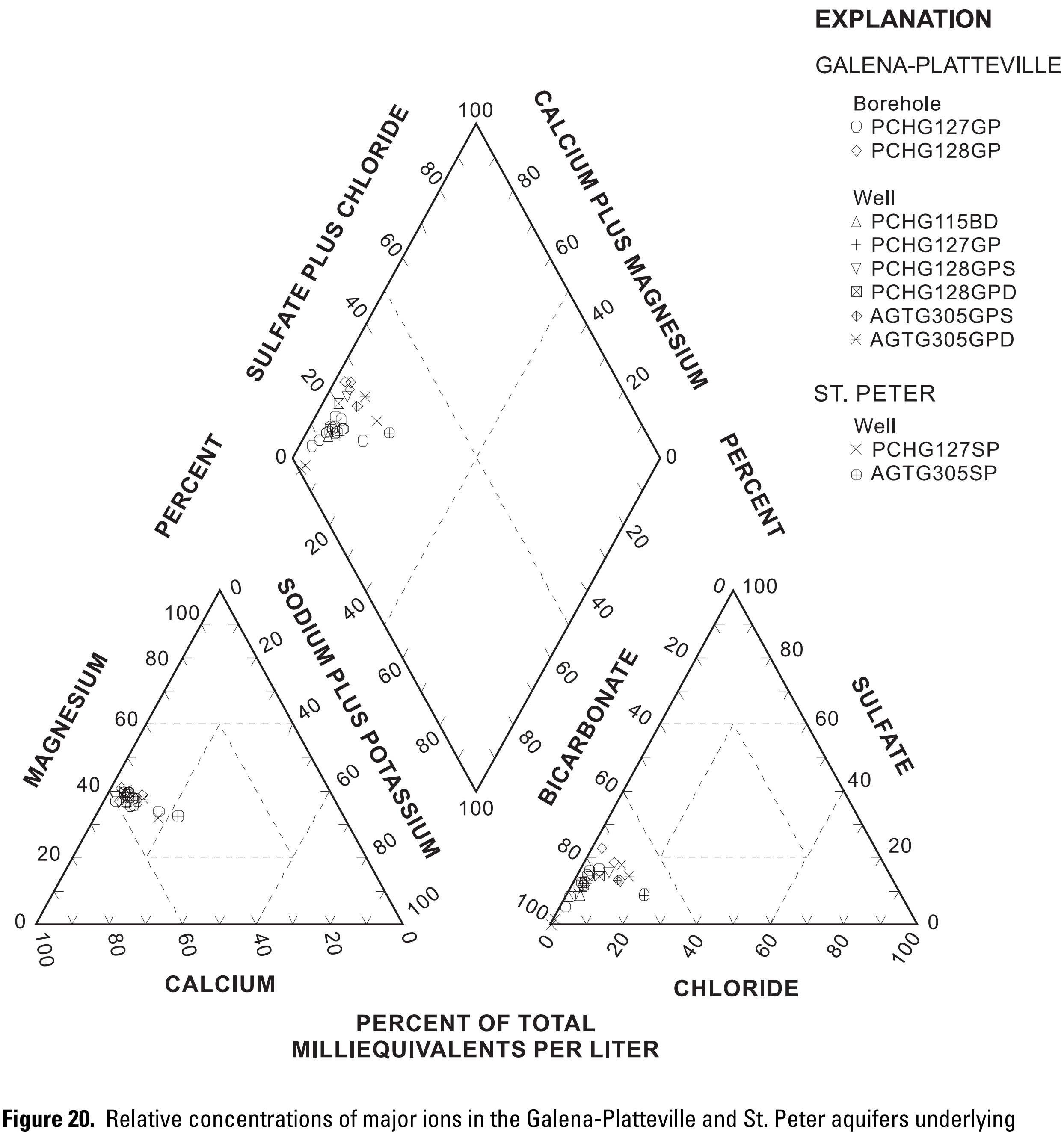


Figure 20. Relative concentrations of major ions in the Galena-Platteville and St. Peter aquifers underlying Belvidere, Illinois.

During March 1999, 15 samples were collected and analyzed for tritium and VOC's at various depths in the glacial drift and bedrock aquifers (table 12; appendixes 3, 4). Tritium is a radioisotope of hydrogen that can be used to determine relative age of ground water, as well as the degree of confinement and vulnerability of aquifers to contamination. Beginning in 1954, with the onset of above-ground nuclear-weapons testing, naturally occurring levels of atmospheric tritium were increased from about 5 tritium units (TU's; equivalent to 16 picocuries per liter) to over 1,000 TU's. Cessation of nuclear testing and radioactive decay have reduced atmospheric levels to current levels of about 50–100 TU's in North America (University of Ottawa, 2000). Tracking the pulse of tritium-enriched water recharging aquifers allows the time since initiation of recharge to be estimated. Presently (2001), ground water with concentrations at or below 1 TU represents recharge that originated before about 1954. The USEPA and IEPA consider aquifers with tritium concentrations at or below 1 TU as "not vulnerable" to contamination and aquifers with tritium concentrations at or above natural levels of 5 TU's as "vulnerable" to contamination (Illinois Environmental Protection Agency, 1999). Differences in tritium concentrations in adjacent aquifers (such as the Galena-Platteville and St. Peter aquifers) separated by an intervening hydrogeologic unit (such as the Glenwood confining unit) may be indicative of the extent of hydraulic connection between the aquifers and the confining capacity of the intervening unit.

Tritium concentrations in samples collected in 1999 ranged from less than or equal to 0.1 TU in the lower part of the Cambrian-Ordovician aquifer (St. Peter and deeper aquifers; municipal well BMW8, open to a depth of 1,390 ft) to about 28.8 TU's in the St. Peter aquifer (monitoring well AGTG305SP, open to a depth of 357.8 ft) (fig. 21; table 12). Excluding the sample from well AGTG305SP, the highest concentration was about 12.5 TU's in the Galena-Platteville aquifer (monitoring well AGTG305GPS, open to a depth of 115.0 ft). In general, tritium concentrations decreased with increased depth in the aquifers.

Elevated concentrations of tritium (greater than about 5 TU's) in samples from wells open in part or whole to the glacial drift and Galena-Platteville aquifers indicate recharge to most depths in these aquifers occurs in less than 45 years and the aquifers are hydraulically connected. The presence of VOC's throughout the entire thickness of both aquifers confirms the strong hydraulic connection between the aquifers (table 12; appendix 4) (Mills and others, 1998, 1999a).

Table 12. Concentrations of tritium and volatile organic compounds in the aquifers underlying Belvidere, Illinois, March 1999

[ft bls, feet below land surface; µg/L, micrograms per liter; --, not applicable; nd, not detected; ≤, less than or equal to]

Aquifer: GD, glacial drift; GP, Galena-Platteville; SP, St. Peter; CO-GP, Cambrian-Ordovician aquifer system (Galena-Platteville and deeper aquifers); CO-SP, Cambrian-Ordovician aquifer system (St. Peter and deeper aquifers)

Well designation	Aquifer	Hydrogeologic feature	Depth of well (ft bls)	Tritium unit[1]	Total concentration of volatile organic compounds (µg/L)
BMW9	GD	--	122	7.3	nd
AGTG305GPS	GP	Bedding-plane parting	115.0	12.5	nd
PCHG128GPS	GP	Bedding-plane parting	121.0	10.2	nd
AGTG305GPD	GP	Bedding-plane parting	251.4	8.4	0.5
PCHG128GPD	GP	Bedding-plane parting	258.5	8.0	1.5
PCHG127GP	GP	--	294.2	9.0	49
AGTG305SP	SP	--	357.8	28.8	10
PCH127SP	SP	--	375.7	.4	[2].5
BMW5	CO-GP	--	610	7.7	1
BMW6	CO-GP	--	868	6.0	1.3
BMW7	CO-GP	--	969	.4	nd
BMW3	CO-GP	--	1,800	11.5	6
BMW4	CO-GP	--	1,800	4.8	.9
BMW2	CO-GP	--	1,860	12.0	14
BMW8	CO-SP	--	1,390	≤.3	[1].6

[1] Analytical results given in detail in appendix 3.

[2] Laboratory contaminant, methylene chloride.

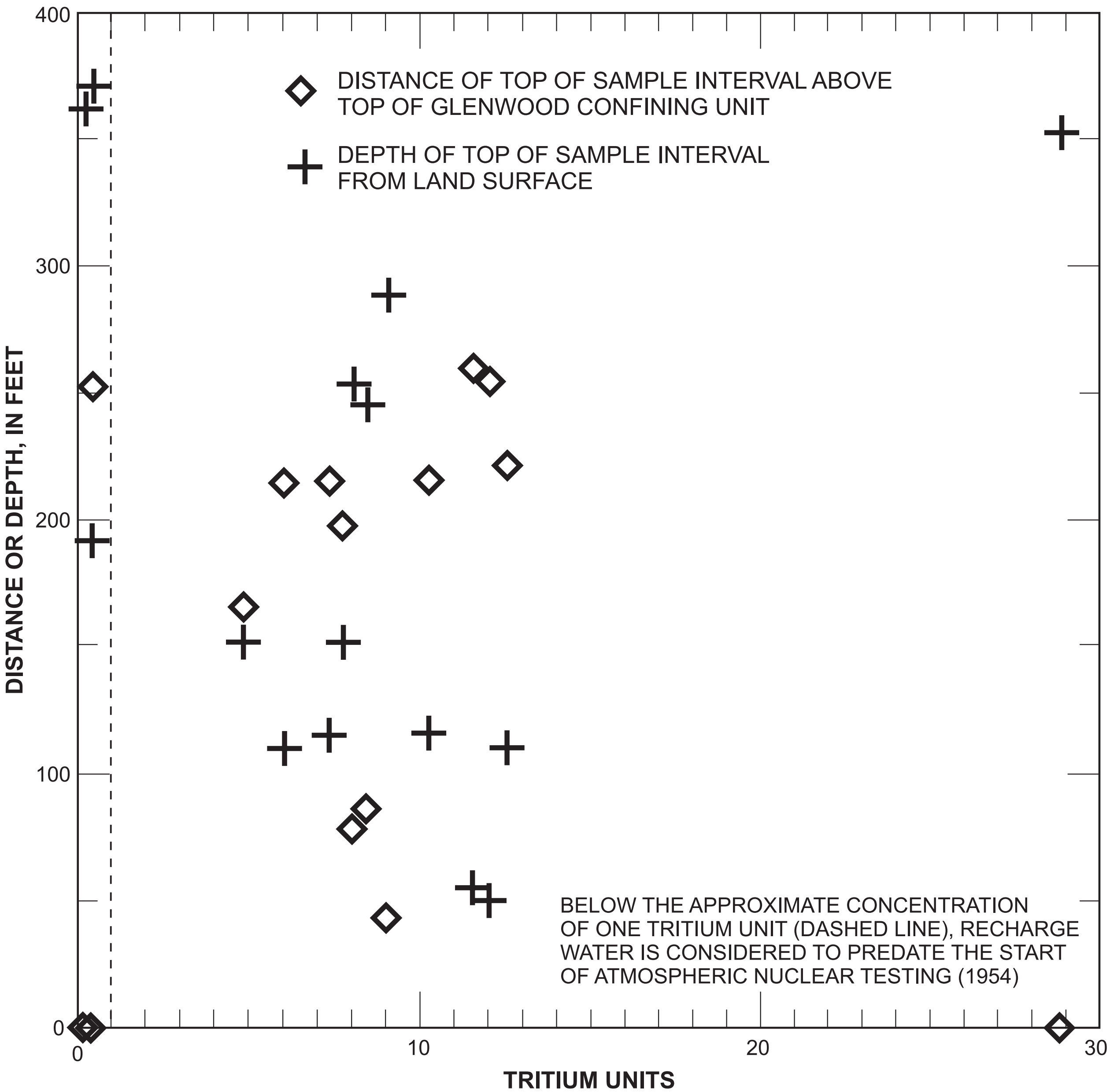


Figure 21. Concentrations of tritium in the aquifers underlying Belvidere, Illinois, March 1999.

Wells open to the sandstone aquifers below the Glenwood confining unit (St. Peter and deeper aquifers) and the overlying Galena-Platteville aquifer, such as municipal wells BMW2–BMW6, seem to readily withdraw water from the Galena-Platteville aquifer. Tritium concentrations were elevated in samples from these wells (about 4.8 to 12.0 TU's) and VOC's periodically have been detected. The low concentration of tritium (about 0.4 TU) in the sample from municipal well BMW7 (open to depths of 192–969 ft) (fig. 1) indicates that the Galena-Platteville aquifer may not be vulnerable to contamination in parts of the study area. Factors that limit vulnerability may include (1) the depth of the open interval, and (2) restricted vertical flow through thick, overlying, fine-grained deposits that fill an ancestral tributary to the Troy Bedrock Valley in this part of the study area.

For the most part, water in sandstone aquifers that underlie the Glenwood confining unit is considered to be recharged before 1954 (tritium concentrations are less than 1 TU); thus, the aquifers are not hydraulically connected and not highly vulnerable to contamination (fig. 21; table 12). Results of tritium analyses correlate well with VOC analyses of the water samples. TCE was detected only in samples determined by tritium analysis to be vulnerable to contamination.

Tritium and VOC data from one well (AGTG305SP) sampled in 1999 indicate that some of the inclined fractures in the Galena-Platteville aquifer may penetrate the Glenwood confining unit and provide preferential pathways for water and contaminant movement between the aquifers overlying and underlying the unit. The highest tritium concentration (28.8 TU) was detected in well AGTG305SP, open to the St. Peter aquifer. Elevated concentrations of TCE also have been detected in this well; sampled three times, concentrations increased from 1 μg/L in 1995 to 9 μg/L in 1999. Review of tritium and VOC analyses of water samples from wells nested with AGTG305SP in the overlying Galena-Platteville aquifer indicate that the elevated tritium and VOC concentrations cannot be attributed to improper well construction. Other explanations for the elevated concentrations include (1) local variability in the thickness, lithology, and hydraulic properties of the Glenwood confining unit, (2) a nearby fracture(s) that penetrates the confining unit, and (or) (3) a nearby unused or rarely used supply well(s) that is open to the aquifers that overlie and underlie the confining unit. Review of drilling logs indicates that the thickness and lithology (and, thus, presumably the hydraulic properties) of the confining unit generally are uniform in this part of the study area. No nearby, deep, unused wells are identified (Brown and Mills, 1995). The presence of a nearby source of TCE contamination (about 200 ft west of the well) supports the likelihood of a fracture in the vicinity of the well. The high tritium concentration (28.8 TU) relative to concentrations in the glacial drift and Galena-Platteville aquifers indicates that the fracture or other pathway may allow rapid movement of water and contaminants deep into the ground-water system.

SIMULATION OF GROUND-WATER FLOW

The description, or conceptual model, of the regional ground-water-flow system underlying Belvidere and vicinity described initially in this report was developed on the basis of hydrogeologic and water-quality data. A numerical model of the flow system was developed to evaluate the conceptual model, estimate water budgets within subsections of the study area, and identify parts of the study area where additional data may be necessary to properly describe the hydrogeologic framework of the flow system. Possible future uses of the numerical flow model include determination of (1) areas contributing recharge to the Belvidere municipal wells and, possibly, other high-capacity wells, (2) discharge locations for ground water underlying known and potential contaminant-source areas, (3) geometry and (or) hydraulic characteristics of the Glenwood confining unit in the deepest parts of the Troy Bedrock Valley, and (4) effects of changing hydrologic stresses, such as increased ground-water withdrawals to satisfy the demands of an increasing population.

The numerical flow model is based on MODFLOW, a quasi-three-dimensional finite-difference computer algorithm (McDonald and Harbaugh, 1988). A fundamental assumption of MODFLOW is that the hydrogeologic units represented by model layers are composed of continuous porous media. Although porosity that affects flow in the Galena-Platteville aquifer consists predominantly of interconnected fractures and bedding-plane partings, the assumption of a continuous porous media is considered reasonable at the regional scale of simulation. The model-cell size in the horizontal direction is greater than the spacing between inclined fractures. The smallest cell size, 250 ft by 250 ft, is substantially larger than the approximate 80 ft or less spacing between fractures (McGarry, 2000). Lateral variations in the hydraulic properties of fractures and bedding-plane partings seem to be at a scale smaller than that of the smallest model-cell size. The anisotropic and heterogeneous character of the Galena-Platteville aquifer seems to be more substantial in the vertical direction of the aquifer than in the horizontal direction. This directional heterogeneity can be accounted for in model simulation by varying the vertical hydraulic conductivity (K_V) of the represented hydrogeologic units. By simulating the entire thickness of the Galena-Platteville aquifer as one model layer, the anisotropy and heterogeneity of the aquifer are considered effectively simulated.

The model was calibrated to steady-state conditions, with the ground-water-flow system considered in equilibrium. Temporal variability in water levels is assumed to represent fluctuation about a long-term-average level. Simulation of steady-state conditions is considered appropriate for the purpose of study. For the calibration, differences between simulated and measured ground-water levels, discharge to streams, and differences in water levels in vertically nested wells were minimized. Determination of best estimates of many of the hydrologic-property values (often referred to as model parameters) was aided by use of an optimization algorithm (Halford, 1992). These estimates were constrained by values from hydrogeologic data.

Model Design

The area represented in the ground-water-flow model is similar to that of the previously described 80-mi^2 study area (see "Description of Study Area") (figs. 1, 22) and includes the city of Belvidere. The area is divided into a model grid of irregularly sized rectangular cells. The smallest cells generally coincide with the city of Belvidere and locations of the municipal wells. The largest cells, 2,000 ft by 2,000 ft, generally coincide with the perimeter boundaries of the model. Numerical calculations of water level and flow direction are applied to the center (node) of each cell.

The cells are oriented parallel to the regional directions of ground-water flow. Flow in the shallow glacial drift and Galena-Platteville aquifers is towards the Kishwaukee River and its principal tributaries. The river generally flows east to west through the study area and its principal tributaries generally flow north to south. Inclined fractures in the Galena-Platteville aquifer are known to convey ground water along pathways oriented obliquely to the model grid. However, the resultant flow system is considered to be local and can be disregarded at the regional scale of the model. Flow in the deep sandstone aquifers (St. Peter, Ironton-Galesville, and Elmhurst-Mt. Simon) that, in part, compose the Cambrian-Ordovician aquifer generally is towards the regional withdrawal centers located east and west of Belvidere.

The hydrogeologic framework represented by the model is based on the stratigraphic and hydraulic-property data described previously in this report. The framework includes the following hydrogeologic units (aquifers and confining unit) as model layers: the glacial drift and Galena-Platteville aquifers (layers 1 and 2, respectively); the Glenwood confining unit (layer 3); and the St. Peter, Ironton-Galesville, and Elmhurst-Mt. Simon aquifers (layer 4) (fig. 23). Aquifers represented in layer 4 are referred to collectively as the sandstone aquifers of the Cambrian-Ordovician aquifer. The relation between hydrogeologic units and model layers are presented below.

Hydrogeologic units			Model layer
glacial drift aquifer			1
Galena-Platteville aquifer	Cambrian-Ordovician aquifer		2
Glenwood confining unit			3
St. Peter aquifer		sandstone aquifers	
Ironton-Galesville aquifer			4
Elmhurst-Mt. Simon aquifer			

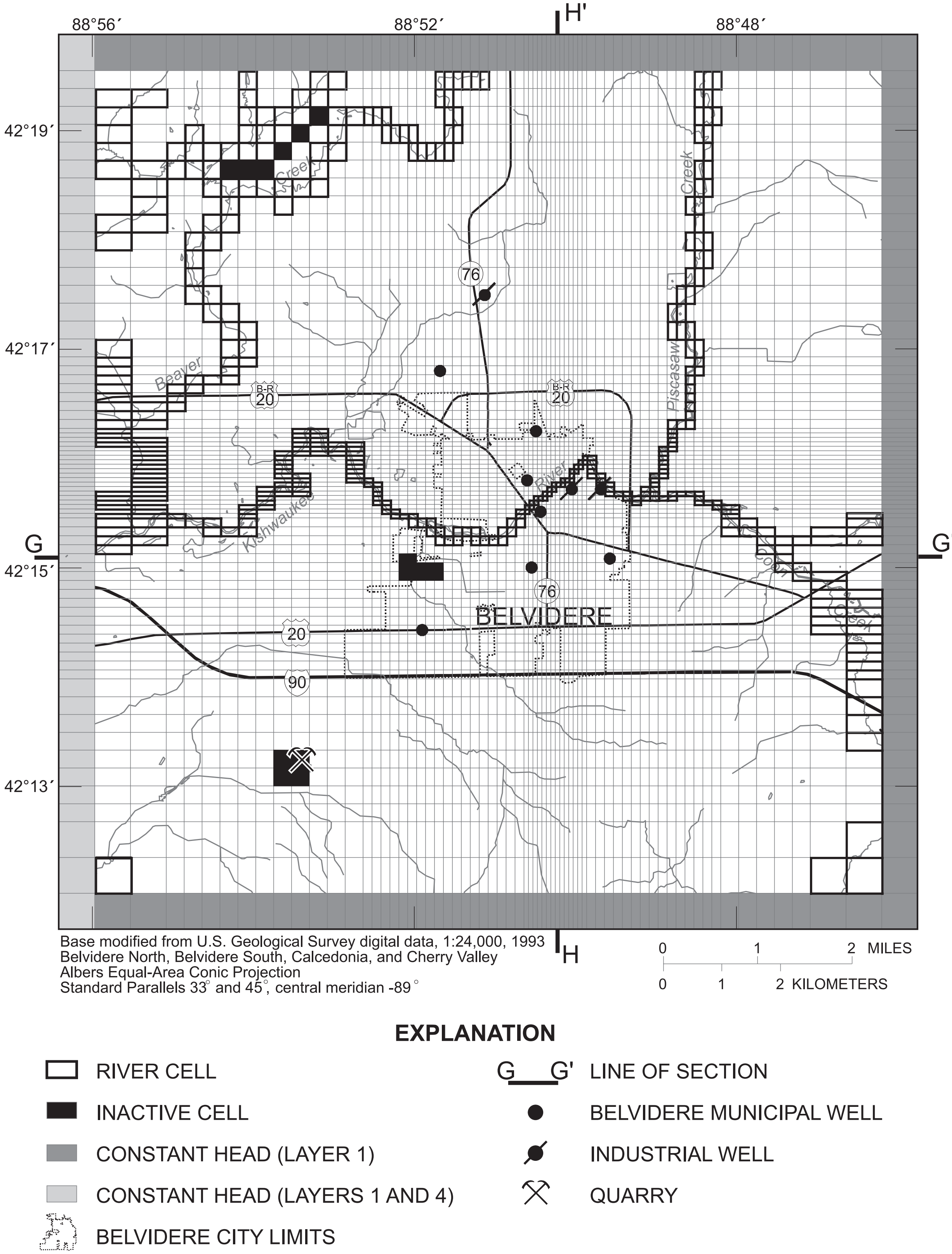


Figure 22. Model grid, boundary conditions, stream sections, and wells used in the simulation of ground-water flow in the aquifers and confining units underlying Belvidere, Illinois.

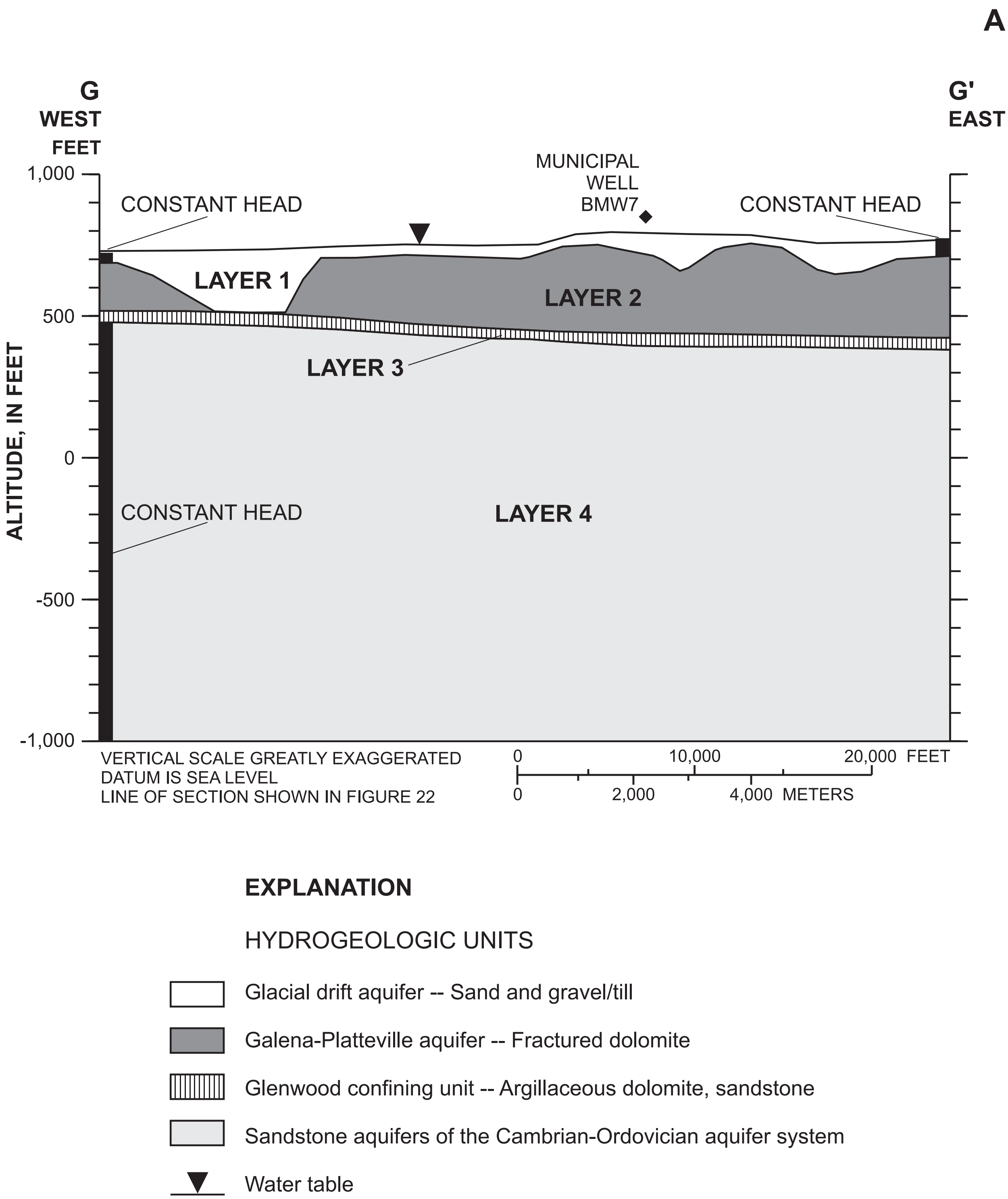


Figure 23. Hydrogeologic sections G-G´ and H-H´ of the Belvidere, Illinois, model area showing boundary conditions and model layers used to represent the aquifers and confining unit: (A) row 50, through the municipal well BMW7 site and (B) column 40, through the Parson's Casket Hardware Superfund site.

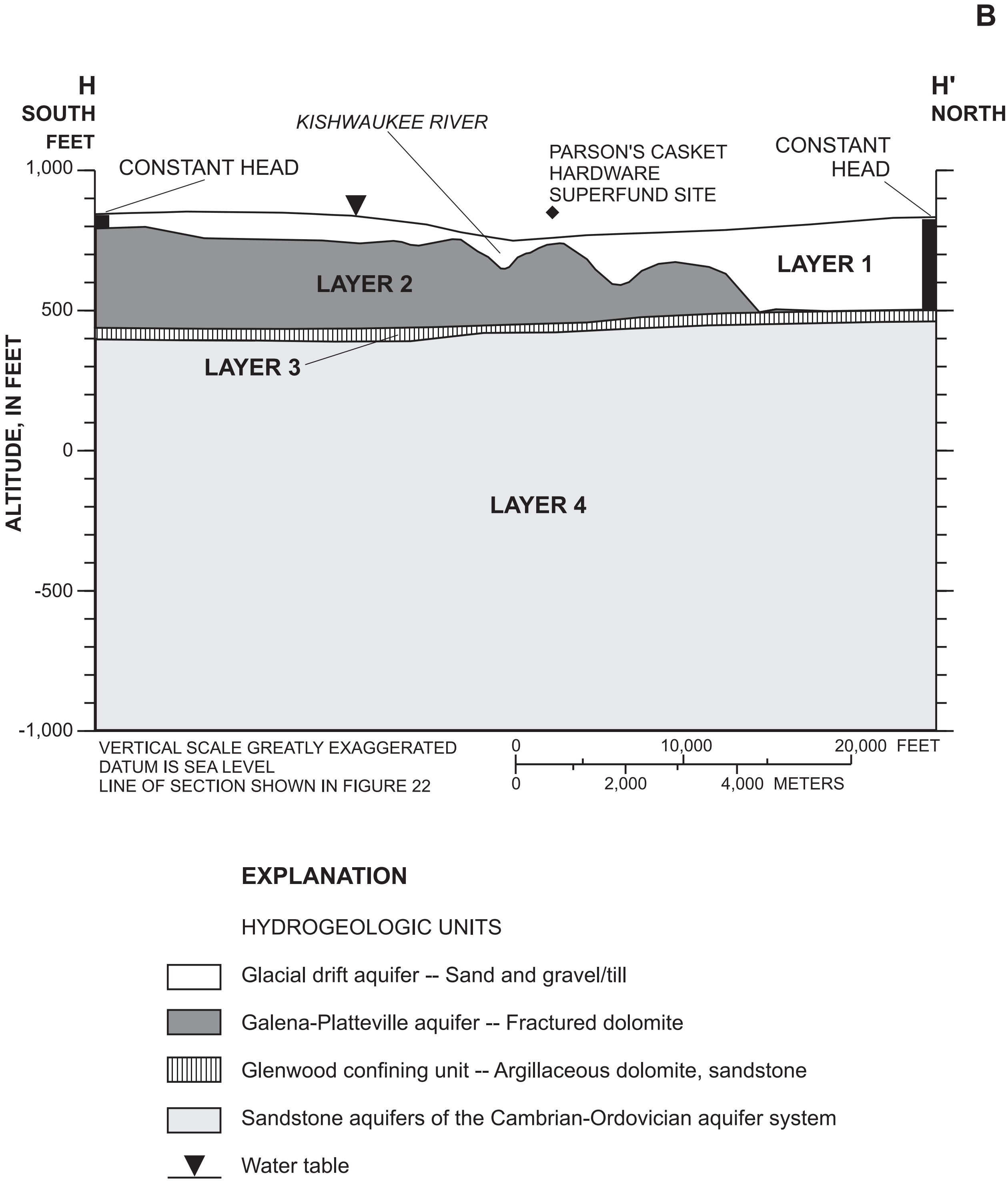


Figure 23. Hydrogeologic sections G-G´ and H-H´ of the Belvidere, Illinois, model area showing boundary conditions and model layers used to represent the aquifers and confining unit: (A) row 50, through the municipal well BMW7 site and (B) column 40, through the Parson's Casket Hardware Superfund site—Continued.

Accurate identification of boundary conditions can affect simulation results greatly near a boundary, particularly in steady-state simulations (Anderson and Woessner, 1992; Bayless and Arihood, 1996). For the most part, nearby natural hydrologic boundaries or sufficient data are not available for ideal delineation of perimeter boundaries of the model area. East of Belvidere, between the regional ground-water-withdrawal centers in the Chicago and Rockford areas, a ground-water divide is present in the Cambrian-Ordovician aquifer. The divide, which shifted eastward during 1991–95 with reduced withdrawals in the Chicago area, approximately coincides with the eastern boundary of the model area (Visocky, 1997, figs. 7, 8). The western boundary of the model area is located to minimize effects on flows and water levels that may be associated with substantial withdrawals in nearby Rockford and Belvidere. The northern and southern boundaries are located more than 3 mi from Belvidere, the area of interest, to ensure that the simulation of flow and water levels in this area is not substantially affected. South of Belvidere, surface-water-drainage patterns indicate a possible ground-water divide in the glacial drift aquifer that may coincide with the western two-thirds of the southern boundary.

All perimeter boundaries of the uppermost aquifer (glacial drift) represented in the model (layer 1) (figs. 22, 23) and the western boundary of the lowermost aquifers (sandstone, layer 4) are designated as constant-head boundaries (figs. 22, 23A); water levels are specified and remain unchanged in these cells during all simulations. Water levels along the constant-head boundaries are estimated from water-level measurements and potentiometric maps (figs. 14, 17) (Mills and others, 1999; Visocky, 1997). For the Cambrian-Ordovician aquifer (represented in model layers 2–4), no wells are identified within 1 mi of the designated model boundary; only 10 wells (7 with available water levels) are identified within 2 mi of the boundary. Additionally, most of the wells open to the Cambrian-Ordovician aquifer are high-capacity wells, where measured water levels, in part, represent the effects of well hydraulics. Water levels specified along the western boundary of the sandstone aquifers (layer 4) approximate the regional drawdown associated with substantial withdrawals in nearby Rockford and Belvidere (Visocky, 1997, fig. 8). Boundaries in the intermediate Galena-Platteville aquifer and Glenwood confining unit (layers 2 and 3, respectively) and the northern, eastern, and southern boundaries of the sandstone aquifers are not designated as constant-head boundaries, because water levels in these units are unavailable in the vicinity of the model boundaries.

A constant-head boundary has potential to allow unlimited cross-boundary flow (flux). Fluxes are not specified for any of the perimeter model boundaries, particularly the western boundary of the sandstone aquifers where some cross flow is expected (ground-water withdrawal rates in Rockford, for wells open to the aquifers, are about seven times those in Belvidere (Kirk, 1987; Avery, 1999)), because accurate hydrogeologic data in the vicinity of the boundaries necessary to compute the fluxes (for example, water levels and K_h) are unavailable. Given that collection of additional field data and compiling the necessary water-level and ground-water withdrawal data from the Rockford area to establish other than a constant-head boundary at its present location are beyond the scope and resources of the study, treatment of this boundary as a constant-head boundary is considered a reasonable alternative to treatment as a specified-flux boundary. Fluxes that were simulated across the model boundaries, including the boundary of the sandstone aquifers, are considered reasonable within the context of flow throughout the regional ground-water system.

Model boundaries consisting of active, undesignated cells are considered no-flow boundaries. The assumption of no horizontal flow through the boundaries of the Galena-Platteville aquifer and Glenwood confining unit is considered reasonable because their generally low hydraulic conductivity likely limits most flow to vertical flow. The assumption of no horizontal flow through the eastern, northern, and southern boundaries of the sandstone aquifers is considered reasonable, because (1) the eastern boundary generally coincides with a divide in the deep part of the ground-water-flow system, and (2) to the north and south of Belvidere flow seems to be primarily to the east and west in response to ground-water withdrawals in the areas of Rockford and Chicago (Visocky, 1997).

Inactive cells are assigned to the uppermost hydrogeologic unit in three interior locations within the model area (fig. 22). The locations are areas where this unit is known or assumed to be unsaturated (fig. 14). Otherwise, such a condition was difficult to account for at the regional scale of simulation.

The lowest part of the Elmhurst-Mt. Simon aquifer (fig. 2) is considered confined and is unused for water supply (possibly because of unacceptable salinity

(Visocky and others, 1985)). Thus, the top of the unused part of the aquifer is considered as the base of the ground-water-flow system and simulated as a no-flow boundary. Alternatively, the base of the flow system may be considered the impermeable granitic rocks of Precambrian age that underlie younger sedimentary units in the area (Willman and others, 1975) and throughout most of the Midwest (Young, 1992).

Thicknesses of the aquifers and confining unit were determined from published information (Berg and others, 1984; Willman and others, 1975) and data collected or compiled by the USGS and USEPA. Thicknesses are considered approximate because of the limited number and spatial distribution of data. Data for determining thicknesses are limited particularly in the vicinity of the Troy Bedrock Valley for the glacial drift and Galena-Platteville aquifers and throughout the study area for the Glenwood confining unit. In the vicinity of the Troy Bedrock Valley, the Galena-Platteville aquifer is assumed to have a minimum thickness of 1 ft and, thus, the Glenwood confining unit is considered uneroded (see "Lithology and Stratigraphy"). Thicknesses of these units, as mapped, are considered reasonable for the purpose of regional simulation of flow.

The Glenwood confining unit is represented explicitly as a model layer. Confining units often are represented implicitly in flow models by use of vertical leakances (Anderson and Woessner, 1992). However, this approach is acceptable only when horizontal flow through a unit is negligible. This condition may not be the case in the deepest parts of the Troy Bedrock Valley. Uncertainty regarding the presence and composition of the confining unit in this area indicates that parts of the unit may be permeable (the weathered upper part, if eroded, and sand-dominated lower part) and, thus, allow considerable horizontal and (or) vertical flow. Treatment of the Glenwood confining unit explicitly as a model layer will assist future evaluation (as additional data become available) of the hydrologic properties of the unit and flow patterns in this part of the Troy Bedrock Valley.

Streams represented in the model include the Kishwaukee River, its principal tributaries (Piscasaw, Beaver, and Coon Creeks), and all other drainages indicated as perennial on USGS 1:24,000-scale topographic maps of the area (fig. 22). The length of a stream reach within a model cell was determined by use of a GIS analytical tool (Environmental Systems Research Institute, Inc., 1991, 1992a, 1992b). Stream widths are assumed as follows: Kishwaukee River below the low-head dam (fig. 1C), 100 ft; Kishwaukee River between the low-head dam and Piscasaw Creek, 150 ft; Kishwaukee River above Piscasaw Creek, 65 ft; Piscasaw and Beaver Creeks, 25 ft; Coon Creek, 40 ft; other tributaries, 5 ft. Average water levels in streams within each model cell are estimated using (1) stream-level data collected at eight locations on the Kishwaukee River in July 1993, and (2) altitude data from USGS topographic maps, in conjunction with a GIS analytical tool (Environmental Systems Research Institute, Inc., 1991, 1992a, b). The Kishwaukee River is assumed to be ponded to an average surface altitude of 750 ft between the low-head dam and Piscasaw Creek (fig. 1C). The altitude of streambeds is estimated by assuming a constant stage of 2 ft above the streambed for all streams. A streambed thickness of 1 ft is assumed for all streams. Streams were simulated with the RIVER package in MODFLOW (McDonald and Harbaugh, 1988); availability of water in the streams was not of concern.

Ranges of K_h, and, thus, initial property values (table 13), for the aquifers and confining unit represented in the model were determined from single- and multiple-well aquifer tests conducted by the USGS and USEPA and from single-well tests conducted by others (Roy F. Weston, Inc., 1988; GZA GeoEnvironmental, Inc., 1994b; Clayton Environmental Consultants, Inc., 1996; K.J. Hlinka, Illinois State Water Survey, written commun., 1995). Specific-capacity data from well-construction records were used to evaluate the spatial variability and probable range of hydrologic-property values, but transmissivities were not calculated specifically from the data. For the glacial drift aquifer (fig. 23), lithologic information from Berg and others (1984) and other data indicate that the hydrologic properties of the aquifer differ substantially in four general areas (figs. 12, 24): (1) the southern one-half of the Troy Bedrock Valley and Kishwaukee River valley, where sand-and-gravel deposits predominate and generally are greater than 50 ft thick, (2) the flood plains of the Kishwaukee River and its principal tributaries, where sand-and-gravel deposits predominate and generally are less than 50 ft thick, (3) the northern part of the study area, including the northern half of the Troy Bedrock Valley, where sand-and-gravel deposits may be present within thicker sequences of glacial till, and (4) the southern part of the study area, where till deposits with some shale predominate. Therefore, each of the four areas of the glacial drift aquifer are represented in the model and considered to have a unique and constant K_h.

Table 13. Initial and calibrated values of hydrologic properties and simulation error for the ground-water-flow model of Belvidere, Illinois, and vicinity

[K_h, horizontal hydraulic conductivity; K_v, vertical hydraulic conductivity; hydraulic conductivity, in feet per day; recharge, in inches per year; --, not applicable; RMSE, root-mean-square error, in feet]

Hydrologic property and zone identifier (in bold)	Model areas	Model layer(s)	Initial values based on conceptual model	Calibrated values	Initial K_h:K_v	Calibrated K_h:K_v
K_h, glacial drift aquifer, (K**VAL**)	Sand-dominated Troy Bedrock Valley/ alluvial valleys	1	280	45	--	--
K_h, glacial drift aquifer, (K**VED**)	Sand-dominated valley edges	1	50	250	--	--
K_h, glacial drift aquifer (K**NWD**)	Sand-till areas	1	5	13	--	--
K_h, glacial drift aquifer (K**TIL**)	Till-dominated areas	1	.001	10	--	--
K_h, Galena-Platteville aquifer (K**GPD**)	--	2	.5	.05	--	--
K_v, glacial drift/Galena-Platteville aquifers (V**GPD**)	Outside Troy Bedrock Valley	1–2	.005	.003	10	16.7
K_v, glacial drift/Galena-Platteville aquifers (V**GPV**)	Within Troy Bedrock Valley	1–2	.005	.001	10	50.0
K_h, Glenwood confining unit (K**GWF**)	--	3	.001	[1].001	--	--
K_v, Galena-Platteville/Glenwood confining unit/sandstone aquifers[2] (V**GWF**)	--	2–4	.0001	.00015	10	6.7
K_h, sandstone aquifers (K**COS**)	--	4	7	4	--	--
K_v, streambed, Kishwaukee River, Piscasaw Creek, and other streams outside of Beaver Creek drainage	--	1	28	2.5	--	--
K_v, streambed, Beaver Creek and its tributaries	--	1	28	.025	--	--
Areal recharge rate (**RCH**)	--	1	10	8.4	--	--
RMSE	--	--	10	--	--	--

[1] Property values initially were adjusted during model calibration; values fixed to the initial estimates were determined to provide the least model error and best satisfy the conceptual understanding of the ground-water-flow system.

[2] Of the Cambrian-Ordovician aquifer system (St. Peter, Ironton-Galesville, and Elmhurst-Mt. Simon aquifers).

For the Glenwood confining unit, a representative K_h (Freeze and Cherry, 1979) was assumed on the basis of core descriptions, natural-gamma activity, and interpretation of tritium data. For the bedrock (Galena-Platteville and sandstone) aquifers and confining unit represented in the model (fig. 23), the K_h of each unit was considered to be constant.

To estimate hydrologic properties of the bedrock aquifers and confining unit and each of the unique areas of the glacial drift aquifer, model-area zones were designated for model calibration. The zones and their abbreviated identifiers are presented in table 13 and figure 24.

Vertical leakances were used to represent vertical ground-water flow between hydrogeologic units. In MODFLOW, vertical leakance typically is treated as K_v divided by the half thicknesses of adjacent hydrogeologic units (McDonald and Harbaugh, 1988). However, because of the contrast in K_v between adjacent units in this flow model, leakance could be approximated by considering only the properties of the less-permeable unit. The initial leakance arrays were equal, in part, to the inverse of the half thickness of the less permeable unit; single values of K_v that multiplied these thickness arrays were estimated during model calibration using the optimization algorithm (table 13).

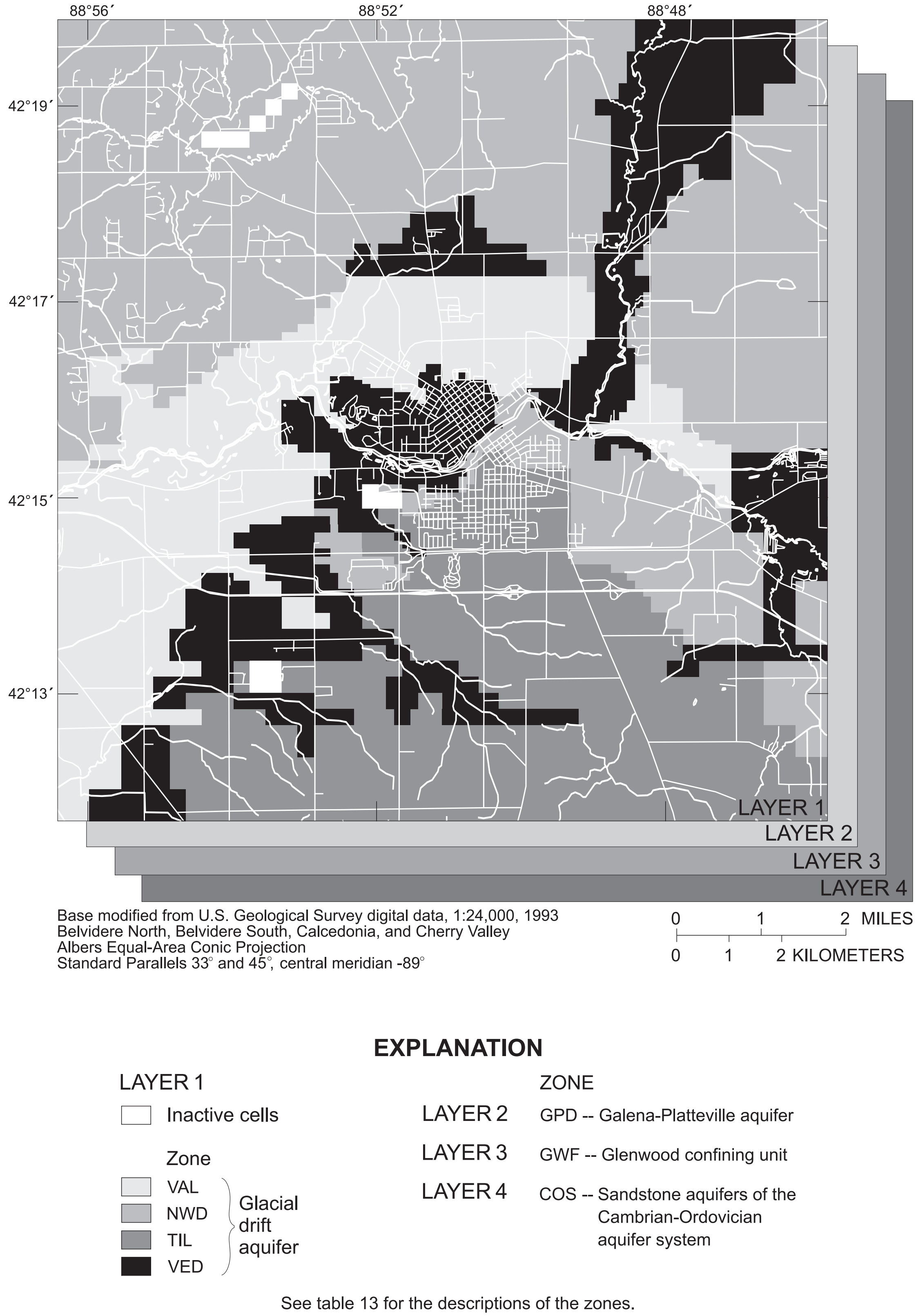


Figure 24. Hydraulically similar areas (zones) for the simulation of ground-water flow in the aquifers and confining unit underlying Belvidere, Illinois.

These values were assumed to be constant throughout each unit and area (zone) represented in the model. The values closely approximate K_v of the less-permeable units, because the contrast in K_v between units is great; flow between units is controlled primarily by the less-permeable units. Evaluation of this approach indicated that leakances essentially are the same, whether or not the properties of the more-permeable units are considered.

For estimates of K_v, an initial K_h:K_v ratio of 0:1 was assumed. K_v (VGPV and VGWF, respectively) was estimated where the (1) glacial drift aquifer overlies the Galena-Platteville aquifer (GPD), within (VAL) and outside (VED, TIL, NWD) the Troy Bedrock Valley, and (2) Glenwood confining unit (VGWF) is overlain by the Galena-Platteville aquifer and is underlain by the sandstone aquifers (COS).

K_v of the streambed of the Kishwaukee River and its tributaries initially was assumed to be 28 ft/d, an order of magnitude less than the initial estimate of K_h of outwash and alluvial sand-and-gravel deposits that compose part of the glacial drift aquifer and the streambed of most principal streams in the area (table 13). A K_h:K_v ratio of about 10:1 is typical of coarse-grained alluvium that usually contains some fine-grained sediments (Todd, 1980). Streambed conductance represents the connection between the stream and ground-water system and is calculated as the product of streambed area and the K_v of the streambed divided by the thickness of the streambed.

Starting water levels for all hydrogeologic units in the model were set above land surface. The model cells were allowed to drain to steady-state levels. Recharge was input as a constant, equally distributed rate to the glacial drift aquifer (model layer 1). Where cells are designated as inactive in this unit (figs. 14, 22), recharge was input to the uppermost active unit underlying these cells. This approach was necessary to suppress water levels in unsaturated areas of the glacial drift aquifer. On the basis of computations using streamflow records (Rutledge, 1993) and literature values for the region (Mills, 1993a; Cravens and others, 1990; Beaty, 1987), a recharge rate of 10 in/yr distributed evenly across the study area initially is assumed. Estimates of recharge using streamflow records were determined for the model-calibration period (1993), when precipitation rates were greater than 150 percent of average annual rates (D.W. Kolpin, U.S. Geological Survey, written commun., 1993), and for a period (1980-93) more representative of the long-term average recharge rate. The assumed recharge rate used in the model simulation approximates the mid-range estimate provided by the use of long-term streamflow records. The estimated rate for 1993 seemed unreasonably high, given the hydrogeologic characteristics of the study area and published recharge rates for similar settings in northern Illinois and northwestern Indiana (Mills, 1993a; Cravens and others, 1990; Beaty, 1987).

Ground-water withdrawals from the study area are included for seven Belvidere municipal wells BMW3-BMW9 (J.A. Grimes, Belvidere Water and Sewer Department, written commun., 1999), three private wells withdrawing more than 1,000,000 gal/yr (K.J. Hlinka, Illinois State Water Survey, written commun., 1995), and one quarry (D.H. Fischer, Rockford Sand and Gravel, Inc., oral commun., 1995) (table 9; figs. 1, 22). Municipal well BMW2 was not in use during the calibration period; BMW3 was used infrequently. Annual total withdrawals by the municipal wells were determined for the period August 1992–July 1993. Annual withdrawal rates for the private wells and quarry are not available for the calibration period; the rates used from other periods are assumed to be representative for the period. All but two of the wells (BMW8 and BMW9) were open to multiple aquifers. Withdrawals from residential wells are not included in the simulation, because total annual withdrawals are likely to be small relative to those by the included high-capacity wells and because much of the withdrawn water is returned locally to the ground-water system through surface discharge or subsurface septic systems.

For multiple-aquifer wells, the distribution of withdrawal rates by aquifer (and confining unit) was determined based on an iterative approach. Flows generated by the model were evaluated and used to manually update unit-specific withdrawal rates for the wells. Discharge to a well was apportioned from each cell that a well intersected based on the transmissivity of the hydrogeologic units that the well is open to and water-level differences between the cell and the well. Water-level differences were estimated with a Theim (1906) model. Initial estimates of the distribution of withdrawal rates in wells were based on relative transmissivities of the hydrogeologic units. In ground-water systems, distribution of flow is affected by the transmissivities of the units, water-level relations between units, and physical characteristics of the wells.

Model Calibration

Calibration of the model consisted of adjusting hydrologic-property values until the differences between simulated and measured ground-water levels and ground-water discharge to streams were minimized. The following number of wells in the given hydrogeologic units were used for model calibration: 89 wells in the glacial drift aquifer (model layer 1), 49 in the Galena-Platteville aquifer (model layer 2), 1 in the Glenwood confining unit (model layer 3), and 21 in the Cambrian-Ordovician aquifer (primarily open to model layer 4) (figs. 25A–25D). Water-level differences measured at five pairs of vertically nested wells also were used for calibration, as were measurement-based estimates of discharge to Piscasaw Creek, Beaver Creek (and its unnamed tributaries), and the collective network of streams in the Kishwaukee River Basin (where located within the model area) (fig. 1B). Steady-state calibration was done to represent ground-water levels in July 1993 and discharge to streams in September 1999. Discharge data from the study area were not available in 1993.

The optimization algorithm (Halford, 1992) used with model calibration allows estimated values of hydrologic properties to be weighted, constrained, or fixed on the basis of confidence in the data. Optimization methods require that the best model solution (set of estimated hydrologic-property values) be defined by an objective function that provides the basis for comparison between simulated and measured values (observations). In the algorithm used, model error is defined by a weighted, sum-of-squares (SS) objective function

$$SS = \sum_{i=1}^{nobs} (Osim - Owmeas), \tag{1}$$

where

nobs is the number of simulated and measured observations that are compared,

Osim is the simulated observation, and

Owmeas is the weighted measured observation.

The weight emphasizes more accurate measurements (with a maximum weight of 1) and allows for the use of multiple measurement types with different units.

Although the sum-of-squares error serves as the objective function, root-mean-square error (RMSE) is reported instead because RMSE is more directly comparable to actual values and serves as a composite of the average and the standard deviation of a set of simulated and measured observations. RMSE is related to the sum-of-squares error by

$$RMSE = \sqrt{SS / \sum_{i=1}^{nobs} w}, \tag{2}$$

where w is the weight factor for the measured observations.

The hydrologic properties selected for optimization of values included recharge (to the uppermost aquifer (glacial drift)) and K_h and K_v (thus, vertical leakance) of each hydrogeologic unit and area of the model (zone). Initial values of hydrologic properties were based on previously discussed sources of data and assumptions. Recharge rates and specified water levels along the western boundary of the sandstone aquifers (model layer 4, fig. 22) also were selected for optimization of values because of the uncertainty of initial estimates. During model calibration, K_v of streambeds and geometries of the hydrogeologic units (zones) were refined to accommodate new data or insights. K_h and K_v were the principal hydrologic properties adjusted during model calibration because they are a large source of error in flow models; values potentially vary up to seven orders of magnitude. Initial and calibrated values of recharge, K_h and K_v of the hydrogeologic units (zones) and K_v of streambeds are given in table 13.

Calibration results, including the differences in simulated and measured water levels and discharge, are summarized in figures 26A–26C. The differences between simulated and measured ground-water levels and simulated potentiometric surfaces in each aquifer and the confining unit (model layers 1–4) are shown in figures 25A–25D. The composite distribution of water-level differences by number of wells within the hydrogeologic units underlying Belvidere and vicinity is shown in figure 27. Overall model error (RMSE) resulting from calibration is given in table 13.

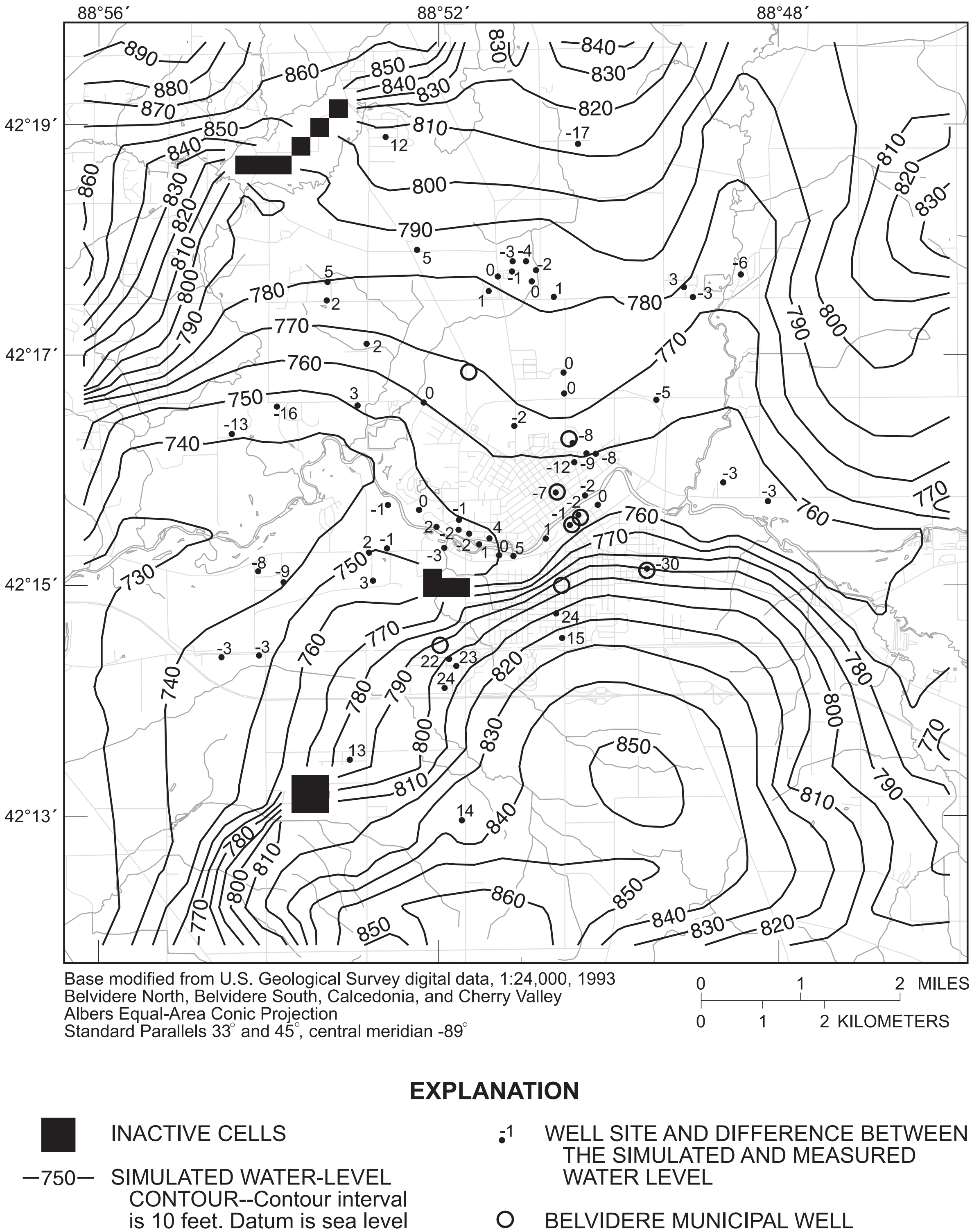
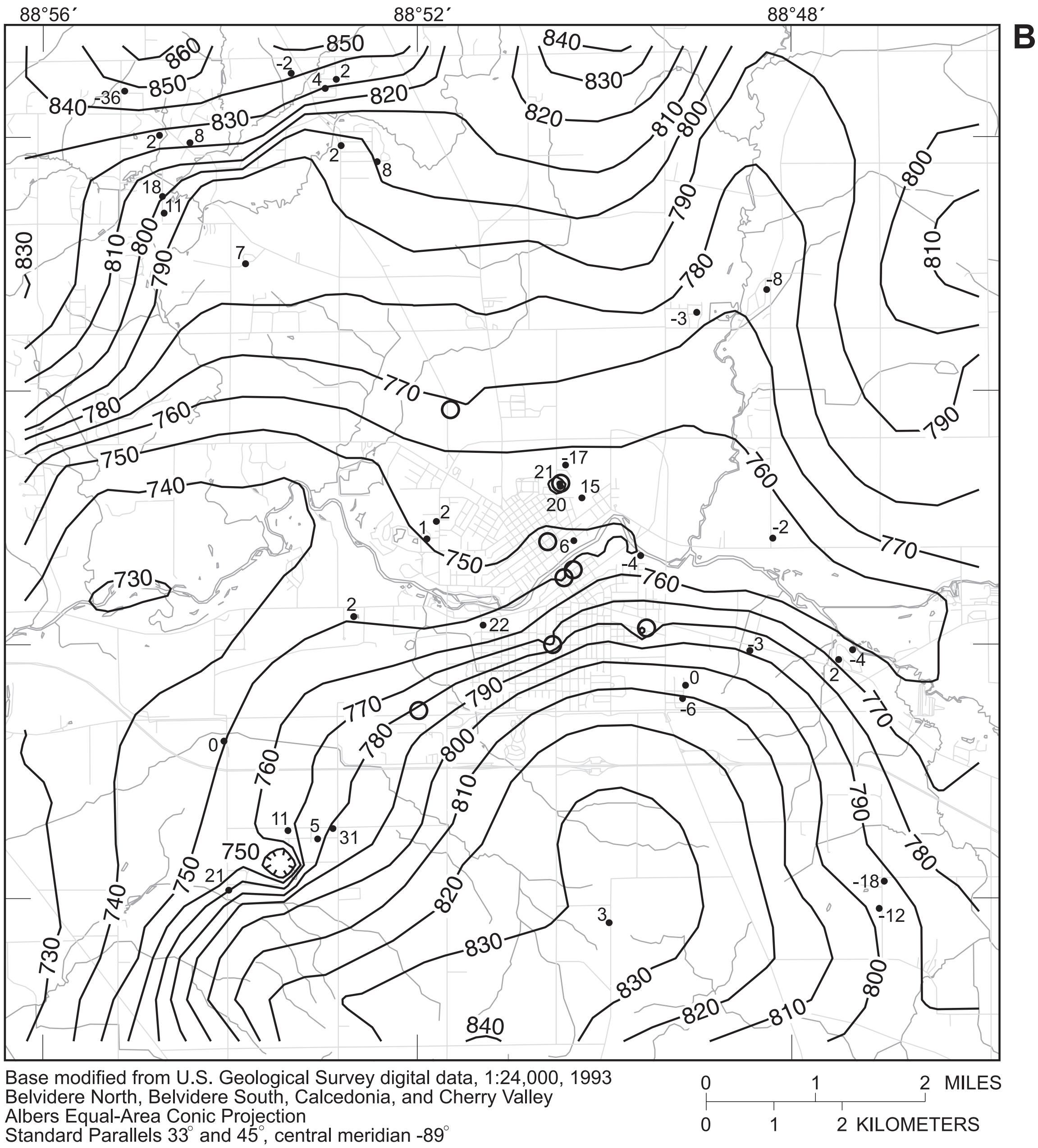


Figure 25. Simulated potentiometric surface and differences between simulated and measured water levels in the (A) glacial drift aquifer (model layer 1), (B) Galena-Platteville aquifer (model layer 2), (C) Glenwood confining unit (model layer 3), and (D) sandstone aquifers of the Cambrian-Ordovician aquifer system (model layer 4) underlying Belvidere, Illinois.



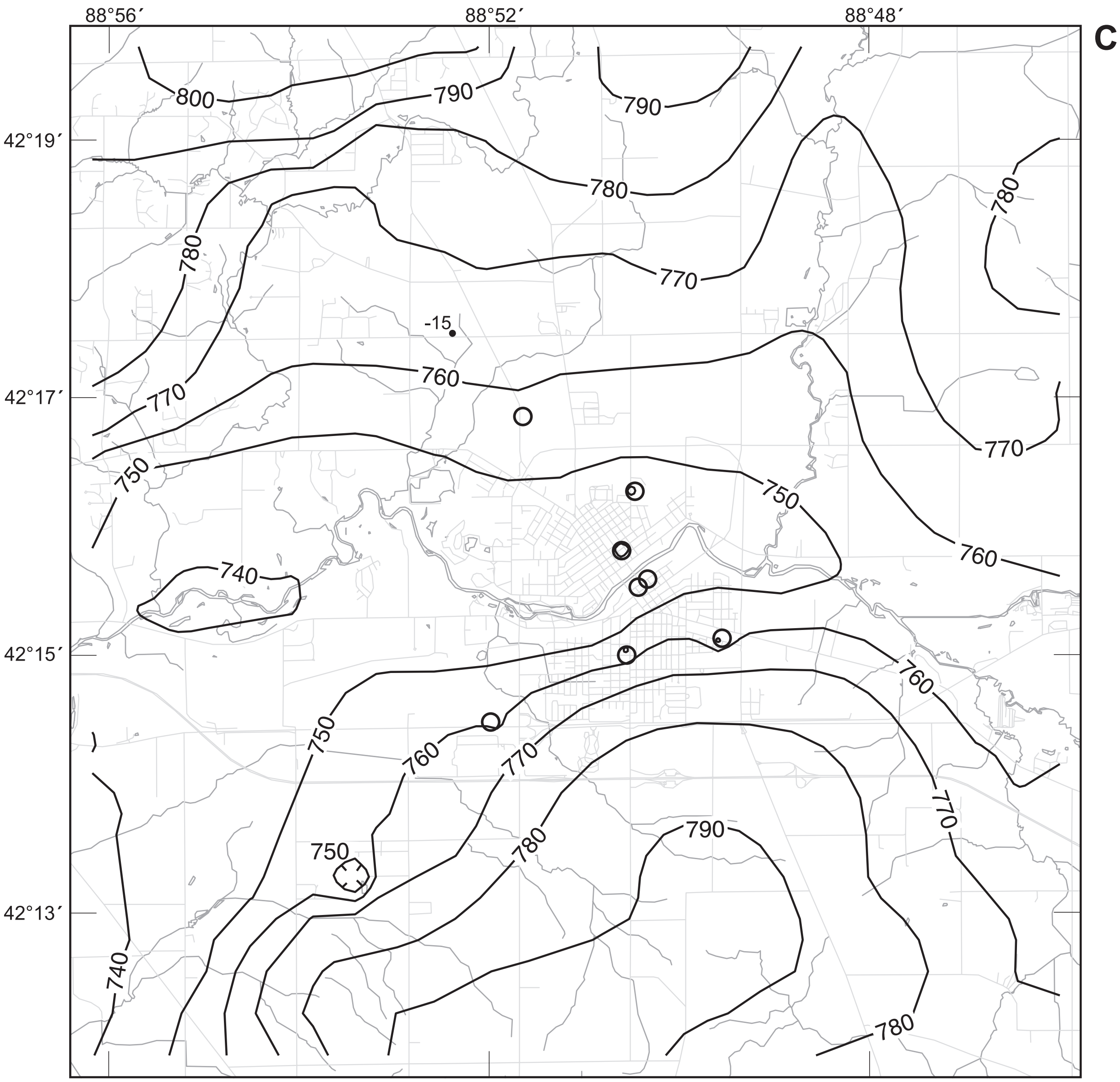
EXPLANATION

—750— SIMULATED WATER-LEVEL CONTOUR--Contour interval is 10 feet. Datum is sea level

•-2 WELL SITE AND DIFFERENCE BETWEEN THE SIMULATED AND MEASURED WATER LEVEL

○ BELVIDERE MUNICIPAL WELL

Figure 25. Simulated potentiometric surface and differences between simulated and measured water levels in the (A) glacial drift aquifer (model layer 1), (B) Galena-Platteville aquifer (model layer 2), (C) Glenwood confining unit (model layer 3), and (D) sandstone aquifers of the Cambrian-Ordovician aquifer system (model layer 4) underlying Belvidere, Illinois–Continued.



Base modified from U.S. Geological Survey digital data, 1:24,000, 1993
Belvidere North, Belvidere South, Calcedonia, and Cherry Valley
Albers Equal-Area Conic Projection
Standard Parallels 33° and 45°, central meridian -89°

0 1 2 MILES

0 1 2 KILOMETERS

EXPLANATION

—750— SIMULATED WATER-LEVEL CONTOUR--Contour interval is 10 feet. Datum is sea level

•-15 WELL SITE AND DIFFERENCE BETWEEN THE SIMULATED AND MEASURED WATER LEVEL

○ BELVIDERE MUNICIPAL WELL

Figure 25. Simulated potentiometric surface and differences between simulated and measured water levels in the (A) glacial drift aquifer (model layer 1), (B) Galena-Platteville aquifer (model layer 2), (C) Glenwood confining unit (model layer 3), and (D) sandstone aquifers of the Cambrian-Ordovician aquifer system (model layer 4) underlying Belvidere, Illinois–Continued.

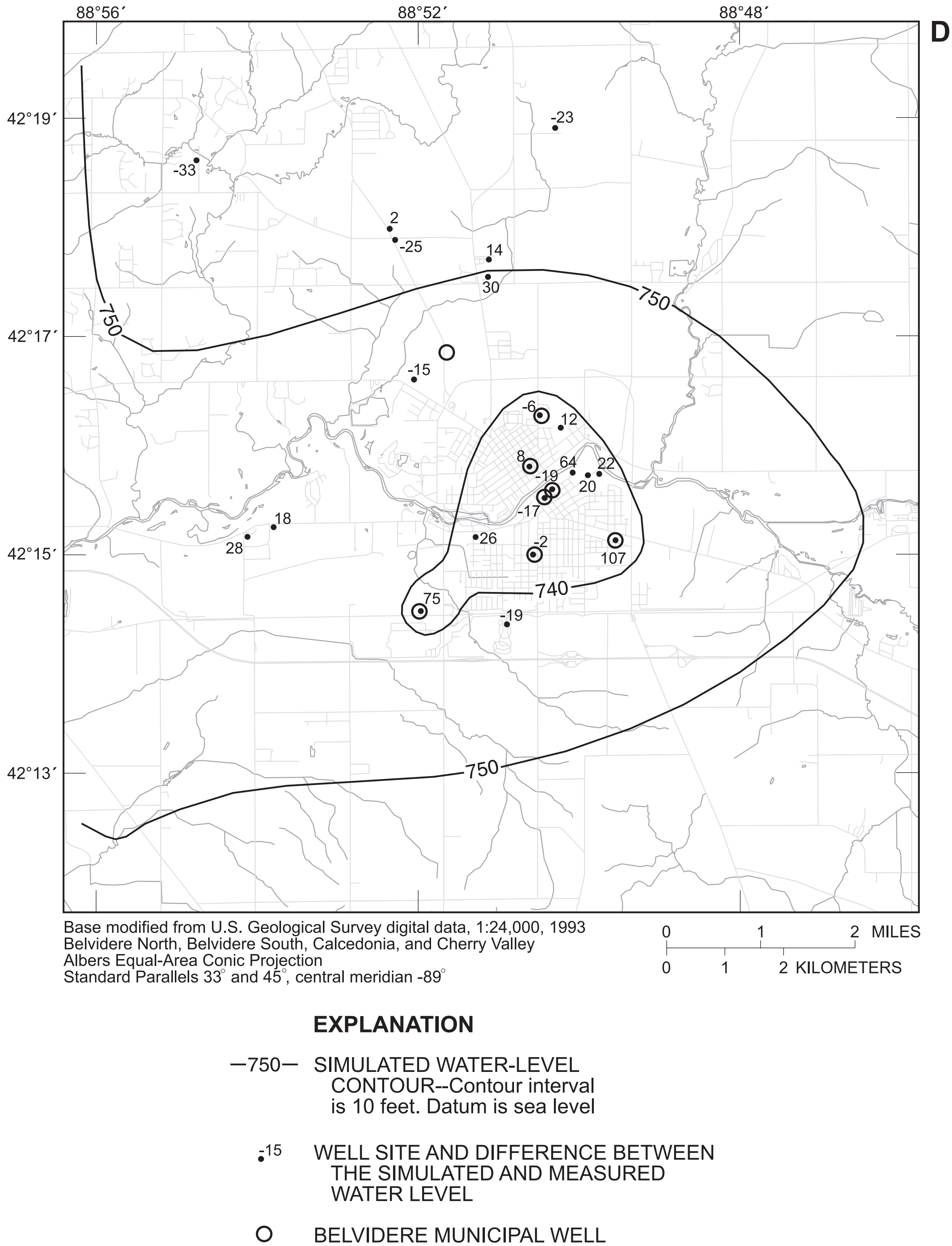
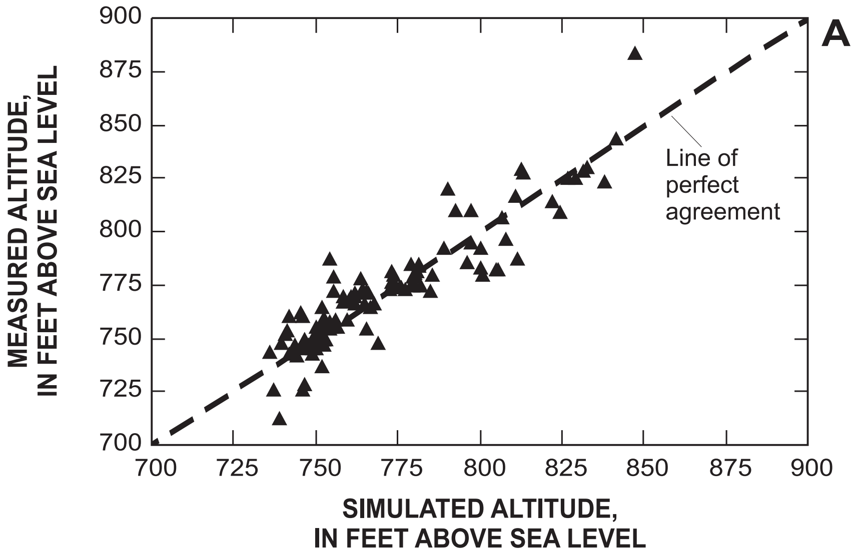
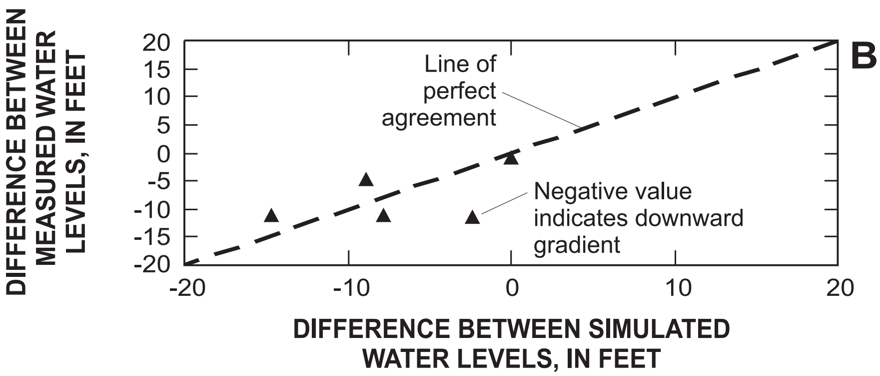


Figure 25. Simulated potentiometric surface and differences between simulated and measured water levels in the (A) glacial drift aquifer (model layer 1), (B) Galena-Platteville aquifer (model layer 2), (C) Glenwood confining unit (model layer 3), and (D) sandstone aquifers of the Cambrian-Ordovician aquifer system (model layer 4) underlying Belvidere, Illinois–Continued.





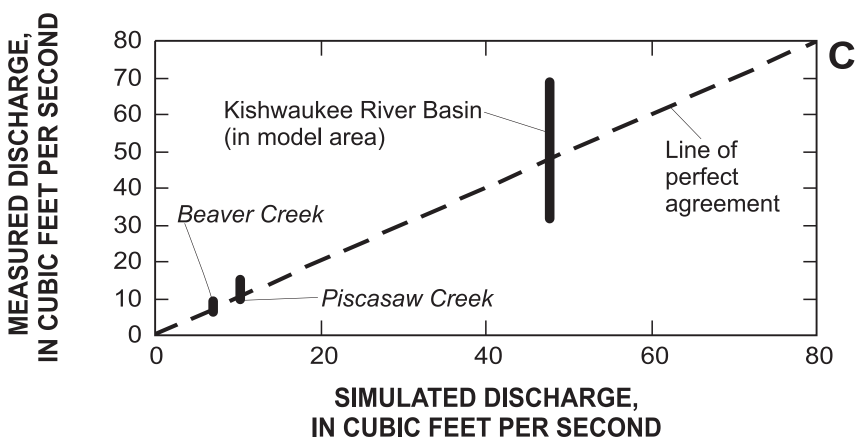


Figure 26. Calibration results for the simulation of ground-water flow in the aquifers and confining unit underlying Belvidere, Illinois: (A) simulated and measured water levels in selected wells, (B) difference between simulated and measured water levels in selected vertically nested wells, and (C) simulated and measured discharge to selected streams (bar represents possible range of streamflow measurement based on 5-percent measurement error).

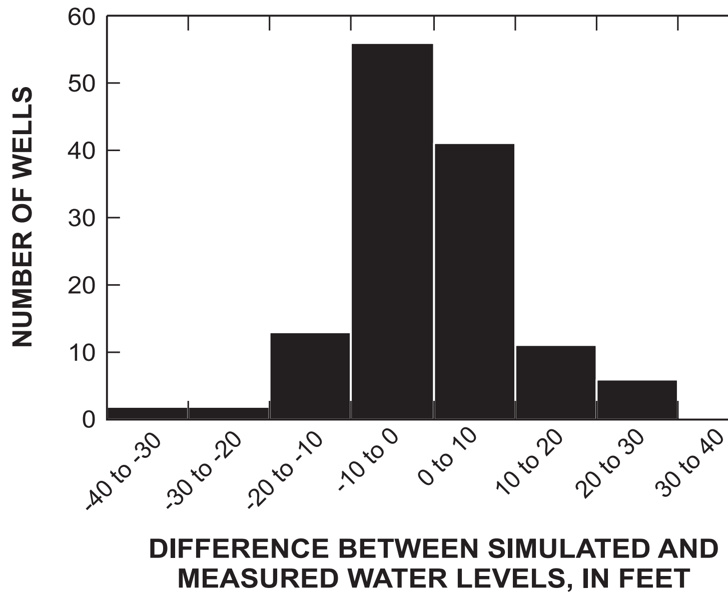


Figure 27. Difference between simulated and measured water levels in the aquifers and confining unit underlying Belvidere, Illinois.

About two-thirds of the simulated values are within 10 ft of measured values. Simulated values generally are within 6 ft in the glacial drift and Galena-Platteville aquifers (model layers 1 and 2, respectively), particularly in the central part of the study area (city of Belvidere). Water-level differences in these units are reasonable, given a measured range of water levels of about 150 ft across the study area. The differences between simulated and measured values are greatest near the boundaries of the study area and in the sandstone aquifers (model layer 4). The magnitude of differences in water levels is relative to the number of available water-level measurements and, in part, the extent to which water levels are affected by ground-water withdrawals at or near time of measurement. Steps were taken during measurements to ensure that wells where water levels were measured for calibration were not recently used, and, thus, water levels represented static to near-static conditions (Mills and others, 1999a). In many cases, particularly for wells open to the sandstone aquifers, measured water levels unavoidably were affected by periodic high volume-rate withdrawals from the measured wells and from nearby wells. Uncertainty regarding specified water levels along model boundaries also likely accounts for the increased difference between simulated and measured water levels near the boundaries.

Anomalous differences in simulated and measured water levels in the glacial drift aquifer are evident in an area that includes temporary well TW22 and wells at the Parson's Casket Hardware site (well PCHG111D, for example) (figs. 1A, 1B, 25A). Simulated water levels range from about 9 to 30 ft lower than measured levels. Review of drillers' logs for municipal well BMW7 (fig. 1B) and other nearby wells indicates a northward-trending buried tributary to the Troy Bedrock Valley extends through this area. Changes in the zone classification and geometry of the glacial drift aquifer in this area resulted in minimal change in the simulated water level. The zone classification was changed from coarse-grained, edge-of-valley deposits (VED) to till deposits (TIL). Initially, the geometry of the buried tributary was not well defined in the model, as based on maps of the bedrock surface (Berg and others, 1984). Geologic data from all wells within 2 mi to the east and south of the above-listed wells were used to better define the geometry of the tributary. Measured water levels in the area of temporary well TW22 may represent perched ground water or inaccurate representation of the transmissivity of the underlying bedrock aquifers in the vicinity of municipal well BMW7.

Agreement between simulated and measured differences in water levels in vertically nested wells is reasonable, given the available data. All wells in which water-level differences were considered are within 3,500 ft of one or more municipal well; water levels within all parts of the Galena-Platteville aquifer are affected differentially by municipal-well withdrawals (Mills and others, 1998). Thus, the measured water levels were not weighted heavily or relied upon substantially for model calibration.

Potentiometric surfaces of the glacial drift and Galena-Platteville aquifers, based on simulated and measured water levels, are in reasonable agreement, including the directions and gradients of ground-water flow (figs. 14, 25A, 25B) (Mills and others, 1999a; plates 1 and 2). Simulated water levels in the sandstone aquifers should be considered approximate, as should the potentiometric surface shown in figure 25D.

Simulated ground-water discharge and possible range in measured discharge (that results from consideration of error in measurement of streamflow) to the stream sections are given in table 10 and shown in figure 26C. Simulated discharges for the three stream sections are within the range of measured discharges. Calibration of the model is most affected and best represented by the Piscasaw and Beaver Creek measurements. The error associated with measured discharge for the Kishwaukee River Basin is large, because of the relatively large streamflow rate of the river and the possibility that all surface-water inputs to the river were not accounted for in the measurement. Additionally, the measured discharge of the Kishwaukee River Basin represents a larger area of flow derived from outside of the model area than that of the Piscasaw and Beaver Creek measurements. Because streamflow measurements, used to derive the measured discharges for calibration, were near the Q_{80} flow duration, the simulation slightly may underestimate average recharge.

Some hydrologic-property values estimated from model calibration noticeably are different than initial estimates of the values (table 13). Calibrated K_h of the sand-dominated Troy Bedrock Valley and alluvial valley deposits (KVAL) (figs. 12, 24) is one-half order of magnitude less than the initial estimate of K_h. K_h for the sand-and-gravel deposits may be lower than indicated by limited field data. Alternatively, the calibrated K_h may account for the hydraulic contribution of low-permeability, fine-grained deposits that are interbedded within the thick sand-and-gravel deposits in this part of the study area.

The calibrated K_h of the sand-dominated edge of the Troy Bedrock Valley (KVED) is one-half order of magnitude greater than the initial estimate of K_h. The sand-and-gravel deposits in this part of the study area may be more homogeneous and (or) coarse-grained than the deposits within the Troy Bedrock Valley.

The calibrated K_h of glacial deposits in the southern part of the study area (KTIL) is four orders of magnitude greater than the initial estimate (0.001 ft/d). Soil-survey and well-construction data (Berg and others, 1984; Brown and Mills, 1995) indicate that these deposits are predominantly till. Thus, a typical value of K_h (Freeze and Cherry, 1979) initially was specified. By specifying this value, model error and estimated hydrologic-property values of other hydrogeologic units were unreasonable and simulated water levels in the area were above land surface. K_h was estimated by optimization in subsequent simulations. The simulation indicates that some sand and gravel may be interbedded with the low-permeability till units. Alternatively, the K_h of the underlying dolomite deposits (KGPD) also may be elevated above normal levels locally.

The calibrated K_h of the dolomite deposits is one order magnitude less than the initial estimate of 0.5 ft/d. This seemingly valid estimate was based on extensive aquifer testing in the immediate vicinity of Belvidere (see “Hydraulic Properties”). The lower value of K_h estimated by simulation indicates that the K_h of the deposits may vary spatially throughout the study area. Values of K_h equal to or less than the simulated value have been recorded in some tested intervals (Mills and others, 1998). Conversely, values of K_h may be elevated locally, as in the southern part of the study area where unexpectedly high values of K_h were simulated for the till deposits. Variability in K_h could be related to variability in the distribution of hydraulically active features, such as fractures, bedding-plane partings, and matrix porosity.

The calibrated ratio of K_h:K_v for the connection of glacial drift and dolomite deposits in the area of the Troy Bedrock Valley (VGPV) is 50. Although similarly large K_h:K_v ratios have been calculated by others (Moench, 1994), the ratio may be somewhat inflated by the estimation method. As previously discussed, the singular estimate of K_v for adjacent units is represented primarily by the hydraulic characteristics of the less permeable unit. The relative contribution of the thick glacial-drift deposits relative to the thinner Galena-Platteville deposits in this part of the study area is unaccounted for in this estimation of K_v. Regardless of the accuracy of estimation, K_v is shown to be an insensitive model property (see “Sensitivity Analysis”). Thus, more realistic estimates of these values likely would not substantially improve the accuracy of the flow simulation.

Initially, a K_h:K_v ratio of 10:1 was assumed for all streambeds represented in the model. Simulation results support this assumption, but the calibrated K_v (2.5 ft/d) is lower than the initially estimated value (28 ft/d). Simulation results indicate that the K_v of the streambeds of Beaver Creek and its tributaries (0.025 ft/d) is considerably lower than that of the beds of other streams in the study area. These results seem reasonable, because Beaver Creek and its tributaries drain the till-rich uplands in the northwestern part of the study area and are consistent with the estimates of K_v of similar streambeds in northern Indiana (Bayless and Arihood, 1996).

Three notable evaluations of model design were made during calibration: (1) Recharge initially was input to two regions of the model area. One region included zones VAL and VED (fig. 24; table 13), that consist of sand-dominated areas where relatively high recharge rates are expected. A second region included zones NWD and TIL (fig. 24; table 13), that consists of till-rich areas where relatively low recharge rates are expected. In early model runs, optimized estimates of recharge for these regions were similar, possibly because the range in K_h of the two regions was more similar than expected, as indicated by the simulated results (table 13). On the basis of this evaluation, a single, areal rate of recharge was input in subsequent simulations. (2) The reasonableness of the specified water levels (constant head) along the western boundary of the sandstone aquifers (model layer 4) were evaluated. Because of uncertainty associated with water-level altitudes in this area and the configuration of the potentiometric surface, the specified water levels were estimated by optimization. Initially, specified water levels represented greater drawdown in the central part of the boundary than to the northern and southern parts, in response to withdrawals in nearby Rockford and Belvidere. Ultimately, input was simplified by specifying a uniform water level along the boundary. The model was shown to be insensitive to variation in the water-level altitudes and configuration of the potentiometric surface along the boundary (see “Sensitivity Analysis”). (3) To evaluate the possible absence of the Glenwood confining unit in parts of the Troy Bedrock Valley (fig. 4), the thickness of the unit was specified in the model as 1 ft in areas where the thickness of the overlying Galena-Platteville aquifer was specified as 1 ft. This alternative simulation indicated an increase of inflow of about 20 percent into the sandstone aquifers. However, the resulting model error and estimated values of the hydrologic properties were similar to those of the calibrated model (within about 1 ft and 10 percent, respectively), as were the simulated water levels. Thus, the results provided little additional insight as to the geometry of the Glenwood confining unit within the deepest parts of the Troy Bedrock Valley.

The simulated quantities of flow for each component of the ground-water system in 1993 are given in table 14. Quantities of flow through six subsections of the ground-water system are given in figure 28. Represented in the subsections are the areas of the glacial drift and Galena-Platteville aquifers within and outside the Troy Bedrock Valley, the Glenwood confining unit, and the sandstone aquifers. The flows provide information about sources, discharge areas, and flow paths for ground water and the general availability of ground water.

Table 14. Simulated water budget for the aquifers and confining unit underlying Belvidere, Illinois, 1993

[Mgal/d, million gallons per day]

Budget component	Flow relative to the ground-water system	
	Inflow (Mgal/d)	Outflow (Mgal/d)
Recharge from precipitation	28.81	0.0
Stream discharge/leakage	2.15	33.06
Withdrawals by wells	.0	2.98
Flow through boundaries with specified water levels	10.64	5.56
Total flow	41.60	41.60

About 69 percent of the inflow to the ground-water system is from precipitation and 26 percent is through the model boundaries (table 14). The relative percentage of inflow from perimeter boundaries is large because the model area does not extend to natural flow boundaries; most of the inflow (about 97 percent) is through boundary cells in areas of glacial drift with specified water levels. Water levels in these cells were approximated from surface topography and stream-surface levels given on USGS 1:24,000-scale topographic maps. As such, the specified water levels may not accurately depict the water table and directions of flow into and out of these boundaries.

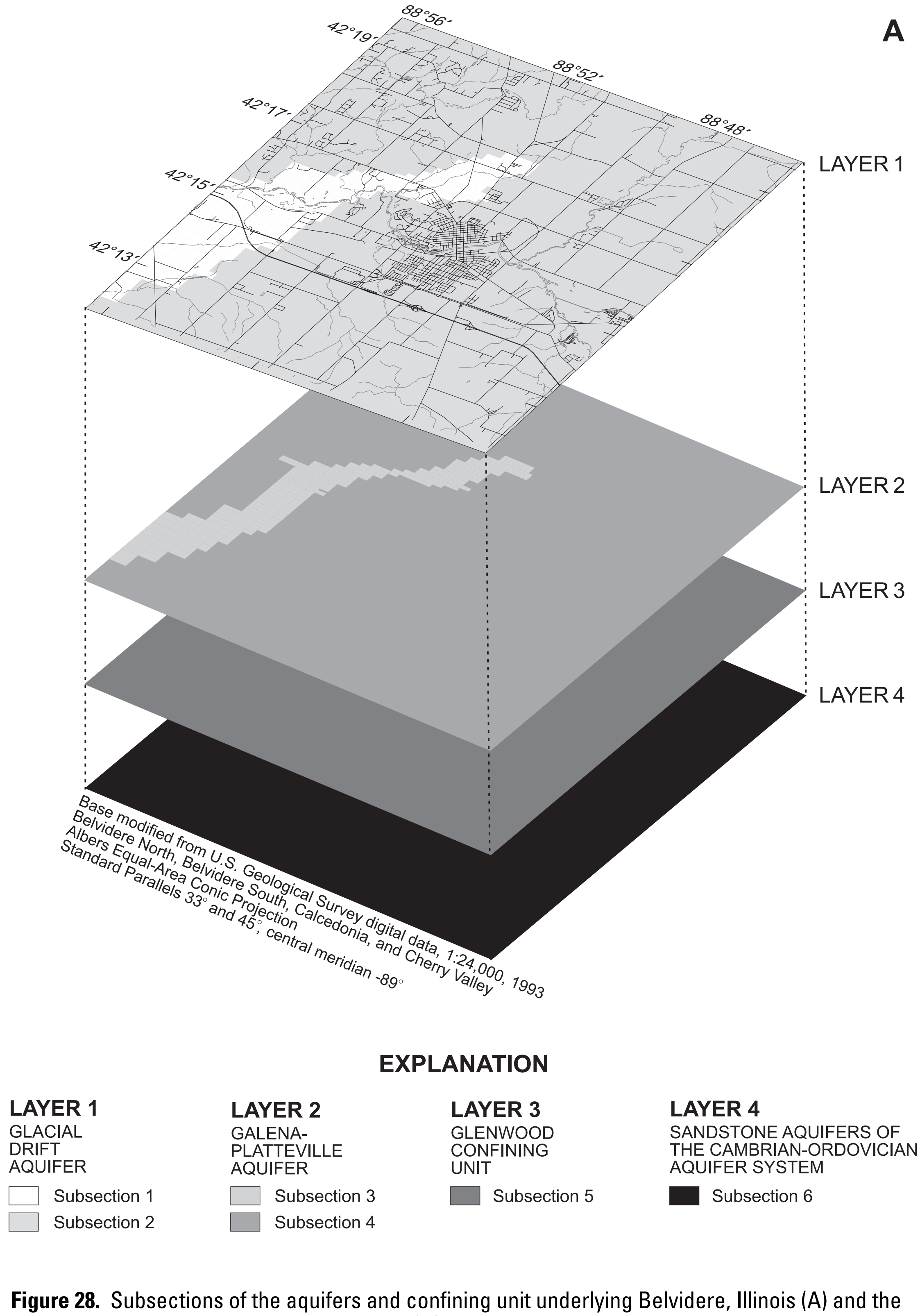


Figure 28. Subsections of the aquifers and confining unit underlying Belvidere, Illinois (A) and the simulated water budget for the subsections (B).

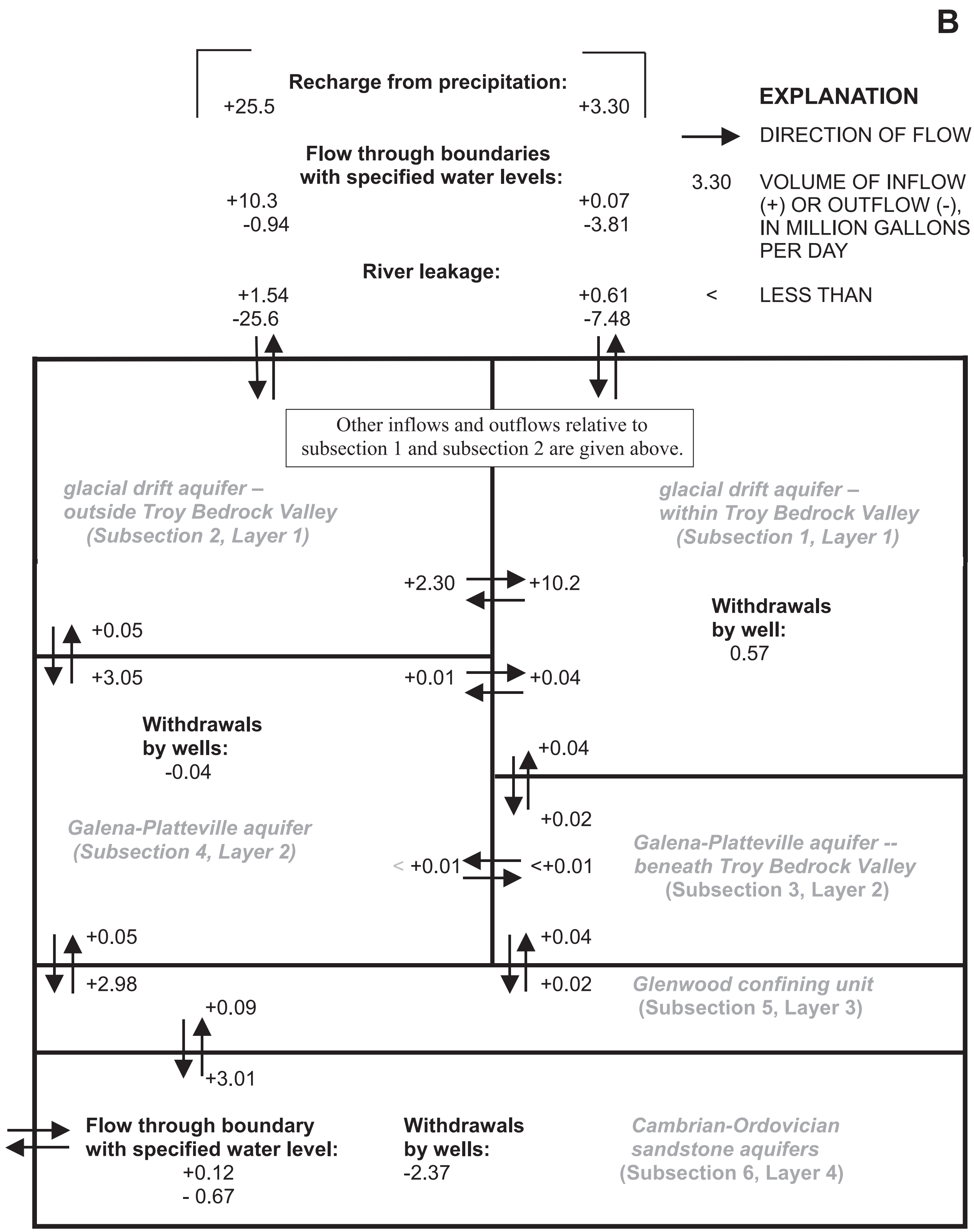


Figure 28. Subsections of the aquifers and confining unit underlying Belvidere, Illinois (A) and the simulated water budget for the subsections (B)–Continued.

Stream leakage into the glacial drift aquifer accounts for about 5 percent of the inflow. Although streamflow measurements indicate an overall increase in streamflow from ground-water discharge along measured stream sections, simulation results indicate local loss of streamflow. Sections where there may be streamflow loss are shown in figure 29. Loss is indicated in 7 percent of the 408 river cells (about 10 percent of the area represented by the cells). In about 90 percent of the cells where loss is indicated, the difference in water level in the stream and underlying glacial drift aquifer is about 1 ft or less. The difference in only two cells is greater (less than 8 ft); these cells are adjacent to the model boundary and in the Beaver Creek Basin, where stream gradients are relatively high. The loss of streamflow may be a result of inaccuracies in estimating and discretizing stream-related altitudes and streambed conductance and (or) simulating ground-water levels.

About 80 percent of the outflow from the ground-water system is by discharge to the streams, 13 percent is through the model boundaries, and 7 percent is by well withdrawals (primarily 6 Belvidere municipal wells) (table 14). About 85 percent of the outflow is through the boundaries of the glacial drift aquifer (model layer 1), where water levels are specified. The typical percentage of outflow by well withdrawals is expected to be greater than that estimated from the 1993 simulation. Although assumed to be a minor contribution to the budget (see “Recharge and Ground-water Withdrawals”), withdrawals from low-capacity wells (primarily residential wells) were not considered in the simulation. Additionally, before and after 1993, Belvidere municipal wells were pumped more regularly, and with expected increases in the population of Belvidere and adjacent areas, the percentage of outflow by well withdrawals is expected to increase.

As indicated by the simulation results illustrated in figure 28, about 77 percent of shallow ground-water discharge to streams occurs in parts of the study area outside the Troy Bedrock Valley. Only a few stream sections overlie the most transmissive areas of the Troy Bedrock Valley (fig. 28A). These areas, where sand-and-gravel deposits predominate and the Galena-Platteville aquifer is less than 100 ft thick, are important discharge areas for flow in the glacial drift aquifer; about 85 percent of available ground water (water not lost to streams or boundaries) outside the valley flows into the valley. Only a small fraction of recharge from precipitation, about 10 percent or 0.95 in/yr, seems to flow to the sandstone aquifers (St. Peter and deeper aquifers). Even in the deepest part of the Troy Bedrock Valley, where the Galena-Platteville aquifer seems to be absent (assumed to be 1 ft thick in the model), the approximately 30-ft thick, low-permeability Glenwood confining unit seems to strongly restrict flow between the overlying glacial drift aquifer and the underlying sandstone aquifers.

The contribution of the fractures and bedding-plane partings to flow within the Galena-Platteville aquifer was not evaluated with the model. The individual contribution of fractures is expected to be relatively small to the overall water budget. These secondary-porosity features have been shown to provide preferential pathways for rapid movement of water and contaminants within the aquifer.

Sensitivity Analysis

Sensitivity analysis was done to determine the relative effect of changes in values of hydrologic properties represented in the ground-water model on model error (RMSE). The sensitivity of individual properties can be used (1) as a measure of reasonableness of estimating a value, (2) as a guide for which values should be estimated, and (3) to evaluate the confidence that one has in calibrated model values that are expected to characterize the ground-water-flow system. Properties that substantially affect model error require accurate values for simulation results to be considered reliable. For hydrologic properties that are insensitive, the appropriateness of a calibrated value with respect to a value of the physical counterpart of the ground-water-flow system is difficult to assess.

The sensitivity of an area of a model can indicate where and what types of new data are most useful to characterizing an aquifer, including where to avoid unnecessary use of resources. For example, an extensive aquifer test may not provide useful results in the vicinity of well TW22, where the difference in simulated and measured water level was 32 ft. Other more easily obtained data to confirm the validity of either water level may be more appropriate; these data might include additional periodic and continuous water-level measurements and geophysical surveys.

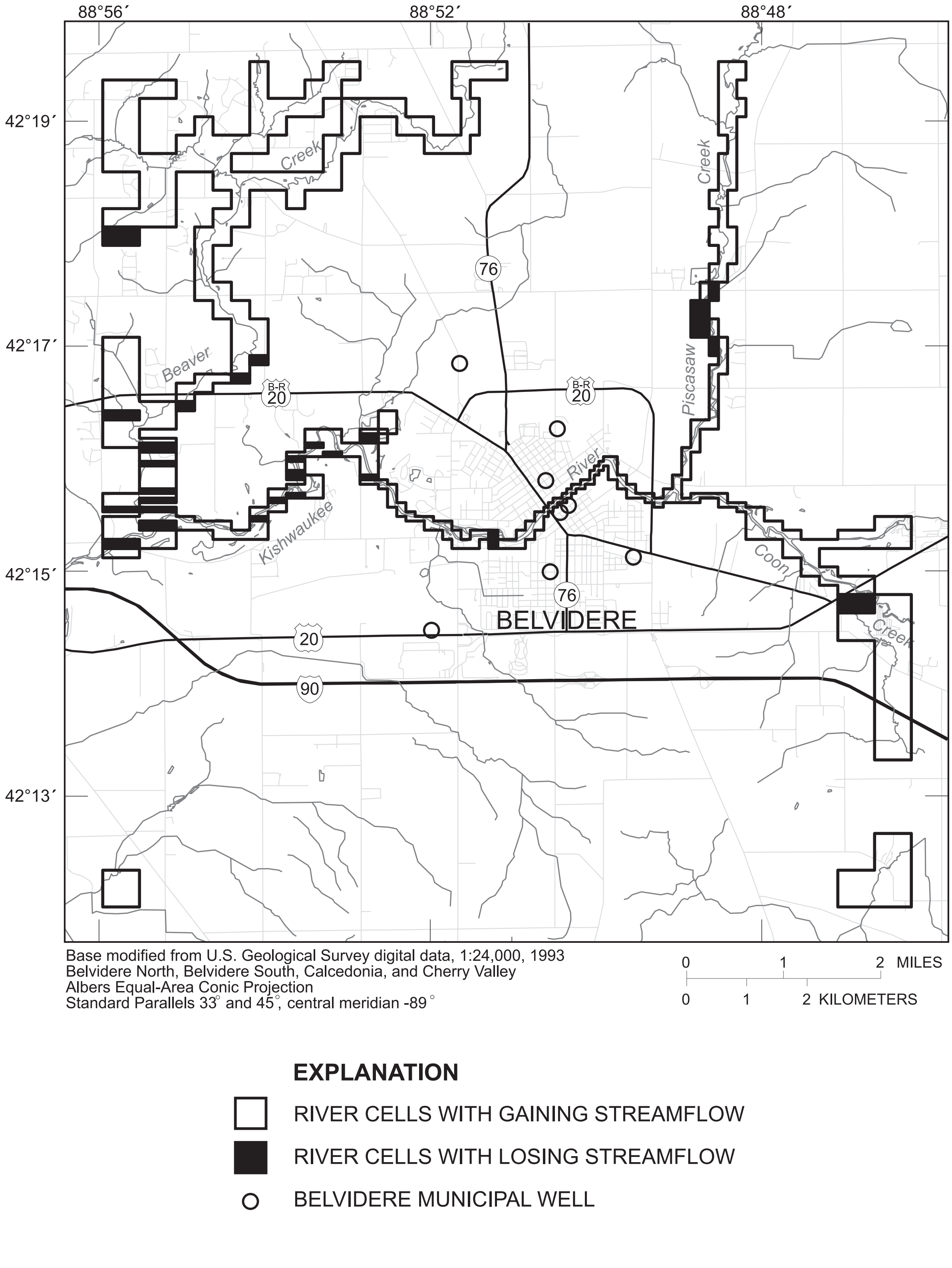


Figure 29. Simulated stream sections in the vicinity of Belvidere, Illinois, where streamflow is gained from and lost to the ground-water-flow system.

Sensitivity analysis was performed by incrementally changing calibrated values of each selected hydrologic property; values of all other hydrologic properties were held constant. Properties examined were the same as those changed during model calibration (table 13). All but one of the properties were changed from 0.2 to 5 times the calibrated value. The specified water level of the sandstone aquifers (St. Peter, Ironton-Galesville, Elmhurst-Mt. Simon; model layer 4) was changed from 50 ft below to 50 ft above the calibrated value of 750 ft to reasonably account for the expected range of error. Model sensitivity was determined by observing changes in model error of the resulting simulations (fig. 30).

This analysis indicates the most sensitive hydrologic properties are recharge (RCH) and K_h of the sand-dominated valley edge of the glacial drift aquifer (KVED). Accurate values for these properties are most important for reliable simulation of ground-water flow. Values for these properties generally are not well determined, particularly at the study-area scale. Additional measurement and mapping of the distribution of these properties and refinements in how they are delineated spatially in the model should improve the reliability of the flow simulation.

The following explanations are offered to account for the asymmetrical sensitivity patterns for recharge and K_h of the sand-dominated valley edge of the glacial drift aquifer (fig. 30). Recharge greater than the calibrated value of 8.4 in/yr seems to increasingly exceed the capacity of the simulated flow system to distribute the recharge water among the hydrogeologic units, streams, and boundaries. Recharge less than about 0.4 times the calibrated value (about 3.4 in/yr) seems to reach a threshold at which an insufficient supply of water is available to maintain stream discharge, water levels in thin parts of the glacial drift aquifer, recharge to the deep aquifers, and withdrawal requirements of the high-capacity wells. The sharp increase in error may occur when model cells begin to dewater rapidly. For the sand-dominated valley-edge deposits of the glacial drift aquifer, values of K_h greater than about 3.5 times the calibrated value (about 875 ft/d) may allow unreasonably high flow to the streams, other parts of the glacial drift aquifer, and (or) the Galena-Platteville aquifer. The relatively low K_v of streambeds and K_h and (or) K_v of adjacent units may restrict the inflow of water.

Other properties generally were insensitive, including the K_v of the glacial drift/ Galena-Platteville aquifers in the area of the Troy Bedrock Valley (VGPV) and K_h of the Galena-Platteville aquifer (KGPD) and Glenwood confining unit (KGWF). Thus, assimilating data from additional measurements and mapping of the distribution of these properties may not improve the reliability of the flow simulation. Assuming that calibrated values of the most sensitive hydrologic properties approximate actual values (are within about 0.5 to 2 times the calibrated values), the simulation results reasonably represent the regional ground-water-flow system underlying Belvidere.

Model and Data Limitations

Simulated ground-water levels, discharge to streams, hydrologic properties, and water budgets are presented in this report. Simulated values often are similar to, but do not precisely match measured values. A ground-water-flow model only can be a numerical approximation of a flow system, particularly a complex system. Furthermore, a model is a non-unique approximation of the flow system because any number of reasonable variations in the hydrologic properties represented in the model may produce equally acceptable results. Assumptions and simplifications are required in the design of a model and must be considered when interpreting simulation results.

The flow system in the vicinity of Belvidere is complex. The processes of glacial and alluvial deposition and the erosion, dissolution, and fracturing of the uppermost bedrock aquifer have resulted in substantial spatial variability in the hydrologic properties of the hydrogeologic units. Parts of the regional Glenwood confining unit also may be absent, allowing direct hydraulic connection between the glacial drift and deep bedrock aquifers. This complexity introduces challenges to simulation of the flow system.

The results of a ground-water-flow model are limited by the accuracy of the (1) input data; (2) fundamental equations that describe ground-water flow through a continuous, porous media; (3) finite-difference approximations of flow equations; and (4) simplifying assumptions concerning the spatial and temporal distribution of data. Also inherent with such models, is the insensitivity to changes in hydrologic properties over small areas. For example, a reduction in withdrawal rates at one well has limited effect on overall simulation results. The reliability of models should be considered relative to the simulation objectives; for example, whether the scale of interest in local or regional.

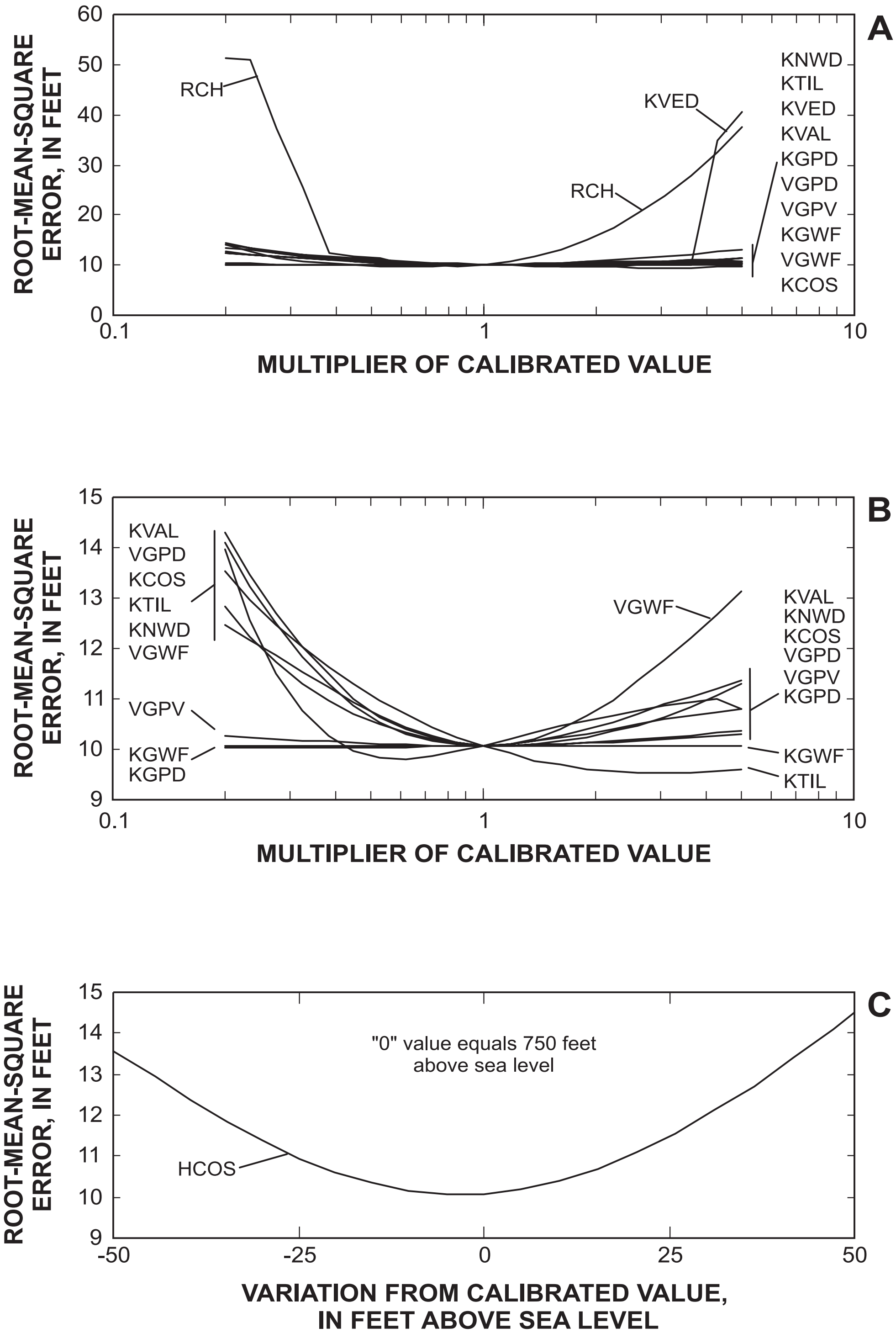


Figure 30. Relation between root-mean-square error and variation in hydrologic-property values for the simulation of ground-water flow in the aquifers and confining unit underlying Belvidere, Illinois: (A) all properties, (B) selected properties, in detail, and (C) specified water level in the sandstone aquifers of the Cambrian-Ordovician aquifer system (model layer 4) along the western boundary of ground-water-flow model (property abbreviations defined in table 13).

For this model, values for some hydrologic properties were taken from measurements or estimates provided or published by others. Possible inaccuracies in the measurements and estimates and the limited spatial distribution of some values may, to some degree, limit the simulated representation of the flow system.

Some hydrogeologic data useful to simulation of ground-water flow in the study area are unavailable, including areal recharge and horizontally and vertically distributed water and hydraulic-conductivity values (most notably from the Glenwood confining unit and sandstone aquifers). The general lack of information on water levels in the sandstone aquifers, particularly in relation to (1) boundaries of the study area and (2) differences between individual sandstone aquifers (St. Peter, Ironton-Galesville, and Elmhurst-Mt. Simon), possibly account for the largest source of model error. Substantial withdrawals in these deep, highly transmissive aquifers seem to affect much of the regional flow system.

The reliability of ground-water-flow models is affected by the choice and accurate representation of boundary conditions. Simulated water levels near model boundaries may be less reliable than simulated water levels that are distant from boundaries. Boundary effects are most notable when there are nearby stresses, such as those imposed by high-capacity wells. Perimeter boundaries of this model were located as far as feasible from such supply wells in and near Belvidere (primarily Belvidere municipal wells and Rockford municipal and industrial wells). Interactions of wells and boundaries were not investigated specifically, but preliminary flowpath analysis (Pollock, 1989) indicates that the boundaries affect simulation of flow induced by substantial ground-water withdrawals by municipal wells from the Cambrian-Ordovician aquifer (primarily the sandstone aquifers).

About 50 percent of the water levels used for calibration were measured in water-supply wells that possibly were affected by recent or nearby withdrawals. For the sandstone aquifers, about 50 percent of the water levels available for calibration were from wells designated in the model as a withdrawal stress on the flow system. These water levels possibly were affected by recent or nearby withdrawals, or well loss, and (or) other factors that do not allow adequate characterization of the water levels in the aquifers. Withdrawal data for the Belvidere municipal wells and other high-capacity wells are available. However, most of these data are total withdrawals from wells open to multiple aquifers (and model layers). Some error is associated with estimating withdrawals distributed among aquifers.

Substantial data, including vertical distribution of K_h and water levels, were available from the glacial drift and Galena-Platteville aquifers underlying the central part of the model area for characterization of the properties of these and all other units. Such data generally were not available for all hydrogeologic units outside the central part of the model area, including the vicinity of the Troy Bedrock Valley.

Outside the Troy Bedrock Valley, the Glenwood confining unit was assumed to be continuous and the hydrologic properties of the unit to be uniform. Absence of the unit within the Troy Bedrock Valley could contribute to substantially different flow patterns than were simulated between the glacial drift aquifer and the lower part of the sandstone aquifers (model layer 4). Additional information regarding the extent and thickness of the Glenwood confining unit in and near the Troy Bedrock Valley is needed for more reliable simulation and better characterization of the hydraulic relation between aquifers in this area. Such characterization could have substantial utility in protection of the quality and future ground-water development in the vicinity of Belvidere.

The altitude of the base of the glacial drift aquifer and top of the Galena-Platteville aquifer primarily was determined from a contoured bedrock-surface-topography map prepared by Berg and others (1984). Mapped contour intervals were 50 ft. The accuracy of the mapped altitudes were checked against known data from selected wells. Where appropriate, data obtained since the bedrock-surface map was prepared were used to update the surface configuration. Average altitudes within each model cell were determined using GIS tools (Environmental Systems Research Institute, Inc., 1991). The general approximation of the geometry of the glacial drift and Galena-Platteville aquifers likely introduces some unquantified error in simulation results. Simulation results may improve by accurately remapping the surface configuration of the Galena-Platteville aquifer. Recently (1998-2001), hundreds of additional wells have been drilled in this rapidly developing area.

Steady-state simulation of ground-water flow is assumed to represent average, long-term conditions. Ideally, temporally related data included in a model, such as recharge, withdrawal, and water-level data, are collected during and representative of the same average time period. In reality, these data only can approximate average conditions. The data often are collected and (or) compiled from different time periods. For example, annualized withdrawal rates are determined from periodically used wells with substantial variability in usage; recharge rates are based on delayed-response processes (discharge to streams); and water levels, used for calibration and correlated with annualized recharge and withdrawal rates, are from a single (synoptic) measurement.

For this simulation, ground-water levels used for calibration targets were collected in July 1993. June was an unusually wet month, with the precipitation rate exceeding the long-term (1961–90) average by about 10 in. Water levels measured in July may not represent average water levels during 1993 or longer-term average levels. In June 1994, water levels in three wells open to the glacial drift aquifer and within 0.5 mi of the Kishwaukee River were from 3.0 to 4.5 ft lower than levels in July 1993. The water levels in June 1994 seem to be more representative of average levels for summer months and annual averages than those of July 1993 (shown, in part, in figure 18A).

Ground-water discharge to streams used for calibration targets was measured in September 1999. To evaluate possible differences in the shallow ground-water systems contributing to stream discharge during the periods when ground-water levels (1993) and stream discharge (1999) were measured for model calibration, water levels were measured in selected wells (appendix 1) and gradients were determined between the wells and the Kishwaukee River. The wells were open to the glacial drift aquifer and were located within 300 to 1,500 ft of the Kishwaukee River. Water levels in the wells were 2.20 to 3.85 ft lower in 1999 than in 1993. This difference indicates discharge measured during the low-flow period of 1999 may have been less than discharge that would have been measured in 1993. In this case, for model calibration, simulated discharge on the upper end of the measured range may best represent discharge conditions in 1993. Discharge to streams during both periods, however, seemed to be relatively constant; the relative percent difference in discharge (U.S. Environmental Protection Agency, 1989) between the two periods averaged less than 10 percent. Along with the elevation of ground-water levels in 1993, there was a proportionally similar elevation in stream stage (Mills and others, 1999a). Thus, although use of discharge targets for 1999 may under-represent such conditions in 1993, the error does not seem to unreasonably affect the reliability of the steady-state simulation.

Withdrawal data from periods other than the calibration period (1993) were included for three wells. These data were from 1986 and 1994 and are assumed to represent average annual withdrawals. Withdrawal rates for the municipal wells vary daily to yearly because of demand and maintenance requirements. During the calibration period, there was limited use of wells BMW2 and BMW3. Well BMW2, with an average annual (1989–93) withdrawal of 0.045 Mgal/d, was not used. Well BMW3, with an average annual withdrawal of 0.034 Mgal/d, was used sparingly (0.004 Mgal/d). Following the calibration period (beginning in 1996), withdrawals from wells BMW2 and BMW3 each increased to about 0.1 Mgal/d. During the calibration period, withdrawals from all wells in the vicinity of Belvidere were about 15 percent lower than the average annual (1989–93) withdrawal rate. During the study period, ground-water withdrawals increased in the Rockford and Belvidere areas and decreased in the Chicago area, affecting water levels and fluxes in the ground-water-flow system.

Although the model discretization for Belvidere and vicinity was finer than that of many regional models that may represent thousands of square miles, the model was designed to simulate the regional flow system. For this purpose, and because a numerical model is a simplified representation of a flow system, the input variables were averaged over many model cells and various hydrogeologic units were assigned uniform hydrologic-property values. As such, the model cannot be expected to account for the heterogeneity of the hydrogeologic units and resulting preferential flow. For example, flow associated with fractures, such as the 260-ft bedding plane cannot be accurately simulated, particularly at a local scale. In the Troy Bedrock Valley, estimated K_h is assumed to represent homogeneous and isotropic deposits of sand and gravel. In actuality, the K_h is a bulk value that represents the thick deposits of sand and gravel and interbedded deposits of glacial till.

Generally, accuracy of a numerical model based on the finite-difference method improves as cell size decreases and the number of layers increases; with additional data, property values and hydrogeologic geometry included in the model can more closely represent actual flow conditions. In most cases, however, the necessary detailed information are unavailable.

Given the spatial limitations associated with model discretization and the related assumptions regarding homogeneity and isotropy, the most appropriate application of simulation results is to areas greater than the dimensions of a single model cell (a minimum of 62,500 ft^2). Additionally, results are most reliable for the shallow glacial drift and Galena-Platteville aquifers in the central part of the study area because (1) most data for delineation of the aquifers and their properties and calibration are from this area, (2) the Kishwaukee River is a permanent and well-suited boundary, and (3) the area is furthest from possible model-boundary effects.

In consideration of possible design and data limitations, this initial numerical model of the ground-water-flow system underlying Belvidere and vicinity is considered a preliminary evaluation tool. The model reasonably satisfies the objectives of the study, including verification of the conceptual model of the regional flow system, estimation of the water budget, and identification of parts of the study area where the collection of additional hydrogeologic data may be necessary. Additionally, the model is considered to be appropriate for preliminary evaluation of alternative ground-water-management strategies and delineation of flow paths and areas contributing recharge to supply wells.

Uncertainties in the simulations possibly could be reduced (with closer agreement of simulated and measured water levels and discharge and more accurate estimation of hydrologic properties in various parts of the ground-water system) by inclusion of additional water-level, hydrologic-property, and geologic-framework data and finer discretization of the model area. Such data could be obtained from more detailed field studies, including long-term aquifer tests, geophysical logging, water-quality sampling, and tracer tests. Such refinements to the model also may allow better characterization of the contribution of preferential flowpaths to contaminant transport in the aquifers and delineation of the areas contributing recharge to water-supply wells.

In summary, potential users of this and other numerical ground-water-flow models should be aware of model limitations. However, the significance of the limitations will depend on the information required from model simulation.

SUMMARY

VOC’s have been detected in samples from municipal and private water-supply wells open to the glacial drift and bedrock aquifers underlying Belvidere, Illinois, and vicinity. To assist efforts to remediate and protect the area's ground water, the USGS, USEPA, and IEPA cooperatively investigated the ground-water-flow system and distribution of contaminants in an 80-mi^2 area that includes the city of Belvidere. During 1992–2000, hydrogeologic and water-quality data were compiled, collected, and analyzed from available sources, and ground-water flow was simulated by use of a numerical model. Hydrogeologic data include lithologic, stratigraphic, geophysical, hydraulic-property, water-level, ground-water withdrawal, and streamflow data. Water-quality data include analyses of water samples primarily for VOC’s and selectively for tritium and inorganic constituents. Data were collected from about 250 wells and 21 surface-water sites. These data were used to describe the hydrogeologic framework of the ground-water-flow system, preferential pathways and directions of ground-water movement and contaminant distribution, ground-water/surface-water relations, and the water budget, as well as to develop and calibrate the ground-water-flow model.

For the purposes of evaluating contaminant distribution, ground-water flow in the vicinity of Belvidere can be described in relation to the glacial drift aquifer, the Galena-Platteville aquifer, and the lower part of the Cambrian-Ordovician aquifer system. The glacial drift aquifer is composed of sand-and-gravel deposits interbedded with fine-grained deposits. Within the Troy Bedrock Valley, located west of Belvidere, the sand-and-gravel deposits are as thick as 260 ft; outside the valley, the deposits range from about 45 ft to less than 10 ft thick. The Galena-Platteville aquifer is composed primarily of fractured dolomite, and reaches a maximum thickness of about 300 ft beneath Belvidere. The lower part of the Cambrian-Ordovician aquifer system is composed of sandstones of the St. Peter, Ironton-Galesville, and Elhurst-Mt.Simon aquifers. The Glenwood confining unit, composed primarily of a 25-ft thick deposit of argillaceous dolomite, separates the Galena-Platteville aquifer and underlying sandstone aquifers. The Galena-Platteville aquifer, and possibly the Glenwood confining unit, are absent in the deepest parts of the Troy Bedrock Valley. The absence of these units could enhance recharge and potential for contamination within the regional Cambrian-Ordovician aquifer system.

Throughout the study area, the Kishwaukee River that flows through Belvidere and its tributaries seem to be gaining flow from ground-water discharge. Measured discharge to the tributaries ranges from about 0.1 ft^3/s to Coon Creek to 15 ft^3/s to Piscasaw Creek. Measured discharge to the Kishwaukee River ranges from about 19 to 69 ft^3/s.

Potentiometric levels in the glacial drift and Galena-Platteville aquifers range from about 900 ft above sea level in the uplands north and south of Belvidere to about 740 ft along the Kishwaukee River. Lateral ground-water flow in the glacial drift aquifer and in the upper half of the Galena-Platteville aquifer is towards the Kishwaukee River and its tributaries. Vertical ground-water flow in these aquifers is predominantly downward, particularly in the upland recharge areas and in the Belvidere area, where affected by substantial ground-water withdrawals.

Estimated horizontal hydraulic conductivity (K_h) of the glacial drift aquifer ranges from about 0.13 to 280 ft/d. The Galena-Platteville aquifer is a dual-porosity unit, with flow through permeable vuggy intervals in the upper two-thirds of the aquifer, and a network of inclined fractures and near-horizontal bedding-plane partings that are distributed throughout the vertical extent of the aquifer. The greatest percentage of flow is through fractures and partings, including partings associated with the weathered surface of the aquifer and at altitudes of about 660, 525, and 485 ft above sea level (referred to as the 125-ft, 260-ft, and 300-ft bedding-plane parting, respectively). Estimated K_h of the aquifer ranges from about 0.005 to 2,500 ft/d. The highest value is associated with the 125-ft parting; the highest average values are associated with the weathered surface of the aquifer and the 260-ft parting. Estimated K_h of the St. Peter aquifer ranges from about 4.7 to 17.5 ft/d.

Water levels in the lower third of the Galena-Platteville aquifer can respond rapidly to withdrawal activity at the municipal wells. Two or more of the six municipal wells open to the Galena-Platteville aquifer seem to intercept the 260-ft and (or) 300-ft partings; near-instantaneous changes in water level of up to 25 ft were recorded at a distance of about 0.25 mi from well BMW6 in a monitoring well screened near the partings. Trace metals at concentrations above regulatory levels have been detected primarily in the glacial drift aquifer and in the immediate vicinity of hazardous-waste sites. VOC's have been detected in all aquifers underlying Belvidere. TCE and PCE are the principal VOC's present at concentrations above regulatory levels, with the largest number of detections and highest concentrations in the glacial drift aquifer. During 1992–99, VOC's were detected at concentrations above MCL's in 18 wells open to the glacial drift aquifer; VOC's generally are not detected farther than 1,000 ft of known or potential source areas (industrial or disposal sites), because most source areas are near the Kishwaukee River, where shallow ground water discharges. Except in the immediate vicinity of a known hazardous-waste site, possible sources of VOC's in the bedrock aquifers were difficult to identify; concentrations of VOC's at most locations in these aquifers were below 5 µg/L. Tritium data collected in conjunction with VOC data indicate that the St. Peter and deeper sandstone aquifers underlying the Glenwood confining unit generally are not vulnerable to contamination. However, fractures and (or) unused wells that may penetrate the confining unit seem to allow limited, localized movement of VOC's to the sandstone aquifers. Downward movement of VOC's seems to be restricted primarily by the confining unit, and, in the immediate vicinity of Belvidere, by lateral movement toward the municipal wells through permeable intervals (including bedding-plane partings) in the Galena-Platteville aquifer.

The ground-water-flow system underlying Belvidere was simulated to test a conceptual model. The four-layer steady-state numerical model represents the glacial drift and Galena-Platteville aquifers, and the sandstone aquifers of the Cambrian-Ordovician aquifer system, separated by the Glenwood confining unit.

The model was calibrated by adjusting values of hydrologic properties until differences in simulated and measured ground-water levels and ground-water discharge to streams were minimized. One-hundred sixty spatially distributed water levels, 5 vertically paired water levels, and 3 measurement-based estimates of ground-water discharge to Piscasaw and Beaver Creeks and to the Kishwaukee River (within the limits of the study area) were used to calibrate the model. Within the limitations of the model design and available data, the steady-state simulation generally verified the conceptualized flow system.

The closest agreement between simulated and measured water levels and streamflow gain/loss was found with the following set of hydrologic-property values:

Horizontal hydraulic conductivity of the glacial drift aquifer within the Troy Bedrock Valley (ft/d) 45

Horizontal hydraulic conductivity of the glacial drift aquifer along the flanks of Troy Bedrock Valley (ft/d)..................................250

Horizontal hydraulic conductivity of the glacial drift aquifer and deposits outside the Troy Bedrock Valley (ft/d).........................10–13

Horizontal hydraulic conductivity of the Galena-Platteville aquifer (ft/d)..........................0.05

Horizontal hydraulic conductivity of the sandstone aquifers of the Cambrian-Ordovician aquifer system (ft/d)..............................4

Vertical hydraulic conductivity of the Glenwood confining unit (ft/d).....................0.00015

Vertical hydraulic conductivity of streambeds (ft/d)....................................... 0.025-2.5

Areal recharge rates (in/yr) 8.4

This set of hydrologic-property values results in model error (RMSE) of 10 ft between all simulated and measured water levels. The sensitivity analysis indicates that accurate estimates of recharge rate and K_h of the deposits composing the sand-dominated valley edge of the glacial drift aquifer and the sandstone aquifers are the most critical information needed for accurate characterization of the flow system with the ground-water model.

The simulation results indicate that (1) ground-water discharge is predominantly to local streams and that a few, small sections of the Kishwaukee River and Piscasaw and Beaver Creeks may be losing flow to the ground-water system, (2) K_h (and, thus, transmissivity) of the glacial drift aquifer within the Troy Bedrock Valley and parts of the Galena-Platteville aquifer may be less than previously expected, and (3) till-dominated deposits in the southern part of the study area may include some previously unrecognized water-yielding interbedded sand and gravel. Additionally, results indicate that about 69 percent of inflow into the ground-water-flow system is from precipitation and 26 percent is contributed from specified boundaries. About 80 percent of the outflow is discharge to streams, 13 percent is associated with specified boundaries, and 7 percent is by withdrawals (primarily six Belvidere municipal-supply wells). About 0.95 in/yr of recharge from precipitation was simulated to flow to the sandstone aquifers.

The general lack of information on potentiometric levels and flows in the aquifers and confining unit near boundaries of the study area and elsewhere in the sandstone aquifers likely accounts for the largest source of model error. Additionally, data generally are not available to verify whether the Glenwood confining unit is present within the deepest part of the Troy Bedrock Valley; inaccurate representation of the geometry of this unit in the model may be another source of error. Since the model-calibration period (1993), ground-water withdrawals have increased in the Rockford and Belvidere areas and decreased in the Chicago area, presumably affecting potentiometric levels, flow directions, and fluxes in the aquifers underlying the study area. The model does not account for zones of preferential flow (primarily bedding-plane partings and inclined fractures in the Galena-Platteville aquifer); thus, does not allow delineation and evaluation of local flow patterns and the possible effect on contaminant distribution. The ground-water-flow model provides insight into spatial-data needs and is considered useful for further analysis of the regional ground-water-flow system and preliminary delineation of the areas contributing recharge to water-supply wells.

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APPENDIXES

Appendix 1. Water levels in selected streams and wells in Belvidere, Illinois, 1993–99

Measurement site designation	River or aquifer	Measurement date	Water-level altitude (feet above sea level)	Change in water level from initial measurement in 1993 (feet)
KR1	Kishwaukee River	07-20-93	763.96	0.00
do.	do.	06-16-94	761.43	-2.53
do.	do.	09-09-99	759.79	-4.17
KR2	Coon Creek	07-21-93	759.94	.00
do.	do.	06-16-94	754.06	-5.88
do.	do.	09-09-99	753.87	-6.07
KR5	Kishwaukee River	07-20-93	753.58	.00
do.	do.	06-16-94	751.47	-2.11
do.	do.	09-10-99	751.0	-2.6
KR8	do.	07-20-93	745.68	.00
do.	do.	06-16-94	739.57	-6.11
do.	do.	09-10-99	739.45	-6.23
KR9	do.	07-20-93	726.71	.00
do.	do.	06-16-94	722.17	-4.54
do.	do.	09-09-99	722.47	-4.24
NSMG101	Glacial drift	07-19-93	755.59	.00
do.	do.	06-01-94	752.61	-2.98
do.	do.	09-22-94	752.24	-3.35
do.	do.	05-08-96	746.60	-8.99
do.	do.	08-27-96	752.82	-2.77
do.	do.	04-22-98	753.08	-2.51
do.	do.	09-10-99	752.58	-3.01
NSMG102	do.	07-19-93	755.79	.00
do.	do.	06-01-94	752.57	-3.22
do.	do.	09-22-94	751.99	-3.80
do.	do.	05-08-96	745.62	-10.17
do.	do.	08-27-96	752.75	-3.04
do.	do.	04-21-98	752.79	-3.00
do.	do.	09-10-99	752.97	-2.82
NSMG103	Glacial drift	07-19-93	755.26	.00
do.	do.	06-01-94	752.28	-2.98
do.	do.	09-22-94	751.71	-3.55
do.	do.	05-08-96	743.66	-11.60
do.	do.	08-27-96	752.57	-2.69
do.	do.	09-12-96	752.30	-2.96
do.	do.	04-23-98	752.90	-2.63
do.	do.	09-10-99	752.64	-2.63
NSMG104	do.	07-20-93	755.4	0.00
do.	do.	06-02-94	752.4	-3.0
do.	do.	04-12-95	752.46	-2.94
do.	do.	06-01-95	753.37	-2.03
do.	do.	05-08-96	737.26	-18.14
do.	do.	08-27-96	752.53	-2.87
do.	do.	09-12-96	752.24	-3.16
do.	do.	04-22-98	752.87	-2.53
do.	do.	09-10-99	752.47	-2.93

Appendix 1. Water levels in selected streams and wells in Belvidere, Illinois, 1993–99–Continued

Measurement site designation	River or aquifer	Measurement date	Water-level altitude (feet above sea level)	Change in water level from initial measurement in 1993 (feet)
NSMG105	do.	07-19-93	755.29	0.00
do.	do.	06-01-94	752.28	-3.01
do.	do.	09-22-94	751.72	-3.57
do.	do.	06-01-95	753.55	-1.74
do.	do.	06-14-95	753.51	-1.78
do.	do.	05-08-96	744.99	-10.30
do.	do.	08-27-96	752.52	-2.77
do.	do.	09-12-96	752.27	-3.02
do.	do.	04-22-98	752.86	-2.43
do.	do.	09-10-99	752.68	-2.61
PCHG115S	do.	07-19-93	770.23	.00
do.	do.	05-30-95	768.44	-1.79
do.	do.	10-14-95	767.44	-2.79
do.	do.	05-08-96	767.03	-3.20
do.	do.	09-10-99	768.03	-2.20
PCHG115D	do.	07-19-93	768.13	.00
do.	do.	06-03-94	763.66	-4.47
do.	do.	05-30-95	763.06	-5.07
do.	do.	10-14-95	762.09	-6.04
do.	do.	05-08-96	760.53	-7.60
do.	do.	09-10-99	764.29	-3.84
PCHG115B	Galena-Platteville	07-19-93	768.03	.00
do.	do.	05-30-95	762.97	-5.06
do.	do.	05-08-96	760.46	-7.57
do.	do.	09-10-99	764.17	-3.86
PCHG115BD	do.	07-19-93	757.04	.00
do.	do.	12-07-94	749.94	-7.10
do.	do.	05-30-95	750.74	-6.30
do.	do.	05-08-96	749.52	-7.52
do.	do.	09-23-96	753.42	-3.62
do.	do.	10-29-96	753.57	-3.47
do.	do.	04-21-98	753.03	-4.01
do.	do.	09-10-99	751.40	-5.64
PCHG127SP	St. Peter	07-19-93	725.66	.00
do.	do.	05-31-94	722.79	-2.87
do.	do.	05-30-95	721.86	-3.80
do.	do.	05-08-96	721.63	-4.03
do.	do.	09-12-96	720.50	-5.16
do.	do.	09-25-96	718.18	-7.48
do.	do.	04-21-98	722.35	-3.31
do.	do.	03-23-99	719.37	-6.29
do.	do.	09-10-99	717.27	-8.39

Appendix 2. Fields-determined characteristics of ground-water quality at selected wells in Belvidere, Illinois, 1998–99

[°C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 Celsius; mv, millivolts; mg/L, milligrams per liter; NTU, nephelometric turbidity unit; --, no data; clr, clear; clr/cldy, clear to cloudy; cldy, cloudy]

Aquifer to which well is open: GP, Galena-Platteville; SP, St. Peter; CO, Cambrian-Ordovician system; OR, Ordovician system; GD, glacial drift

Well designation	Sample date	Aquifer to which well is open	pH (standard units)	Temperature (°C)	Specific conductance (µS/cm)	Oxidation-reduction potential (Eh) (mv)	Dissolved oxygen (mg/L)	Turbidity (NTU)
AGTG305GPS	04-21-98	GP	6.85	11.7	683	42	--	clr
do.	03-22-99	GP	7.07	11.4	833	--	0.04	clr
AGTG305GPD	04-20-98	GP	7.02	11.1	657	46	.06	0.17
do.	03-22-99	GP	7.38	11.4	489	14	.08	cldy
AGTG305SP	04-20-98	SP	7.05	11.0	837	185	--	.88
do.	03-22-99	SP	7.17	11.6	539	131	.13	clr
BMW2	04-28-98	CO	6.74	12.2	1,140	120	--	clr
do.	03-24-99	CO	6.93	11.9	1,103	98	1.05	clr
BMW3	04-20-98	CO	6.88	13.7	1,073	142	--	clr
do.	03-24-99	CO	6.95	13.8	1,142	110	3.00	clr
BMW4	04-27-98	CO	7.01	11.8	772	25	--	clr
do.	03-22-99	CO	7.38	11.6	494	84	--	clr
BMW5	04-20-98	OR	6.99	11.8	712	2	--	clr
do.	03-23-99	OR	7.14	11.5	621	0	--	--
BMW6	03-23-99	CO	7.18	11.2	558	34	--	--
BMW7	03-23-99	CO	7.29	12.6	460	0	--	clr
BMW8	03-23-99	CO	7.26	12.1	446	-12	--	clr
BMW9	03-24-99	GD	7.29	10.4	614	-24	1.04	clr
NSMG101	04-22-98	GD	6.82	11.7	1,132	187	--	clr
NSMG102	04-21-98	GD	6.76	13.9	933	80	--	clr/cldy
NSMG103	04-22-98	GD	6.77	12.4	1,190	194	--	clr
NSMG104	04-22-98	GD	6.79	12.1	1,328	53	--	clr
NSMG105	04-22-98	GD	6.67	14.5	1,504	194	--	clr
PCHG115BD	04-21-98	GP	6.82	11.0	586	-55	.09	14
PCHG116D	04-22-98	GD	6.84	10.9	762	214	--	clr
PCHG119D	04-27-98	GD	7.10	12.3	936	70	--	cldy
PCHG125D	[1]04-28-98	GD	6.36	10.1	462	175	--	cldy
PCHG125B	[2]04-28-98	GP	--	12.0	816	182	--	clr
PCHG127GP	04-21-98	GP	6.76	11.0	645	90	.08	4.1
do.	03-23-99	GP	7.20	13.0	659	-50	.03	clr
PCHG127SP	04-21-98	SP	6.83	10.9	559	-54	.13	clr
do.	03-23-99	SP	7.36	11.7	526	-74	.03	clr
PCHG128GPS	04-21-98	GP	6.85	11.5	657	-2	--	clr
do.	03-22-99	GP	7.14	11.3	676	-36	--	clr
PCHG128GPD	04-21-98	GP	7.00	10.8	655	6	.09	0.2
do.	03-23-99	GP	7.22	11.4	599	-18	.06	clr
PCHG436B	04-20-98	GP	6.97	11.7	[3]982	177	--	clr
PCHG436GPS	04-27-98	GP	7.05	11.9	530	-14	--	cldy
PCHG133D	04-27-98	GD	7.07	14.8	813	115	--	cldy
do.	03-23-99	GD	7.10	13.4	709	162	--	clr/cldy
PCHG134D	04-27-98	GD	6.89	12.3	923	56	--	clr
do.	03-24-99	GD	7.05	11.9	879	97	2.84	clr
PCHG135D	04-27-98	GD	7.04	12.2	941	147	--	cldy
do.	03-23-99	GD	7.25	12.9	730	96	--	clr/cldy

[1] Well was pumped dry on 04-27-98 and 04-28-98; sampled after water level recovered about 90 percent of static level. Field characteristics generally were stable except for specific conductance. Fluctuating value was recorded as high as 911 microsiemens per centimeter.

[2] Field characteristics were measured at the end of sampling. Water sample was collected with a peristaltic pump and contained substantial air; specific-conductance measurements fluctuated.

[3] Water sample was collected with a peristaltic pump; air in flow-through cell results in values fluctuating by about +/- 30 microsiemens per centimeter.

Appendix 3. Concentrations of metals, cyanide, and tritium in ground water at selected wells in Belvidere, Illinois, 1998–99

[All concentrations of metals represent total fraction; μg/L, micrograms per liter; pCi/L, picocuries per liter; TU, tritium unit; NA, not analyzed; ND, not detected; <, less than]

Aquifer to which well is open: GP, Galena-Platteville; SP, St. Peter; CO, Cambrian-Ordovician system; OR, Ordovician system; GD, glacial drift

Well designation	Sample date	Aquifer to which well is open	Aluminum (μg/L)	Antimony (μg/L)	Arsenic (μg/L)	Barium (μg/L)	Cadmium (μg/L)	Chromium (μg/L)	Cobalt (μg/L)	Copper (μg/L)
AGTG305GPS	04-21-98	GP	[1]64.2	ND	ND	[1]76.1	[1]0.4	[1]1.7	ND	[1]19.8
do.	03-22-99	GP	NA	NA	NA	NA	NA	NA	NA	NA
AGTG305GPD	04-20-98	GP	[1]215	ND	ND	[1]97.5	[1].4	[1]1	ND	[1]17.3
do.	03-22-99	GP	NA	NA	NA	NA	NA	NA	NA	NA
AGTG305SP	04-20-98	SP	[1]53.6	ND	ND	[1]58.6	[1]1	[1]1.6	2.9	[1]43.3
do.	03-22-99	SP	NA	NA	NA	NA	NA	NA	NA	NA
BMW2	04-28-98	CO	[1]75.8	ND	ND	[1]66.5	ND	[1].65	ND	[2]8.0
do.	04-28-98	CO	[1]31.7	ND	ND	[1]65.4	ND	ND	ND	[2]8.1
do.	03-24-99	CO	NA	NA	NA	NA	NA	NA	NA	NA
BMW3	04-20-98	CO	[1]59.8	ND	ND	[1]68.6	[1]1	ND	ND	ND
do.	03-24-99	CO	NA	NA	NA	NA	NA	NA	NA	NA
BMW4	04-27-98	CO	[1]27.8	ND	ND	[1]291.1	ND	ND	[2]1.3	[2]1.2
do.	03-22-99	CO	NA	NA	NA	NA	NA	NA	NA	NA
BMW5	04-20-98	OR	[1]34.4	ND	ND	[1]153	[1].9	ND	ND	[1]29.2
do.	03-23-99	OR	NA	NA	NA	NA	NA	NA	NA	NA
BMW6	03-23-99	CO	NA	NA	NA	NA	NA	NA	NA	NA
BMW7	03-23-99	CO	NA	NA	NA	NA	NA	NA	NA	NA
BMW8	03-23-99	CO	NA	NA	NA	NA	NA	NA	NA	NA
BMW9	04-24-99	GD	NA	NA	NA	NA	NA	NA	NA	NA
NSMG101	04-22-98	GD	[1]95.7	ND	ND	[1]59.3	[1].5	[1]1.5	2.1	[1]12.8
NSMG102	04-21-98	GD	[1]60.2	ND	ND	[1]65.5	[1]1.1	1,030	4.4	[1]59.8
NSMG103	04-23-98	GD	[1]44.7	ND	3.5	[1]61.8	ND	[1]14	ND	[1]9.4
NSMG104	04-22-98	GD	[1]71.2	ND	ND	[1]62.8	[1].3	9	1.8	[1]24.8
NSMG105	04-22-98	GD	[1]44.7	ND	ND	[1]87	ND	44.8	2.6	[1]18.1
PCHG115BD	04-21-98	GP	ND	ND	6.8	[1]99	ND	[1]1.4	ND	[1]1.4
PCHG116D	04-22-98	GD	[1]100	ND	ND	[1]82.8	[1]1.2	[1].8	3	[1]553
do.	04-22-98	GD	[1]68.1	ND	ND	[1]82.9	[1].3	ND	2.8	[1]520
PCHG119D	04-27-98	GD	[1]34.3	ND	ND	[1]64.4	ND	25.6	ND	[2]6.4
PCHG125D	04-28-98	GD	449.5	ND	ND	[1]73.1	[2].4	17.8	[2]3.4	[2]7.8
PCHG125B	04-28-98	GD	[1]85.2	ND	ND	[1]73.9	ND	ND	[1]1.6	ND
PCHG127GP	04-21-98	GP	[1]160	ND	4.3	[1]248	[1].4	[1].8	ND	[1]24.6
do.	04-21-98	GP	[1]172	ND	6.7	[1]249	[1]1.7	[1]1	ND	[1]63.6
do.	03-23-99	GP	NA	NA	NA	NA	NA	NA	NA	NA
PCHG127SP	04-21-98	SP	[1]83.3	ND	ND	[1]804	[1].7	ND	ND	[1]71
do.	03-23-99	SP	NA	NA	NA	NA	NA	NA	NA	NA
PCHG128GPS	04-21-98	GP	[1]41.2	[1]3.3	ND	[1]126	ND	ND	ND	[1]5.8
do.	03-22-99	GP	NA	NA	NA	NA	NA	NA	NA	NA
PCHG128GPD	04-21-98	GP	[1]61.2	ND	[1]5.4	[1]216	[1]1.1	4.7	ND	ND
do.	03-23-99	GP	NA	NA	NA	NA	NA	NA	NA	NA
PCHP436B	04-20-98	GP	[1]180	ND	ND	[1]73.6	[1].3	ND	ND	[1]7.1
PCHG436GPS	04-27-98	GP	254.2	ND	ND	[1]83.0	ND	[1]1.0	ND	[2]3.7
PCHG133D	04-27-98	GD	378.3	ND	ND	[1]93.1	ND	185.6	[2]1.3	[2]7.2
PCHG134D	04-27-98	GD	[1]40.9	ND	ND	[1]62.8	ND	24.8	[2]2.0	[2]2.4
PCHG135D	04-27-98	GD	147.5	ND	ND	[1]76.4	ND	137.2	[2]3.4	[2]6.9

[1] Concentration is estimated; specific reason for estimated designation can be obtained from the U.S. Geological Survey.
[2] Constituent detected in sample blank.

Appendix 3. Concentrations of metals, cyanide, and tritium in ground water at selected wells in Belvidere, Illinois, 1998–99–Continued

Well designation	Sample date	Aquifer to which well is open	Lead (μg/L)	Mercury (μg/L)	Nickel (μg/L)	Selenium (μg/L)	Vanadium (μg/L)	Zinc (μg/L)	Cyanide (μg/L)	Tritium (pCi/L)	Tritium (TU)
AGTG305GPS	04-21-98	GP	[1]57.1	ND	[1]4.2	ND	ND	[1]12.9	[1]2.6	NA	NA
do.	03-22-99	GP	ND	NA	NA	NA	NA	NA	NA	40.0	12.5 ± 0.8
AGTG305GPD	04-20-98	GP	[1]20.2	ND	[1]3.2	ND	ND	[1]12	[1]4	NA	NA
do.	03-22-99	GP	NA	NA	NA	NA	NA	NA	NA	26.9	8.4 ± .6
AGTG305SP	04-20-98	SP	[1]40.7	ND	[1]8.1	ND	ND	[1]16.8	[2]3	NA	NA
do.	03-22-99	SP	NA	NA	NA	NA	NA	NA	NA	92.2	28.8 ± 1.8
BMW2	04-28-98	CO	[1]4.9	ND	ND	[1]2.0	ND	[1]41.5	ND	NA	NA
do.	04-28-98	CO	[1]6.0	[1]0.2	ND	ND	ND	[1]79.4	ND	NA	NA
do.	03-24-99	CO	NA	NA	NA	NA	NA	NA	NA	38.4	12.0 ± .8
BMW3	04-20-98	CO	[1]36	ND	[1]2.6	[1]2.1	ND	[1]42.7	[1]3.4	NA	NA
do.	03-24-99	CO	NA	NA	NA	NA	NA	NA	NA	36.8	11.5 ± .8
BMW4	04-27-98	CO	[1]1.9	[1].3	[2]3.8	ND	ND	[1]12.7	ND	NA	NA
do.	03-22-99	CO	NA	NA	NA	NA	NA	NA	NA	15.4	4.8 ± .4
BMW5	04-20-98	OR	[1]17.6	ND	[1]6.4	ND	ND	[1]19.4	[1]2.2	NA	NA
do.	03-23-99	OR	NA	NA	NA	NA	NA	NA	NA	24.6	7.7 ± .5
BMW6	03-23-99	CO	NA	NA	NA	NA	NA	NA	NA	19.2	6.0 ± .4
BMW7	03-23-99	CO	NA	NA	NA	NA	NA	NA	NA	1.3	.4 ± .3
BMW8	03-23-99	CO	NA	NA	NA	NA	NA	NA	ND	<.32	-.2 ± .3
BMW9	04-24-99	GD	NA	NA	NA	NA	NA	NA	NA	23.4	7.3 ± .5
NSMG101	04-22-98	GD	[1]22.9	ND	ND	[1]2.5	ND	[1]10.1	[1]3.9	NA	NA
NSMG102	04-21-98	GD	[1]31.9	ND	96	[1]2.2	5.1	[1]9.2	[1]7.1	NA	NA
NSMG103	04-23-98	GD	[1]ND	ND	[1]6.3	ND	ND	[1]5.3	[1]3.5	NA	NA
NSMG104	04-22-98	GD	[1]23.7	ND	ND	ND	ND	[1]10.3	[1]4.7	NA	NA
NSMG105	04-22-98	GD	[1]21.8	ND	[1]42.6	ND	ND	[1]13.1	[1]2.5	NA	NA
PCHG115BD	04-21-98	GP	[1]2.4	ND	[1]4.4	ND	ND	[1]5.4	[1]4	NA	NA
PCHG116D	04-22-98	GD	[1]48.3	ND	[1]219	ND	ND	[1]18.1	[1]6.6	NA	NA
do.	04-22-98	GD	5.3	ND	[1]221	ND	ND	[1]6	[1]7.2	NA	NA
PCHG119D	04-27-98	GD	[1]2.6	ND	[1]62.2	[1]2.9	ND	[1]5.8	ND	NA	NA
PCHG125D	04-28-98	GD	[1]11.1	ND	[1]114.5	[1]2.9	[2]1.4	[1]15.0	ND	NA	NA
PCHG125B	04-28-98	GD	[1]1.9	ND	171	[1]2.6	ND	[1]11.2	ND	NA	NA
PCHG127GP	04-21-98	GP	[1]18.2	ND	[1]2.7	ND	ND	[1]23.6	[1]1.4	NA	NA
do.	04-21-98	GP	[1]30.8	ND	[1]4.9	ND	ND	[1]21.1	[1]5.7	NA	NA
do.	03-23-99	GP	NA	NA	NA	NA	NA	NA	NA	28.8	9.0 ± .6
PCHG127SP	04-21-98	SP	[1]53.2	ND	[1]2.8	ND	ND	[1]31.3	[1]4.7	NA	NA
do.	03-23-99	SP	NA	NA	NA	NA	NA	NA	NA	1.3	.4 ± .3
PCHG128GPS	04-21-98	GP	[1]7.5	ND	[1]1.9	ND	ND	[1]9.8	ND	NA	NA
do.	03-22-99	GP	NA	NA	NA	NA	NA	NA	NA	32.6	10.2 ± .8
PCHG128GPD	04-21-98	GP	[1]50.4	ND	[1]6.9	ND	ND	[1]41.5	[1]4.2	NA	NA
do.	03-23-99	GP	NA	NA	NA	NA	NA	NA	NA	25.6	8.0 ± .5
PCHP436B	04-20-98	GP	[1]7.7	ND	[1]2.1	[1]2.9	ND	[1]7.5	[1]3.9	NA	NA
PCHG436GPS	04-27-98	GP	[1]2.3	ND	[1]2.5	ND	ND	[1]13.1	[1]1.5	NA	NA
PCHG133D	04-27-98	GD	[1]3.6	ND	60.9	ND	[1]1.9	[1]20.1	ND	NA	NA
PCHG134D	04-27-98	GD	[1]2.0	ND	84.6	[1]2.6	ND	[1]4.9	ND	NA	NA
PCHG135D	04-27-98	GD	[1]3.3	ND	64.7	ND	[2]1.1	[1]12.8	ND	NA	NA

[1] Concentration is estimated; specific reason for estimated designation can be obtained from the U.S. Geological Survey.
[2] Constituent detected in sample blank.

Appendix 4. Concentrations of volatile organic compounds detected in ground water at selected wells in Belvidere, Illinois, 1998–99

[µg/L, micrograms per liter; ND, not detected; NA, not analyzed]

Aquifer to which well is open: GP, Galena-Platteville; SP, St. Peter; CO, Cambrian-Ordovician system; OR, Ordovician system; GD, glacial drift

Well designation	Sample date	Aquifer to which well is open	Trichloro-ethene (µg/L)	Tetra-chloro-ethene (µg/L)	1,1,1-Tri-chloro-ethane (µg/L)	1,2-Di-chloro-ethene total[1] (µg/L)	1,4-Dioxane (µg/L)	Tetra-hydro-furan (µg/L)	1,1-Di-chloro-ethane (µg/L)	1,1-Di-chloro-ethene (µg/L)	1,2-Di-chloro-ethane (µg/L)	Benzene (µg/L)	Toluene (µg/L)
AGTG305GPS	[2]04-21-98	GP	ND	ND	ND	ND	ND[3]	ND[3]	ND	ND	ND	ND	3
do.	03-22-99	GP	ND	ND	ND	ND	NA	NA	ND	ND	ND	ND	ND
AGTG305GPD[4]	04-20-98	GP	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
do.	03-22-99	GP	0.5	ND	ND	ND	NA	NA	ND	ND	ND	ND	ND
AGTG305SP	04-20-98	SP	6	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
do.	03-22-99	SP	9	ND	ND	1	NA	NA	ND	ND	ND	ND	ND
BMW2	[5]03-24-99	CO	8	5	ND	1	ND	ND	ND	ND	ND	ND	ND
do.	03-24-99	CO	8	5	ND	1	NA	NA	ND	ND	ND	ND	ND
BMW3	03-24-99	CO	1	5	ND	ND	NA	NA	ND	ND	ND	ND	ND
BMW4	04-27-98	CO	ND	ND	ND	ND	ND	ND	ND	ND	1	12	ND
do.	03-22-99	CO	ND	ND	ND	ND	NA	NA	ND	0.9	ND	ND	ND
BMW5	04-20-98	OR	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
do.	03-23-99	OR	ND	1	ND	ND	NA	NA	ND	ND	ND	ND	ND
BMW6	[6]03-23-99	CO	ND	ND	ND	ND	NA	NA	ND	.6	ND	ND	ND
BMW7	03-23-99	CO	ND	ND	ND	ND	NA	NA	ND	ND	ND	ND	ND
BMW8	[5]03-23-99	CO	ND	ND	ND	ND	NA	NA	ND	ND	ND	ND	ND
BMW9	03-24-99	GD	ND	ND	ND	ND	NA	NA	ND	ND	ND	ND	ND
NSMG101	04-22-98	GD	3	ND	ND	ND	ND	ND	ND	ND	ND	ND	2
NSMG102	04-21-98	GD	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	2
NSMG103	04-22-98	GD	4	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
NSMG104	[7]04-22-98	GD	18	35	ND	ND	ND	ND	ND	ND	ND	ND	ND
NSMG105	04-22-98	GD	2	[7]49	ND	ND	ND	ND	ND	ND	ND	ND	2
PCHG115BD	04-21-98	GP	48	9	3	12	ND	ND	5	1	ND	ND	ND
PCHG116D	04-22-98	GD	[7]220	2	160	2	5	ND	3	4	ND	ND	ND
do.	04-22-98	GD	[7]220	ND	[7]140	ND	4	ND	ND	3	ND	ND	ND
PCHG119D	04-21-98	GD	140	190	56	19	5	ND	ND	2	ND	ND	ND
PCHG125D	04-28-98	GD	49	ND	15	ND	ND	1	ND	ND	ND	ND	ND
do.	04-28-98	GD	48	ND	15	ND	NA	NA	ND	ND	ND	ND	ND
PCHG125B	[8]04-23-98	GP	360	250	170	6	5	ND	ND	3	ND	ND	ND
PCHG127GP	04-21-98	GP	48	ND	ND	3	5	ND	ND	ND	ND	ND	ND
do.	04-21-98	GP	47	ND	ND	3	4	ND	ND	ND	ND	ND	ND
do.	03-23-99	GP	45	ND	ND	4	NA	NA	ND	ND	ND	ND	ND
PCHG127SP	[9]04-21-98	SP	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
do.	03-23-99	SP	ND	ND	ND	ND	NA	NA	ND	ND	ND	ND	ND
PCHG128GPS	04-21-98	GP	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
do.	03-22-99	GP	ND	ND	ND	ND	NA	NA	ND	ND	ND	ND	ND
PCHG128GPD	[10]04-21-98	GP	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
do.	03-23-99	GP	.5	ND	ND	ND	NA	NA	ND	ND	ND	ND	ND
PCHG436B	04-20-98	GP	ND	2	ND	ND	ND	ND	ND	ND	ND	ND	ND

Appendix 4. Concentrations of volatile organic compounds detected in ground water at selected wells in Belvidere, Illinois, 1998–99–Continued

Well designation	Sample date	Aquifer to which well is open	Trichloro-ethene (μg/L)	Tetra-chloro-ethene (μg/L)	1,1,1-Tri-chloro-ethane (μg/L)	1,2-Di-chloro-ethene total[1] (μg/L)	1,4-Dioxane (μg/L)	Tetra-hydro-furan (μg/L)	1,1-Di-chloro-ethane (μg/L)	1,1-Di-chloro-ethene (μg/L)	1,2-Di-chloro-ethane (μg/L)	Benzene (μg/L)	Toluene (μg/L)
PCHG436GPS	04-27-98	GP	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
do.	04-27-98	GP	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PCHG133D	04-27-98	GD	8	21	4	5	ND	ND	ND	ND	ND	ND	ND
do.	03-23-99	GD	10	26	6	8	NA	NA	ND	ND	ND	ND	ND
PCHG134D	04-27-98	GD	380	39	150	8	12	ND	4	10	ND	ND	ND
do.	03-24-99	GD	380	[7]28	110	ND	NA	NA	ND	ND	ND	ND	ND
do.	03-24-99	GD	370	[7]28	100	ND	NA	NA	ND	ND	ND	ND	ND
PCHG135D	04-27-98	GD	6	86	4	9	ND	ND	ND	ND	ND	ND	ND
do.	03-23-99	GD	7	59	7	34	NA	NA	6	ND	ND	ND	ND

[1] The samples collected in March 1999 were analyzed for the individual isomers of 1,2-dichloroethene. Detections represent cis-1,2-dichloroethene

[2] Reporting limit for samples collected by the U.S. Geological Survey (USGS) in 1998 is 10 micrograms per liter (μg/L); concentrations of detected compounds less than the reporting limit are estimated. Reporting limit for samples collected by the USGS in 1999 are 1 to 5 μg/L; concentrations of detected compounds less than 1 μg/L, the reporting limit, are estimated.

[3] Reporting limits for 1,4-dioxane and tetrahydrofuran are 5μg/L; concentrations less than or equal to the reporting limits are estimated.

[4] Tentatively identified compound: unknown1, 6 μg/L; unknown2, 4 μg/L; unknown3, 6 μg/L; 9-(trimethylsilyoxy)-4-trim, 4 μg/L; unknown4, 5 μg/L; unknown5, 4 μg/L. All concentrations are estimated.

[5] Also detected methylene chloride: 0.6 μg/L (estimated).

[6] Also detected chloroform: 0.7 μg/L (estimated).

[7] Concentrations are estimated; specific reason for estimated designation can be obtained from the USGS.

[8] Water sample was collected with a peristaltic pump near the pressure limits of the pump. Air contained in the discharge tubing.

[9] Also detected methylene chloride: 0.5 μg/L (estimated).

[10] Tentatively identified compound: unknown, 7 μg/L (estimated).

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