Prepared in cooperation with the City of Richmond, Indiana

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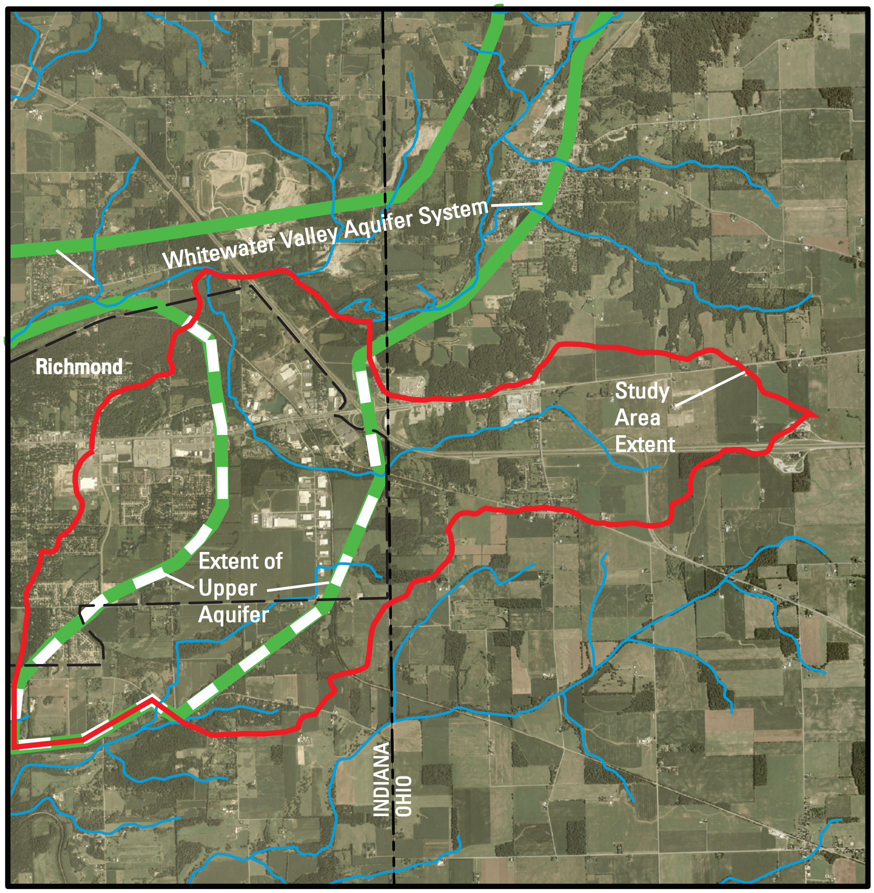

Scientific Investigations Report 2006–5281

**U.S. Department of the Interior
U.S. Geological Survey**

Cover. Orthophotograph showing the approximate extent of the upper aquifer in a part of the Whitewater Valley aquifer system near Richmond, Indiana. From U.S. Department of Agriculture scanned aerial photography, July 19, 2003, Leaf on, 1-meter ground resolution, Universal Transverse Mercator projection, Zone 16.

Hydrogeology, Ground-Water-Age Dating, Water Quality, and Vulnerability of Ground Water to Contamination in a Part of the Whitewater Valley Aquifer System near Richmond, Indiana, 2002–2003

By Paul M. Buszka, Lee R. Watson, and Theodore K. Greeman

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Conversion Factors, Water-Quality Units, Datum, and Acronyms

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
	Area	
acre	0.4047	hectare (ha)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	2.59	square kilometer (km^2)
	Volume	
cubic meter (m^3)	264.2	gallon (gal)
liter (L)	0.2642	gallon (gal)
milliliter (mL)	0.03381	ounce, fluid (oz)
cubic centimeter (cm^3)	0.03381	ounce, fluid (oz)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
	Mass	
picogram (pg)	3.527×10^{-11}	ounce, avoirdupois (oz)
microgram (µg)	3.527×10^{-8}	ounce, avoirdupois (oz)
milligram (mg)	3.527×10^{-5}	ounce, avoirdupois (oz)
milligram per day (mg/d)	3.527×10^{-5}	ounce, avoirdupois, per day (oz/d)
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	0.002205	pound, avoirdupois (lb)
	Pressure	
atmosphere, standard (atm)	101.3	kilopascal (kPa)
millimeters of mercury (mm Hg)	3.386	kilopascal (kPa)

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

$$°F = (1.8 \times °C) + 32$$

Altitude, as used in this report, refers to distance above the vertical datum. Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83) in figures 1 through 5 and figure 8.

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27) in figures 6, 12, and 13.

Hydraulic conductivity is given in units of feet per day.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25ºC).

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L), micrograms per liter (µg/L), or picograms per liter (pg/L). Chemical concentrations and water temperature are given in metric units.

A milligram per liter is a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water. For concentrations less than 7,000 mg/L, the numerical value for milligrams per liter is the same as for concentrations in parts per million.

A concentration of 1,000 micrograms per liter is equivalent to 1 milligram per liter. For concentrations less than 7,000 mg/L, the numerical value for milligrams per liter is the same as for concentrations in parts per million.

A concentration of 1 million picograms per liter (pg/L)—also picograms per kilogram (pg/kg)—is equivalent to 1 milligram per liter.

A millimole per liter is a unit expressing the concentration of chemical constituents in solution as the weight of a chemical substance, in milligrams, in a liter of water, divided by the atomic weight of one atom or molecule of its composition elements, in grams (one mole). A micromole per liter is a unit expressing the concentration of chemical constituents in solution as the weight of a chemical substance, in micrograms, in a liter of water, divided by the atomic weight of one atom or molecule of its composition elements, in grams (one mole). These units are used in this report to describe concentrations of dissolved gases and constituents in a water sample.

A milliequivalent is defined as a weight of a chemical substance, divided by the atomic weight of its composition elements and the assumed charge of the species. For example, calcium and magnesium have assumed charges of 2 and sodium and potassium have assumed charges of 1. The proportion of major cations and anions in water samples are described graphically in this report as concentrations in milliequivalents per liter.

A nephelometric turbidity unit (NTU) is a unit of measure used to report the turbidity of water. Turbidity is a measure of the cloudiness of water and is measured by the amount of light that is scattered and absorbed instead of transmitted through the water by a standard light-measuring device, or nephelometer.

Acronyms used in this report:

CFC	Chlorofluorocarbon compound
CFC-12	Dichlorodifluoromethane (CF_2Cl_2)
CFC-11	Trichlorofluoromethane ($CFCl_3$)
CFC-113	Trichlorotrifluoroethane ($C_2F_3Cl_3$)
DAR	Ratio of deethylatrazine to atrazine concentrations in water
DEA	Deethylatrazine
DEET	N,N-diethyl-meta-toluamide
DWEL	Drinking-water equivalency level
N	Nitrogen
NAWQA	National Water-Quality Assessment Program
NSDWR	National Secondary Drinking Water Regulation
NWQL	National Water Quality Laboratory
P	Phosphorus
pptv	Part per trillion by volume
RPD	Relative percent difference
SC	Specific conductance
SF_6	Sulfur hexafluoride
SVOC	Semivolatile organic compound
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
VOC	Volatile organic compound

Hydrogeology, Ground-Water-Age Dating, Water Quality, and Vulnerability of Ground Water to Contamination in a Part of the Whitewater Valley Aquifer System near Richmond, Indiana, 2002–2003

By Paul M. Buszka, Lee R. Watson, and Theodore K. Greeman

Abstract

Assessments of the vulnerability to contamination of ground-water sources used by public-water systems, as mandated by the Federal Safe Drinking Water Act Amendments of 1996, commonly have involved qualitative evaluations based on existing information on the geologic and hydrologic setting. The U.S. Geological Survey National Water-Quality Assessment Program has identified ground-water-age dating; detailed water-quality analyses of nitrate, pesticides, trace elements, and wastewater-related organic compounds; and assessed natural processes that affect those constituents as potential, unique improvements to existing methods of qualitative vulnerability assessment. To evaluate the improvement from use of these methods, in 2002 and 2003, the U.S. Geological Survey, in cooperation with the City of Richmond, Indiana, compiled and interpreted hydrogeologic data and chemical analyses of water samples from seven wells in a part of the Whitewater Valley aquifer system in a former glacial valley near Richmond. This study investigated the application of ground-water-age dating, dissolved-gas analyses, and detailed water-quality analyses to quantitatively evaluate the vulnerability of ground water to contamination and to identify processes that affect the vulnerability to specific contaminants in an area of post-1972 greenfield development.

The aquifer system in the study area includes an unconfined sand and gravel aquifer used for public-water supply (upper aquifer) and a confined sand and gravel aquifer (lower aquifer) separated by a till confining unit. Several hydrogeologic and cultural measures indicate that the upper aquifer is qualitatively vulnerable to contamination: the upper aquifer is unconfined and has a shallow depth to the water table (from about 4.75 to 14 feet below land surface), low-permeability sediments in the unsaturated zone are thin (less than 10 feet thick), estimated ground-water-flow rates through the upper aquifer are relatively rapid (the highest estimated rates ranged from 0.44 to about 5.0 feet per day), and potential contaminant sources were present.

Ground-water-age dates indicate that ground-water samples represented recharge from about the time greenfield development began south of the ground-water-flow divide and that changes in water quality would lag changes in contaminant inputs. Estimates of ground-water age, computed with dichlorodifluoromethane (CFC-12) and trichlorotrifluoroethane (CFC-113) concentrations in water samples collected from seven observation wells in February and March 2003, indicated that water in the upper aquifer had recharged within about 13 to 30 years before sampling. Ground-water ages were youngest (from about 13 to 15 years since recharge) in water from the shallow wells along the glacial-valley margin and oldest (30 years) in water from a well at the base of the aquifer in the valley center. Ground-water ages determined for the shallow wells may be affected by mixing of recent recharge with older ground water from deeper in the aquifer, as indicated by upward hydraulic gradients between paired shallow and deep wells in the upper aquifer. Other parts of the Whitewater Valley aquifer system with similar hydrogeologic characteristics could be expected to have similarly young ground-water ages and residence times.

Analyses of water samples collected from the seven observation wells in August and September 2002 indicated that concentrations of chloride, sodium, and nitrate generally were larger in ground water from the upper aquifer than in other parts of the Whitewater Valley aquifer system. Drinking-water-quality standards for Indiana were exceeded in water samples from one well for chloride concentrations, from four wells for dissolved-solids concentrations, and from one well for nitrate concentrations. Application of low-level methods for trace-element analyses determined that concentrations of aluminum, cobalt, iron, lithium, molybdenum, nickel, selenium, uranium, vanadium, and zinc were less than or equal to 8 micrograms per liter; concentrations of arsenic, cadmium, chromium, and copper were less than or equal to 1 microgram per liter. Application of low-level analytical methods to water samples enabled the detection of several pesticides and volatile, semivolatile, and wastewater-related organic compounds;

concentrations of individual pesticides and volatile organic compounds were less than 0.1 microgram per liter and concentrations of individual wastewater organic compounds were less than 0.5 microgram per liter. The low-level analytical methods will provide useful data with which to compare future changes in water quality.

Results of detailed water-quality analyses, ground-water-age dating, and dissolved-gas analyses indicated the vulnerability of ground water to specific types of contamination, the sequence of contaminant introduction to the aquifer relative to greenfield development, and processes that may mitigate the contamination. Concentrations of chloride and sodium and chloride/bromide weight ratios in sampled water from five wells indicated the vulnerability of the upper aquifer to road-deicer contamination. Ground-water-age estimates from these wells indicated the onset of upgradient road-deicer use within the previous 25 years. Nitrate in the upper aquifer predates the post-1972 development, based on a ground-water-age date (30 years) and the nitrate concentration (5.12 milligrams per liter as nitrogen) in water from a deep well. Vulnerability of the aquifer to nitrate contamination is limited partially by denitrification. Detection of one to four atrazine transformation products in water samples from the upper aquifer indicated biological and hydrochemical processes that may limit the vulnerability of the ground water to atrazine contamination. Microbial processes also may limit the aquifer vulnerability to small inputs of halogenated aliphatic compounds, as indicated by microbial transformations of trichlorofluoromethane and trichlorotrifluoroethane relative to dichlorodifluoromethane. The vulnerability of ground water to contamination in other parts of the aquifer system also may be mitigated by hydrodynamic dispersion and biologically mediated transformations of nitrate, pesticides, and some organic compounds. Identification of the sequence of contamination and processes affecting the vulnerability of ground water to contamination would have been unlikely with conventional assessment methods.

Introduction

The Federal Safe Drinking Water Act Amendments of 1996 mandated states to assess the sources of water used by public-water systems within each state, inventory the contaminants within each source area, and assess the susceptibility of individual public-water systems to contamination (U.S. Environmental Protection Agency, 2006). The terms “susceptibility” and “vulnerability” are used to refer to the possibility for ground water to become contaminated because of potential sources of contamination; “vulnerability” is used in this report. Ground-water vulnerability commonly is determined by the proximity of potential contaminant sources, ground-water-flow and recharge rates, characteristics of contaminants, and other factors (Focazio and others, 2003). For example, several glacial aquifers in Indiana have been identified qualitatively as vulnerable to contamination because of their hydrogeologic characteristics: thin, permeable, unsaturated zones enable rapid transmission of recharge to the aquifer and permeable, saturated zones enable rapid horizontal movement of water and contaminants (Beaty and Clendenon, 1988; Fenelon and Moore, 1996; Kay and others, 2002). These vulnerability classifications could be improved by additional hydrologic-data collection and analyses that classify the residence time of ground water in an aquifer, whether specific types of contaminants already have reached ground water in very small concentrations, and hydrochemical and microbial processes that affect rates of specific contaminant entry to and removal from an aquifer. These enhancements can enable communities to better prioritize the potential for specific contaminants and sources to pollute the water source and to rank approaches to protect their drinking-water supply.

The U.S. Geological Survey (USGS) is involved in investigations of methods that can enhance the assessment of aquifer vulnerability to contamination (Focazio and others, 2003). The USGS National Water-Quality Assessment Program specifically has identified ground-water-age dating; detailed water-quality analyses of nitrate, pesticides, trace elements, and wastewater-related organic compounds; and assessed natural processes that affect those constituents as potential, unique improvements to existing techniques of vulnerability assessment (Eberts and others, 2005). For example, estimates of the time of ground-water recharge, such as using concentrations of chlorofluorocarbons (CFCs) or tritium/helium (Plummer and others, 1993; Rowe and others, 1999; Nelms and others, 2003), can indicate the residence time of ground water and associated contaminants. Analyses of trace elements in water can be done, using trace-level methods with reporting limits that are substantially less than applicable criteria for drinking-water quality (Faires, 1993; Garbarino, 1999; Indiana Administrative Code, 2006). The trace-level methods can provide baseline data to compare with results of future sampling and evaluate concentration trends before water-quality standards are exceeded (Ivahnenko and others, 1996). Analyses of pesticides and their transformation products (Adams and Thurman, 1991), volatile organic compounds (Buszka and others, 1995), and wastewater-related organic compounds (Seiler and others, 1999) in ground-water samples can identify prior influences of human activity and, by association, the vulnerability of an aquifer to contamination by these and similar compounds. Analyses of oxidation-reduction conditions by use of dissolved-gas concentrations (Rowe and others, 1999) and identification of transformations of human-affected compounds, such as atrazine (Adams and Thurman, 1991) and chlorofluorocarbon compounds, can indicate chemical or biological processes that may affect or delay contaminant transport in ground water.

An assessment of ground-water quality also can involve determining concentrations of other dissolved constituents such as major cations and anions, alkalinity, and nutrients. Concentrations of major cations and anions, including calcium, magnesium, sodium, potassium, chloride, sulfate, fluoride, and silica, can be compared with water-quality standards to evaluate possible limitations on water use and can be used to interpret possible sources of contaminants. Nutrients, including nitrate, nitrite, ammonia, organic nitrogen, orthophosphate, and phosphorus, can be compared with water-quality standards (for nitrate and nitrite) and with data ranges from other studies to interpret human effects on water quality. For example, Nolan and Hitt (2003, p. 9–10) reported concentrations of nutrients in samples of shallow ground water in the United States that were unaffected by human influences: less than 1.1 mg/L as N for nitrate (75th percentile of 320 samples), 0.01 mg/L as N for nitrite, 0.02 mg/L as N for ammonia (median of 78 samples), and 0.01 mg/L as phosphorus (as P) for orthophosphate (median of 67 samples); concentrations greater than these can be used to indicate possible human effects on nutrient concentrations in ground water.

The USGS, in cooperation with the City of Richmond, Indiana, conducted a study in 2002 and 2003 to evaluate the application of advanced ground-water-age dating, dissolved-gas analyses, and detailed analytical techniques to better describe ground-water quality, classifications of the vulnerability of ground water to contamination, and chemical and biological processes that affect that vulnerability to contamination in areas of new development. The study was done in a part of the Whitewater Valley aquifer system (fig. 1), which is the most-productive aquifer system in the Whitewater River Basin of east-central and southeastern Indiana (Beaty and Clendenon, 1988). The Whitewater Valley aquifer system is used for industrial, municipal, and residential water supply but is highly susceptible to contamination because of its lack of overlying clay or fine-grained layers and its shallow depth to ground water (Beaty and Clendenon, 1988, p. 55 and plate 3; Indiana Department of Environmental Management, 1986, p. 152 and 155). Richmond obtains some of its drinking water from production wells in an upper, unconfined part of the aquifer system (referred to in this report as the upper aquifer) in a former glacial valley on the east side of Richmond (fig. 2). A part of the upper aquifer that extends from about 0.2 to about 1.8 mi south of U.S. Highway 40 (US 40) was designated by City of Richmond ordinance in 1999 as an Aquifer Protection District (City of Richmond, Indiana, 2006; Robert Goodwin, Richmond Advisory Plan Commission, written commun., June 7, 1999) (fig. 2).

Hydrologic interpretations are needed to provide information to enable public interests to plan to accommodate apparent aquifer vulnerability in areas of new or greenfield development over the Whitewater Valley aquifer system and in other shallow glacial aquifers. The term greenfield development refers to the development of previously undeveloped (green) parcels in suburban or nonurban locations with limited existing infrastructure and development (Schroeer, 1999). Land use over the upper aquifer and in an associated surface watershed near Richmond includes agricultural areas that have been industrially or commercially developed since about 1972. Based on the proximity of the aquifer to recent (after about 1972) commercial and industrial development, it was determined that an investigation of this particular study area would provide a useful, transferable example of the application of ground-water-age dating, dissolved-gas analyses, and detailed analytical techniques to refine classifications of hydrogeology, water quality, and hydrochemical processes that affect assessments of ground-water vulnerability in glacial aquifer systems of the midwestern United States.

Purpose and Scope

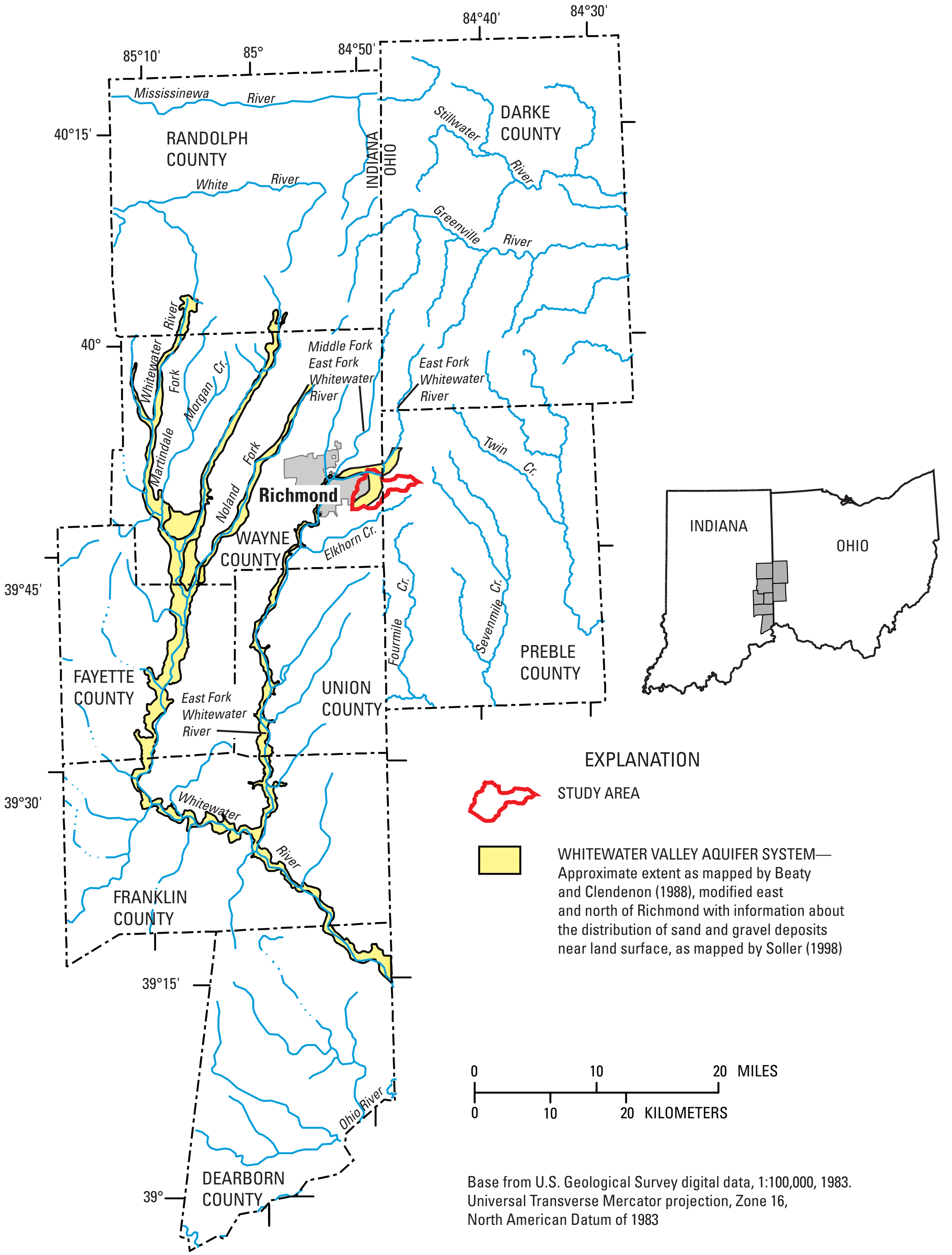
This report describes the results of a USGS study conducted in 2002 and 2003 in cooperation with the City of Richmond, Indiana. The study applied techniques of ground-water-age dating, dissolved-gas analyses, and detailed chemical analyses to evaluate hydrogeology, ground-water flow, water quality, and the vulnerability of ground water to contamination in a shallow, unconfined glaciofluvial aquifer (the upper aquifer) in a part of the Whitewater Valley aquifer system near Richmond, Indiana. To identify ground-water quality that potentially was affected by changes in land-use practices, the study focused on an area that had undergone urban development after about 1972. The report describes

1. The hydrogeology of the aquifer system in the study area, with special emphasis on the upper aquifer;
2. Interpretations of ground-water-age dating, using chlorofluorocarbons compounds (CFCs) to understand the residence time of ground water in the upper aquifer relative to changes in land use;
3. The quality of water in the upper aquifer, based on a one-time sampling, chemical analysis, and interpretation relative to land use and water-quality standards; and
4. A characterization of the vulnerability of ground water in the upper aquifer to contamination and indications of hydrochemical and biological processes that affect that vulnerability with respect to specific contaminants.

The study was intended to provide water-resource managers with methods and examples of the types of baseline data needed to implement effective assessments of the vulnerability of ground water to contamination in this and in other parts of the Whitewater Valley aquifer system and in other shallow aquifers in similar hydrogeologic settings throughout the glaciated midwestern United States. Information describing the study area, land use, data-collection methods, and methods of data analysis also is included in this report.

Description of the Study Area

The study area included about 8.6 mi^2 in east-central Indiana (eastern Wayne County) and west-central Ohio (western Preble County) and included part of the City of Richmond, Ind. (fig. 1). The study focused on a part of the Whitewater Valley aquifer system in a former glacial valley (Gooding,



Base from U.S. Geological Survey digital data, 1:100,000, 1983.
Universal Transverse Mercator projection, Zone 16,
North American Datum of 1983

Figure 1. Study area near Richmond, Indiana, relative to the Whitewater Valley aquifer system and major streams, Indiana and Ohio.

1957) that extends south from the East Fork Whitewater River and south and southwest approximately to where Short Creek crosses Wernle Road (fig. 2). The upper aquifer in the study area has an area of about 3.5 mi^2 and is the source of ground water for public-supply wells on the east side of Richmond, Ind. (By USGS policy and Indiana Code IC 5-14-3-4 [Indiana Legislative Services Agency, undated], the location of water-supply wells are identified neither by coordinates nor shown on maps.) Richmond obtains its public-water supply from the Middle Fork East Fork Whitewater River and from ground water (Indiana-American Water, 2006). The study area also included the watersheds of streams that flow across and potentially contribute recharge to the upper aquifer: an unnamed tributary to the East Fork Whitewater River and parts of the watersheds of Short Creek and the East Fork Whitewater River (fig. 3). An area of detailed study that included industrial and commercial development after about 1972 over the upper aquifer was selected for installation of wells, water sampling, and detailed data analysis (fig. 3). The area of detailed study encompasses approximately 2.7 mi^2 of the area of the upper aquifer, or about 77 percent of its extent.

The study area is in the central part of the New Castle Till Plains and Drainageways Physiographic Division of the Central Till Plain region (Gray, 2000, p. 6 and plate 1). The New Castle Till Plains and Drainageways Physiographic Division near the study area is characterized by thin deposits of till (less than 50 ft to 100 ft thick), terminal moraine deposits (Gray, 2000, p. 6; Woodfield, 1994, fig. 68, p. 158), and valley-train deposits where tributaries of the Whitewater River have incised valleys. The southerly to southwesterly trending valleys that cross this physiographic division make up a distinguishing physiographic feature of the region (Gray, 2000); therefore, a study of this setting should be representative of other parts of the Whitewater Valley aquifer system and similar hydrogeologic settings in the midwestern United States.

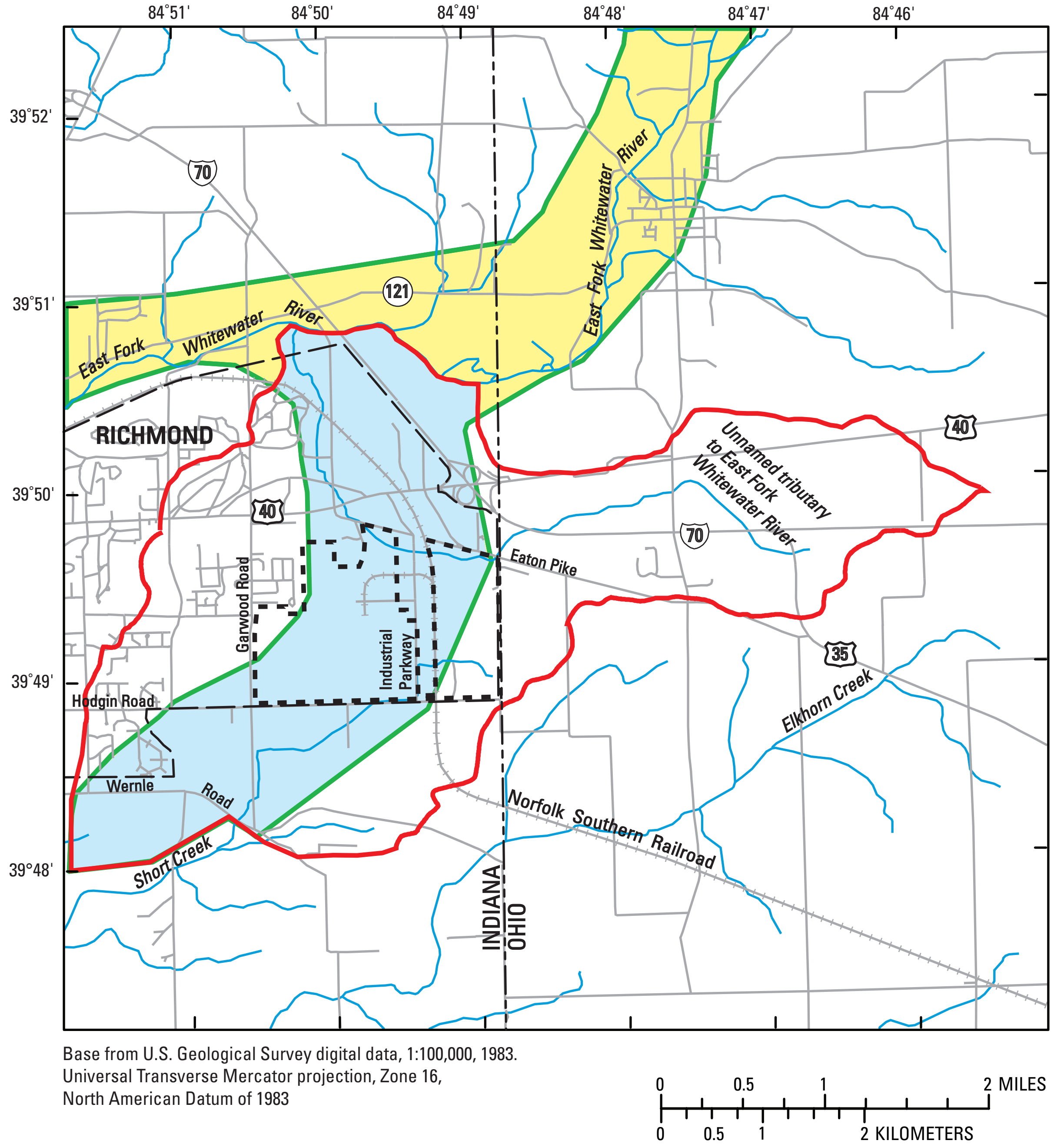
Short Creek (fig. 3) and its tributaries drain the southern half of the former glacial valley to the southwest, following the valley through the study area and eventually discharging to the East Fork Whitewater River. An ephemeral, unnamed tributary to the East Fork Whitewater River drains the eastern and northern parts of the study area (fig. 3). Parts of the study area in Indiana that are east and west of the former glacial valley have soils derived from fine-grained till deposits (Blank, 1987). Runoff and ground-water discharge from these areas and similar areas of Ohio likely drain to Short Creek and its tributaries, to the unnamed tributary to the East Fork Whitewater River, and directly to the East Fork Whitewater River.

Land-surface altitudes in the center of the former glacial valley range from 1,050 to 1,055 ft above the vertical datum (U.S. Geological Survey, 1981) and decrease to about 1,031 ft to the southwest where Short Creek crosses Garwood Road. Land-surface altitudes also decrease from the valley center to about 960 ft where the East Fork Whitewater River borders the study area (U.S. Geological Survey, 1981). The valley is flanked by ridges to the northwest and west (highest altitudes of about 1,090 ft) and southeast and east (highest altitudes of about 1,170 ft). For comparison, watersheds that drain across the former glacial valley have land-surface altitudes of about 1,170 ft near the headwaters of Short Creek and about 1,200 ft near the headwaters of the unnamed tributary to the East Fork Whitewater River (U.S. Geological Survey, 1981).

The climate of Wayne County, Indiana, is continental and is characterized by strongly marked seasons (Scheeringa, 2002). The study area is in the transition zone between a cool, temperate, continental climate to the north and a warm, temperate, continental climate to the south. Summers are hot and humid; winters are cold and damp. Temperatures range from an average high/low of 1.2 /8.2°C in January to a high/low of 29.2/16.4°C in July, based on weather data for Richmond from 1971 through 2000 (Midwestern Regional Climatic Center, 2005a). The average annual temperature for Richmond was 10.4°C from 1971 through 2000 (Midwestern Regional Climatic Center, 2005a). Monthly precipitation ranges from an average of 2.51 in. in January to 4.41 in. in May, based on weather data for Richmond from 1971 through 2000 (Midwestern Regional Climatic Center, 2005b). The average annual precipitation for Richmond was 39.55 in./yr from 1971 through 2000 (Midwestern Regional Climatic Center, 2005b). Precipitation is greatest from March through July but is received each month of the year.

Land-Use Characteristics

Land uses in the study area may contribute contaminants that affect ground-water quality in the upper aquifer. Land uses were classified for the study area by visually interpreting scanned aerial photography taken in July 2003 (U.S. Department of Agriculture, 2003). The part of the study area that overlies the upper aquifer mainly was agricultural land that was cultivated for corn and soybeans at the time of this study. Agricultural land uses may be nonpoint sources of nutrients, pesticides, and bacterial contaminants (U.S. Environmental Protection Agency, 2004). Areas with industrial and commercial land uses included those along Industrial Parkway (fig. 4, table 1) that have developed since about 1972 (Richmond Palladium-Item, 1972) and a mixture of pre-and post-1972 commercial and industrial development over the upper aquifer near US 40. Commercial and industrial areas may be point sources of a variety of nutrients, trace elements, synthetic and human-affected organic compounds, and bacteria (U.S. Environmental Protection Agency, 2004). Other land uses that overlay the aquifer include residential and forested areas. Single-family residences in the study area, such as those along Hodgin Road, Eaton Pike, and parts of Garwood Road that are not in large housing developments, mainly produce water from domestic wells and dispose of domestic wastewater through septic systems (table 1). Septic systems may be sources of nutrients, bacteria, and a variety of synthetic organic compounds (U.S. Environmental Protection Agency, 2004). Principal transportation land uses (fig. 4) that crossed the upper aquifer include US 40; several local roads

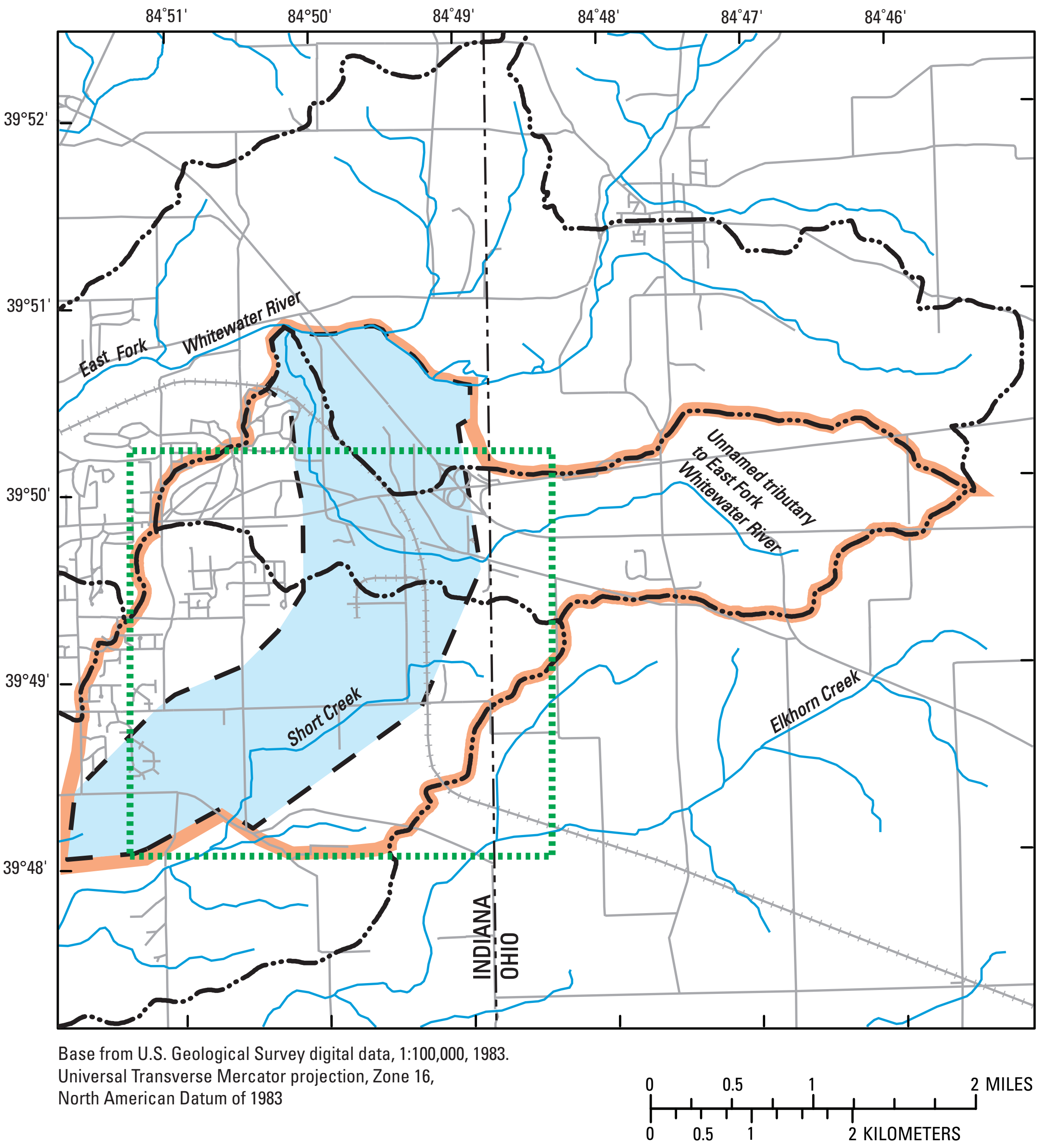


Base from U.S. Geological Survey digital data, 1:100,000, 1983.
Universal Transverse Mercator projection, Zone 16,
North American Datum of 1983

EXPLANATION

🟦	FORMER GLACIAL VALLEY AND UPPER AQUIFER—Approximate extent
🟨	COARSE-GRAINED STRATIFIED SEDIMENT, WHITEWATER VALLEY AQUIFER SYSTEM—Approximate extent of sand and gravel deposits near land surface, as mapped by Soller (1998), and modified using information about the distribution of the Whitewater Valley aquifer system from Beaty and Clendenon (1988). Represents the general distribution of the Whitewater Valley aquifer system
—	STUDY AREA—Includes the watershed of the unnamed tributary to East Fork Whitewater River and parts of the watersheds of Short Creek and the East Fork Whitewater River
▪▪▪▪	AQUIFER PROTECTION DISTRICT—Approximate extent as defined in City of Richmond, Indiana, Ordinance 33–1999
— —	RICHMOND, INDIANA, CITY LIMIT

Figure 2. Location of the study area, the approximate extent of coarse-grained sediments of the Whitewater Valley aquifer system, the former glacial valley and upper aquifer, and the Aquifer Protection District near Richmond, Indiana.



Base from U.S. Geological Survey digital data, 1:100,000, 1983.
Universal Transverse Mercator projection, Zone 16,
North American Datum of 1983

EXPLANATION

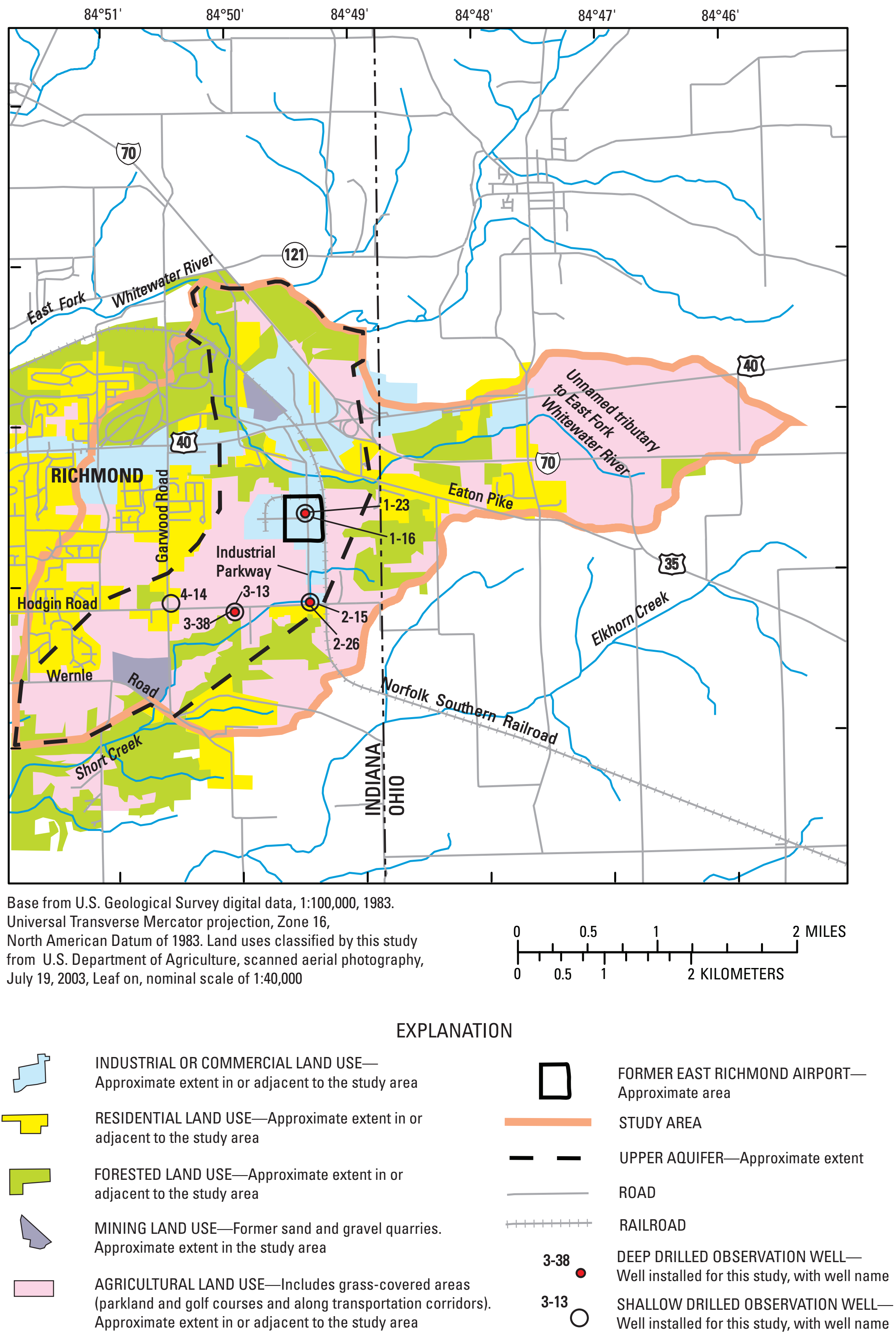
▨ FORMER GLACIAL VALLEY AND UPPER AQUIFER—Approximate extent

▬ STUDY AREA—Includes the watershed of the unnamed tributary to East Fork Whitewater River and parts of the watersheds of Short Creek and the East Fork Whitewater River

–··– WATERSHED BOUNDARY—Approximate extent of the watersheds of the unnamed tributary to East Fork Whitewater River and parts of Short Creek and the East Fork Whitewater River

······ AREA OF DETAILED STUDY—Map extent for figures 6, 12, and 13

Figure 3. Location of the study area relative to selected surface watersheds, the upper aquifer, and the area of detailed study near Richmond, Indiana.



Base from U.S. Geological Survey digital data, 1:100,000, 1983.
Universal Transverse Mercator projection, Zone 16,
North American Datum of 1983. Land uses classified by this study
from U.S. Department of Agriculture, scanned aerial photography,
July 19, 2003, Leaf on, nominal scale of 1:40,000

Figure 4. Developed areas, structures, and land uses in the study area relative to the upper aquifer and observation wells installed for this study near Richmond, Indiana, 2003.

Table 1. Major land-use categories and activities in the study area near Richmond, Indiana, 2003.

Land-use category	Type of activity	General location	Water supply	Wastewater disposal
Agriculture	Primarily cultivation of corn and soybeans	West of Industrial Parkway and north and south of Hodgin Road; also east of the Norfolk Southern Railroad (Indiana and Ohio); and on both sides of Eaton Pike, I-70, and US 40 (Ohio)	None; individual domestic or farm wells	Septic systems at farm residences; drain tiles discharge to Short Creek near Hodgin Road.
Residential	1. Residences, primarily on lots of about 1 acre or more	1. Along Hodgin Road, parts of Garwood Road, near Eaton Pike/US 35 (Indiana and Ohio) and US 40 (Ohio)	1. Individual domestic wells	1. Septic systems.
	2. Higher-density residential developments, primarily on lots less than about 1 acre	2. West of upper aquifer on east and west sides of Garwood Road, north and south of Hodgin Road and near US 40 (Indiana)	2. Municipal water supply in higher-density residential developments (Indiana)	2. Sanitary sewers.
Industrial	1. Plastics manufacturing, clay-target fabrication, industrial machinery and equipment, auto parts and supplies, materials handling and heavy machinery, wood treating, refrigeration	1. Along Industrial Parkway	1. Municipal water supply and some private wells	1. Sanitary sewers.
	2. Plastics manufacturing, concrete products, logistics, warehousing, and storage	2. North and south of US 40 (Indiana)	2. Municipal water supply and some private wells	2. Sanitary sewers.
Commercial	1. Building contractor, storage, indoor athletic facility along Industrial Parkway	1. Along Industrial Parkway	1. Municipal water supply	1. Mainly sanitary sewers (Indiana).
	2. Retail, gas stations, auto repair, restaurants, offices, and hotels, north and south of US 40	2. Near US 40	2. Municipal water supply	2. Mainly septic systems (Ohio).
Forested	Land not cultivated or developed	Along Short Creek (creek shown in fig. 4), south of Hodgin Road; north of US 40 along northern extent of study area; individual areas east of Norfolk Southern Railroad (Indiana and Ohio)	None	None.

such as Industrial Parkway, Hodgin Road, and Garwood Road; and a railroad. Transportation-related sources of contaminants may include highway runoff, deicers, and spills of materials transported along roadways or railroads (U.S. Environmental Protection Agency, 2004).

From about 1944 through about 1972, the former East Richmond Airport occupied land adjacent to and extending about 1,300 ft west of a railroad right of way (fig. 4) (Stegall, 1999; Richmond Palladium-Item, 1972; U.S. Geological Survey, 1960). The airport had a grass landing strip and several small buildings (U.S. Geological Survey, 1960). As of 1966, pesticide and nitrogen fertilizers were stored at the facility (Buck, 1997). At that time, the airport was used as a staging facility for crop-dusting operations. Many of the industrial and commercial land uses developed after about 1972 are in areas on or adjacent to the former airport along what is now Industrial Parkway.

Land uses in the parts of the watersheds that are upstream from the upper aquifer may affect ground-water quality. This may occur where surface water infiltrates into the upper aquifer or where ground water from adjacent deposits discharges to the upper aquifer. Land in the upstream parts of these watersheds principally was used for cultivated agriculture or was forest. Some land along US 40 and parts of US 35 was commercially developed, and some residential development was dispersed throughout the area. The principal transportation-related land uses in these watersheds include a railroad and the roads and right-of-way along US 40, I-70, US 35, and several smaller roads.

Methods of Data Collection and Analysis

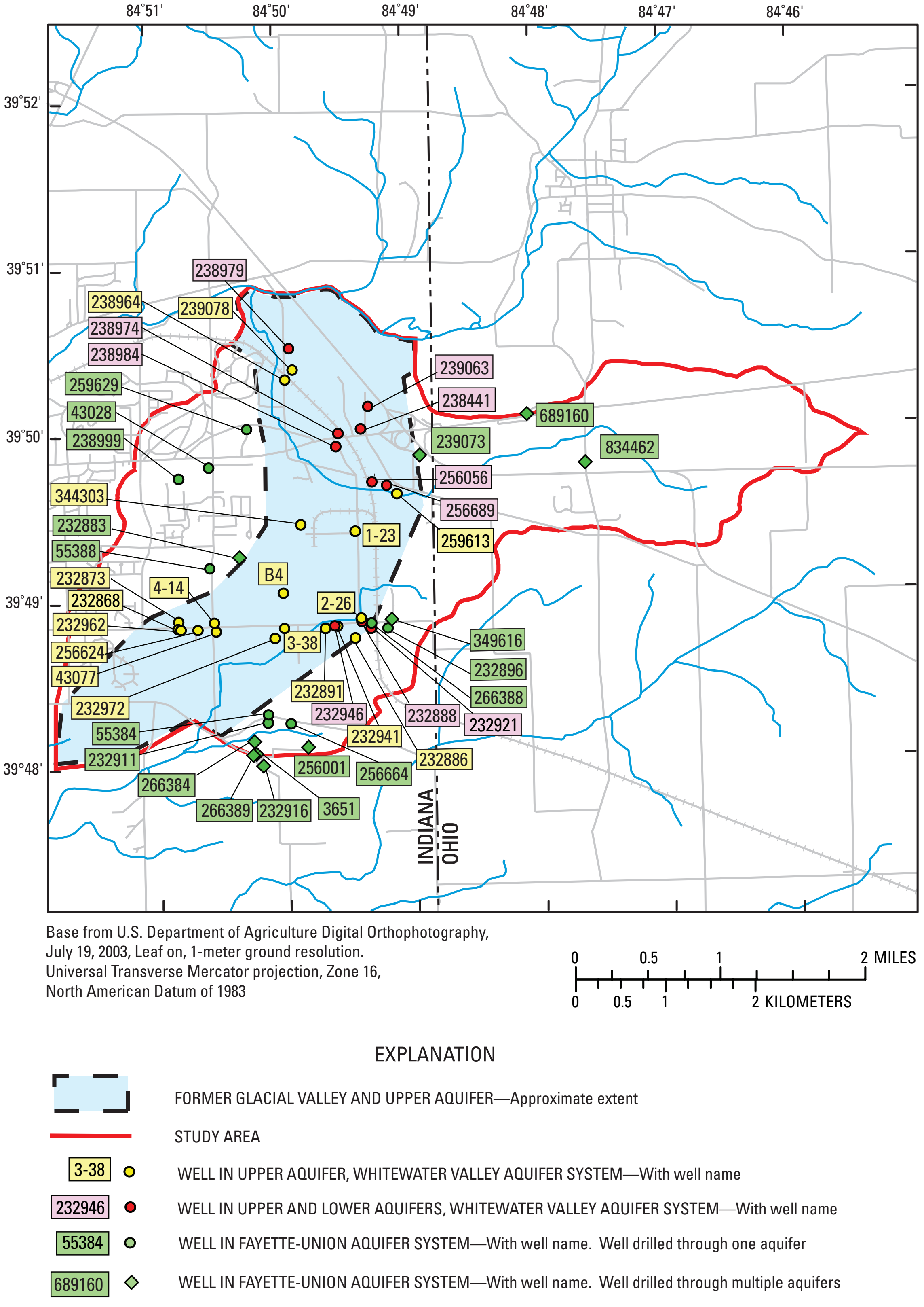
Data collection included installation of observation wells to obtain ground-water levels and collect samples for chemical analysis. Lithologic data were collected during well installation and through borehole geophysical logging of natural gamma radiation. Additional lithologic data were compiled from on-line water-well-log databases (Indiana Department of Natural Resources, 2005; Ohio Department of Natural Resources, 2006) and boring logs from a previous geotechnical study (West and Bergman, 1973) (fig. 5). Water samples were collected for chemical analysis from the upper aquifer to estimate the temperature of ground-water recharge, interpret the age of ground water, describe water quality, and describe indicators of vulnerability to contamination. Quality-assurance samples also were collected during water sampling to identify any problems with sampling-equipment cleaning and to evaluate sampling reproducibility and (or) variability.

Well-Site Selection and Installation

Observation wells were installed for this study (table 2 and fig. 6) to obtain hydrogeologic data and provide a long-term network that would enable measurement of water levels and sampling of ground-water quality in the upper aquifer. Seven observation wells were installed at four sites (fig. 4): two wells within an industrial area (wells 1-16 and 1-23); two wells in a commercial area near the corner of Industrial Parkway and Hodgin Road (wells 2-15 and 2-26); two wells in an agricultural area (wells 3-13 and 3-38); and one well in an area between single-family residences and an agricultural area (well 4-14). The first number in each observation-well identifier is the site number; the second number is the approximate depth of the base of the well screen from land surface, in feet. At three sites, paired shallow and deep wells were installed to enable comparison of water levels, ground-water-age estimates, and water quality near the water table and at the base of the upper aquifer.

A hollow-stem-auger drilling system was used to install the observation wells. Split-barrel core samples were taken at the completion depth of the deepest well at each site and classified on site. All well screens and casings were constructed from flush-joint threaded, 2-in.-inside-diameter, polyvinyl chloride components. Well screens were slotted with 0.010-in. openings and were 10 ft in length for the shallow wells (wells 1-16, 2-15, 3-13, and 4-14) and 5 ft in length for the deep wells (wells 1-23, 2-26, and 3-38). The augers, soil-sampling equipment, and well components were cleaned before use and between drilling of each well. Water used during well installation was potable and was obtained from the Richmond municipal water supply. The annular space surrounding the observation-well screens was filled by collapse of natural material. Bentonite grout was used to fill the annular space from approximately 2 ft above the top of the screen to within 5 ft of land surface. The annular space was filled with concrete from the top of the grout to the land surface. Flush-mount surface casings were used.

Observation wells were developed by pumping to obtain a hydraulic connection between the well and the aquifer and until water-quality parameters stabilized. The observation wells sustained pumping rates during development that ranged from 3.5 to 5.0 gal/min. Well-development equipment was cleaned before use and between wells with a dilute detergent solution and was rinsed with deionized water. During well development, pH, specific conductance, water temperature, and dissolved oxygen were measured with a multiparameter water-quality meter fitted with a flow-through chamber attached to the pump discharge hose. Turbidity was measured with a portable turbidimeter. Well development was considered complete when values of water produced during development stabilized to within 0.25 standard units for pH, to 50 μS/cm for specific conductance, and within 10 percent for dissolved oxygen and turbidity. Well development was completed at least 1 week before the initial water-quality sampling.



Base from U.S. Department of Agriculture Digital Orthophotography,
July 19, 2003, Leaf on, 1-meter ground resolution.
Universal Transverse Mercator projection, Zone 16,
North American Datum of 1983

EXPLANATION

- FORMER GLACIAL VALLEY AND UPPER AQUIFER—Approximate extent
- STUDY AREA
- 3-38 ● WELL IN UPPER AQUIFER, WHITEWATER VALLEY AQUIFER SYSTEM—With well name
- 232946 ● WELL IN UPPER AND LOWER AQUIFERS, WHITEWATER VALLEY AQUIFER SYSTEM—With well name
- 55384 ● WELL IN FAYETTE-UNION AQUIFER SYSTEM—With well name. Well drilled through one aquifer
- 689160 ◇ WELL IN FAYETTE-UNION AQUIFER SYSTEM—With well name. Well drilled through multiple aquifers

Figure 5. Selected wells used to interpret extent and thickness of the upper aquifer and wells drilled into the lower aquifer or the Fayette-Union aquifer system near Richmond, Indiana. The Fayette-Union aquifer system is laterally adjacent to the upper and lower aquifers; it consists of thin sand and gravel units (less than 10 feet thick) within variably thick till sequences.

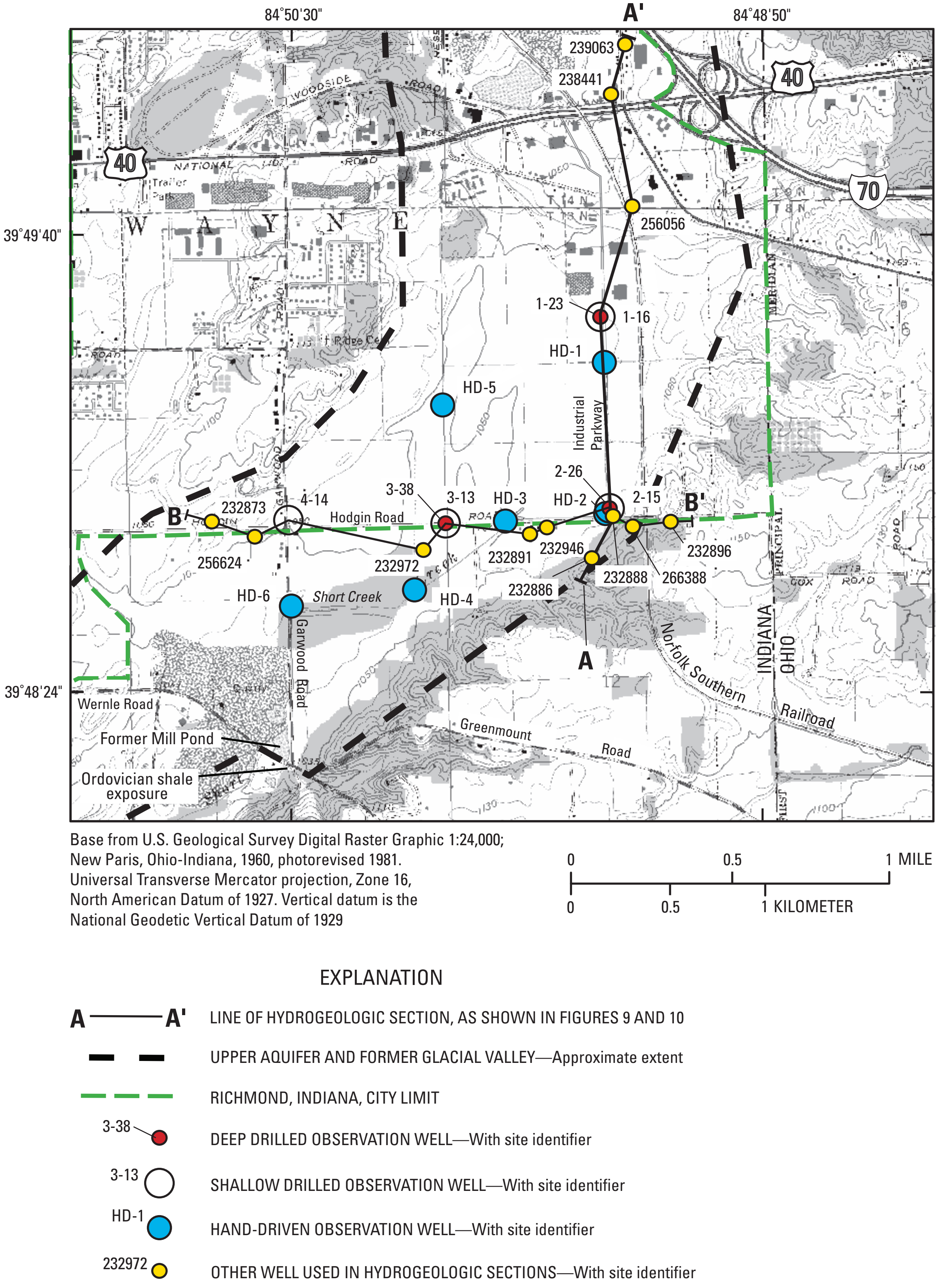
Table 2. Selected characteristics of observation wells installed for this study in the upper aquifer near Richmond, Indiana.

[USGS, U.S. Geological Survey; vertical datum is National Geodetic Vertical Datum of 1929; negative distance to measuring point from land surface indicates that measuring point is below land surface]

Well name	USGS station-identification number	Land-surface altitude (feet above vertical datum)	Distance to measuring point from land surface (feet)	Total depth from measuring point (feet)	Measuring-point altitude[1] (feet above vertical datum)	Well-screen length (feet)	Screened interval (feet above vertical datum)
Observation wells							
Well 1-16	394924084492501	1,053.01	-0.28	16.8	1,052.73	10	1,035.9–1,045.9
Well 1-23	394924084492502	1,052.88	-.30	23.3	1,052.58	5	1,029.3–1,034.3
Well 2-15	394852084492501	1,058.42	-.33	15.9	1,058.09	10	1,042.2–1,052.2
Well 2-26	394852084492502	1,058.38	-.20	26.7	1,058.18	5	1,031.5–1,036.5
Well 3-13	394851084500001	1,043.16	-.20	11.4	1,042.96	10	1,031.6–1,041.6
Well 3-38	394851084500002	1,043.56	-.21	38.1	1,043.35	5	1,005.3–1,010.3
Well 4-14	394852084503301	1,046.76	-.31	14.0	1,046.45	10	1,032.5–1,042.5
Hand-driven wells							
Well HD-1	394916084492501	[2]1,053.78	2.51	15.0	1,056.29	3	1,041.3–1,044.3
Well HD-2	394852084492601	[2]1,049.11	2.73	7.0	1,051.84	3	1,044.8–1,047.8
Well HD-3	394851084494701	[2]1,039.64	3.17	7.1	1,042.8	3	1,035.7–1,038.7
Well HD-4	394840084500701	[2]1,034.76	3.00	7.0	1,037.76	3	1,030.8–1,033.8
Well HD-5	394910084500001	[2]1,042.13	2.12	7.0	1,044.25	3	1,037.3–1,040.3
Well HD-6	394838084503301	[2]1,031.34	2.85	7.2	1,034.19	3	1,027.0–1,030.0

[1] The measuring point is a mark on the top of the casing of the well.

[2] Streambed elevation at the time well elevations were surveyed.



Base from U.S. Geological Survey Digital Raster Graphic 1:24,000;
New Paris, Ohio-Indiana, 1960, photorevised 1981.
Universal Transverse Mercator projection, Zone 16,
North American Datum of 1927. Vertical datum is the
National Geodetic Vertical Datum of 1929

Figure 6. Area of detailed study with observation wells installed for this study, selected other wells, and lines of hydrogeologic sections A-A′ and B-B′ through the upper aquifer near Richmond, Indiana.

Natural gamma activity was measured in wells 1-23, 2-26, and 3-38 as an aid to classify aquifer lithology. The geophysical logging was done after well development. Natural gamma geophysical logs are used widely for identifying the lithology of aquifer materials (Keys, 1990). Fine-grained sediments that contain abundant clay generally also contain larger amounts of naturally occurring radioisotopes that emit more gamma radiation than do coarse-grained sediments. In this study, a gamma-radiation count of about 60 counts per second or less is considered to indicate coarse-grained sediments, based on a comparison of the gamma log and driller's-log data. Coarse-grained sediments, such as sand and gravel, are considered aquifer materials in this study.

Hand-driven, temporary wells were installed at six sites (HD-1, HD-2, HD-3, HD-4, HD-5, and HD-6) in Short Creek and its tributaries (fig. 6, table 2). These wells were used to measure water levels at the water table in the upper aquifer and as reference points to measure surface-water-stage altitudes outside the well casings. Hand-driven wells were constructed by hammering a 2-in.-diameter steel well point and casing into the streambed. Screen openings in the well points ranged from 0.010 to 0.040 in.; the screens were 3 ft long. The hand-driven wells were removed after the data collection was complete.

Ground-Water-Quality Sampling and Analyses

Water samples were collected from observation wells during late August and early September 2002. The cap was removed from each well, and the water level was allowed to equilibrate before the depth to water was measured with an electric measuring tape. Using the depth to water in the well, the total depth of the well, and the diameter of the well, the volume of water in the well was calculated to determine the minimum volume of water to be pumped from the well prior to sample collection. A submersible, positive-displacement pump constructed of polytetrafluoroethylene and stainless-steel components was used to purge and sample the wells.

Equipment used for sampling was cleaned before sampling each well, using a sequential rinse with (1) a dilute solution of laboratory-grade, non-phosphate detergent and tap water; (2) tap water; (3) a 5-percent solution of trace-element-grade hydrochloric acid in deionized water; and (4) deionized water. The pump intake was set in each well about 2 ft below the static water level and lowered farther only if required by drawdown in the well. Withdrawals from the well were monitored by volumetric measurement. During purging of wells sampled in August and September 2002, the five field parameters—pH, specific conductance, dissolved oxygen, water temperature, and turbidity—were monitored. Water withdrawn from the well was routed through a flow-through chamber of a multiparameter water-quality meter to measure pH, specific conductance, dissolved oxygen, and water temperature. Turbidity was monitored by periodically collecting and analyzing a pumped sample. The wells were purged prior to sample collection so that not less than three times the amount of water standing in the well was removed. When a minimum of three volumes of water were pumped and the field parameters had stabilized, the flow-through chamber was disconnected and the sample collection was begun. Water pumped from the wells was discharged away from the wells to prevent cycling or artificial recharge to the wells.

Samples were collected, filtered, preserved, and processed in the field according to protocols required and recommended by the USGS Field Manual for the Collection of Water-Quality Data (U.S. Geological Survey, variously dated). Those protocols specified the order in which bottles were filled, filtering equipment and techniques, sample preservation, holding time, and shipping requirements. Bottles, filtering media and equipment, and sample preservatives for each type of sample or analytical schedule were supplied through the USGS National Water Quality Laboratory (NWQL) in Lakewood, Colorado, for quality-assurance purposes.

The water samples were analyzed for concentrations of selected major cations and anions, alkalinity, nutrients, trace elements, pesticides and their transformation products, volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs), and wastewater-related organic compounds (table 3, back of report), using low-level analytical techniques when available. Samples for analysis of major cations and anions, alkalinity, nutrients, and trace elements were field filtered with a 0.45-micrometer pore-size capsule filter; a new filter was used for each well. All other samples were not filtered before shipment to the laboratory. Samples for analyses of pesticides and their transformation products and wastewater-related organic compounds were filtered at the NWQL when they were prepared for analysis. Samples for analysis of major cations (calcium, magnesium, sodium, and potassium) and trace elements were acidified in the field by addition of sufficient nitric acid to reach a sample pH of less than 2.

A filtered sample was collected from each well for a field titration of alkalinity, the acid-neutralizing capacity of the water (Rounds and Wilde, 2001). The titration was done with a temperature-compensating digital pH meter that was calibrated daily. A calibration log was recorded to monitor the performance and maintenance of the meter and the probe. The titration apparatus consisted of the meter, a digital titrator for the addition of acid, a battery-powered magnetic stirrer with a polytetrafluoroethylene stir bar, and glassware. Lot numbers and expiration dates of the acid cartridges were recorded.

Water was collected during the August and September 2002 sampling for quantitative analysis of dissolved gases (methane, carbon dioxide, nitrogen, oxygen, and argon) and sulfur hexafluoride. Dissolved-gas samples were analyzed at the USGS Dissolved Gas Laboratory in Reston, Virginia; methods used are outlined in Busenberg and Plummer (2000). Two samples from each well were analyzed for dissolved-gas concentrations; the first sample collected was considered the water sample, and the second sample was considered the sequential duplicate.

Because of an aquifer-mineral-related interference with sulfur hexafluoride concentrations, additional ground-water samples were collected in February and March 2003 to analyze the concentrations of CFCs in water and compute estimates of ground-water ages. These compounds included dichlorodifluoromethane (CFC-12 or CF_2Cl_2), trichlorofluoromethane (CFC-11 or $CFCl_3$), and trichlorotrifluoroethane (CFC-113 or $C_2F_3Cl_3$). The same submersible pump as described previously was fitted with refrigeration-grade 0.25-in. copper tubing at its outlet. The pump was placed near the top of the well screen or at least 5 ft below the water table for shallow wells that intersected the water table. The pump and copper tubing were purged with at least 18.9 L of ground water and were sampled, using methods described by Busenberg and Plummer (1992). Specific conductance, pH, and temperature of the ground water were recorded during well purging before CFC sample collection; dissolved oxygen and turbidity were not monitored during this activity.

Five glass ampoules of water were collected from each well for CFC analysis. The ampoules were purged with nitrogen and sealed, using a MAPP (liquefied petroleum gas combined with methylacetylene-propadiene) blowtorch to eliminate atmospheric contact with the sample. The sealed samples were submitted for analysis to the USGS Dissolved Gas Laboratory in Reston, Virginia. Analyses were done with a purge-and-trap extraction, followed by compound separation with a gas chromatograph and compound detection with an electron-capture detector (Busenberg and Plummer, 1992). Three samples from each well were analyzed for concentrations of CFCs, with a detection limit of about 1 pg/kg of water.

Quality-Assurance Sampling and Analyses

Field quality-assurance components included multi-parameter water-quality-meter calibration, turbidimeter-operation checks, equipment cleaning between sampling sites, sample-custody documentation, and field quality-control samples. Quality-assurance data were collected to identify problems with cleaning of sampling equipment (equipment blanks) and to evaluate the reproducibility of the sampling (sequential duplicates).

Before use each sampling day, the electrometric multimeter was calibrated, using laboratory-grade calibration solutions and following manufacturer's procedures and protocols in the USGS Field Manual for the Collection of Water-Quality Data (U.S. Geological Survey, variously dated). Performance of the portable nephelometric turbidimeter was checked daily, using standard cells and following manufacturer's procedures and protocols in the USGS Field Manual for the Collection of Water-Quality Data (Anderson, 1998).

Equipment blanks were collected and analyzed to determine whether the water samples were being contaminated by the sampling equipment or by residue from previous samples. Equipment blanks were prepared by pumping either deionized water or organic-free water through the sampling apparatus after the pre-sampling cleaning protocol. Deionized water was used to prepare the equipment blank for analyses of major cations and anions and nutrients and trace elements. Reagent-grade organic-free water was used to prepare all other equipment blanks. The equipment blank collected before sampling well 2-15 was analyzed for all constituents, except volatile organic compounds. A second equipment blank collected before sampling well 4-14 was analyzed only for volatile organic compounds.

Concentrations of constituents and properties in equipment blanks were compared with analytical results from water samples to assess whether sample-collection interferences may be present. The results were grouped in the following categories:

1. No equipment interference; constituent was not detected in the equipment blank(s) or not detected in the water sample.
2. No apparent equipment interference; constituent concentration in one or more water samples was more than 10 times the largest concentration detected in the equipment blank(s).
3. Potential interference; constituent concentration in one or more water samples was within 10 times the largest concentration detected in the equipment blank(s).

Sequential duplicates were used to evaluate the reproducibility of the sampling and analysis. A sequential duplicate is a sample collected in immediate succession to the water sample from the same source, using the same equipment and methods. Sequential duplicates were collected from well 3-13 for major cations and anions, nutrients, and pesticides and from well 1-23 for trace elements, volatile and semivolatile organic compounds, and wastewater-related organic compounds. Sequential duplicates from well 3-13 and 1-23 were analyzed for manganese. Sequential duplicates were submitted to NWQL with water samples for identical analyses. The difference between analyses from a water sample and its sequential duplicate was evaluated, using the relative percent difference (RPD) statistic. The RPD is the absolute value of the difference of the two concentrations of a single constituent divided by the average of the sum of the concentrations, expressed as a percent. An RPD comparison was made only when constituent concentrations were detected in the water sample, the sequential duplicate, or both. The RPDs were computed for the paired water sample and sequential duplicate as

$$RPD = \left|(SD-WS)/((SD+WS)/2)\right| \text{ x } 100, \qquad (1)$$

where

RPD is the relative percent difference,
SD is the concentration in the sequential duplicate, and
WS is the concentration in the water sample.

The RPD statistic describes the difference in concentrations between two samples that were identical in their handling and analysis and that should be identical in composition. If the RPD of an analysis was within 25 percent, the water-quality-sample result met the precision objectives of this study. If the RPD was greater than 25 percent, the water-quality-sample result was reported, but the concentration for that analysis was flagged with the letter “Q” in data tables to indicate that the concentration was an estimate.

In several cases, an estimated RPD was computed because a constituent in a paired water sample or sequential duplicate had a concentration that was less than the reporting limit. In those cases, the concentration used to compute the estimated RPD for the sample whose value was less than the reporting limit was set equal to half of the reporting limit for that constituent. For example, if the concentration of aluminum in a water sample was 7 mg/L but the concentration in the sequential duplicate was not detected at a reporting limit of 1 mg/L, the aluminum concentration used for the RPD computation for the sequential duplicate would be 0.5 mg/L, and the resulting estimated RPD would be 173 percent. The estimated RPD was computed to provide a general concept of one possible RPD for that water sample. Water samples with estimated RPDs greater than 25 percent also were flagged with the letter “Q” in data tables to indicate that the concentration in the sample was estimated.

Estimation of Ground-Water Age

Measurements of three CFC compounds were made to estimate the age of ground water in the upper aquifer. Ground-water age is defined as an estimated number of years since infiltrating water reached the water table and recharged the aquifer. Ground-water-age estimates are apparent ages. Estimates are based on interpretations of measured concentrations of CFCs in ground water and on processes affecting the CFCs from the time of entry into the aquifer with recharge until the time they are sampled. The following description of ground-water-age dating methods and their interpretation are paraphrased from Plummer and Busenberg (1999) and Rowe and others (1999).

CFCs are stable, synthetic, halogenated alkanes that were developed in the early 1930s as refrigerants. Production of CFC-12 began in 1931, followed by CFC-11 in 1936. Many other CFC compounds, most notably CFC-113, have been produced since. Precipitation that recharged the aquifer within the past 50 years is assumed to have contained CFCs. The concentrations of the CFCs in the atmosphere and in recharge have changed through the passage of time; these changes can be used to indirectly estimate ground-water age.

To compute the age of a ground-water sample, concentrations of each CFC compound in a water sample are divided by the appropriate Henry’s Law constant. This result gives the partial pressure of the compound in air from the unsaturated or vadose zone above the water table when water infiltrated below the water table and became isolated from the atmosphere. The solubility (C) of a CFC compound (D) relates to the equilibria between gas and water phases, as described by Henry’s Law:

$$C_D = K_{D\,(T,S)} \text{ x } P_D\ , \tag{2}$$

where

K is the Henry’s law constant for the dating compound at a defined average recharge temperature (T) and salinity (S) and

P is the partial pressure, under atmospheric conditions (Schwarzenbach and others, 1993), of the respective CFC compound.

The sensitivity of ground-water-age estimates to recharge temperature was simulated by substituting two separately derived estimates of average recharge temperature into the computation of ground-water age. The solubility of dissolved gases (such as CFCs, argon, and nitrogen) depends on the average recharge temperature of the ground-water sample. For this study, two average recharge-temperature estimates were computed to estimate ground-water age: (1) the average recharge temperature derived from dissolved-gas measurements and (2) a fixed recharge temperature equal to the average annual air temperature of 10.4°C for Richmond (Midwestern Regional Climatic Center, 2005a). The latter method was used because typical recharge temperatures in an aquifer near Dayton, Ohio, were estimated to be generally close to the average annual air temperature (within about 1 to 2°C; Rowe and others, 1999, p. 35).

Recharge temperatures were estimated with the ratio of dissolved nitrogen to argon gas in water samples (Rowe and others, 1999). The concentrations of nitrogen and argon in water infiltrating below the water table may be expected to be in equilibrium with the atmosphere at the prevailing surface pressure and temperature (Heaton and Vogel, 1981). Nitrogen and argon concentrations were normalized, using an assumed recharge altitude to a pressure of 760 mm of mercury, to limit altitude effects on comparison of gas solubility. Nitrogen and argon concentrations in ground water also were corrected for the amount of excess air[1] introduced into ground water. Recharge temperatures then were estimated by comparing the normalized concentrations of nitrogen and argon gas with a plot of nitrogen-argon solubilities in water at 760 mm of mercury with excess air contents ranging from 0 to 20 cm^3/kg of water (Heaton and Vogel, 1981), using gas-solubility data from Weiss (1970).

The recharge altitudes for ground water sampled from shallow wells were assumed to be similar to the water-table altitudes measured during this study, rounded to about the nearest foot. Recharge altitudes used for dissolved gas and CFC computations at shallow wells were 1,040 ft at well

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[1] Excess air refers to the volume of dissolved gas present in a liter of ground water in excess of that predicted by an equilibrium of infiltrating water with the atmosphere. Excess air typically is incorporated into the dissolved-gas content of ground water when infiltrating water entraps air in bubbles and carries them below the water table (Heaton and Vogel, 1981).

1-16, 1,050 ft at well 2-15, 1,038 ft at well 3-13, and 1,040 ft at well 4-14. In deeper wells, the ground-water recharge likely occurred at greater altitudes than at the sampled depth. Therefore, the recharge altitudes for ground water at deeper wells were based on land-surface altitudes upgradient from each well. Recharge altitudes used for dissolved-gas and CFC-based ground-water-age computations at shallow wells were assumed to be 1,060 ft for wells 1-23, 2-26, and 3-38.

Excess air can affect ground-water-age dates. Introduction of excess air adds CFCs to ground water and, if not accounted for in age interpretation, causes a young-age bias. Because atmospheric concentrations and ratios between CFCs are leveling off (fig. 7), dating becomes extremely sensitive to introduction of even small amounts of CFCs from excess air.

Excess nitrogen in a water sample can create errors in the CFC-based estimate of ground-water age. Excess nitrogen can originate from biogeochemical processes in an aquifer, such as denitrification. Denitrification produces more nitrogen gas than would be dissolved if the water were in equilibrium with soil gas at the time of recharge. Excess nitrogen in a sample must be subtracted from the amount of excess air to account for the overestimate of excess air in that sample. In this manner, an accurate estimate of the amount of each CFC in recharge to ground water can be computed.

The calculated partial pressures of CFCs in each water sample then were compared with the reconstructed record of atmospheric concentrations of each CFC compound throughout the period of record (fig. 7) to infer the age of each water sample (Rowe and others, 1999). Interpretations of ground-water age depend on the assumption that CFC concentrations are in equilibrium with gases in the soil and that CFC concentrations are equal to those in the atmosphere (Rowe and others, 1999). This assumption is reasonable because of the shallow depth to water (less than 10 ft) and the permeable soils throughout much of the study area.

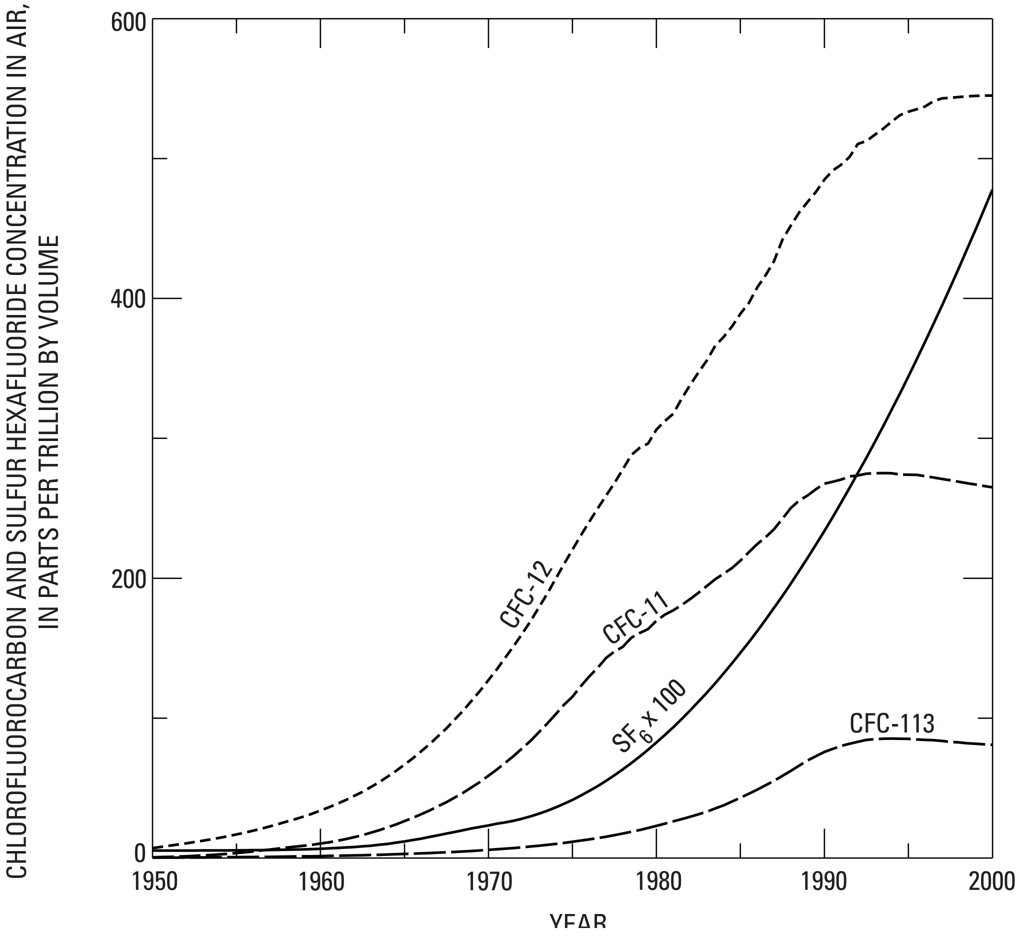


Figure 7. Atmospheric concentrations of dichlorodifluoromethane (CFC-12), trichlorofluoromethane (CFC-11), trichlorotrifluoroethane (CFC-113), and sulfur hexafluoride (SF_6) for air in North America.

Hydrogeology of a Part of the Whitewater Valley Aquifer System

The Whitewater Valley aquifer system is the most-productive glacial aquifer system in the part of eastern Indiana shown in figure 1, with typical well yields of 500 gal/min throughout most of the area (Beaty and Clendenon, 1988, p. 43). The aquifer system includes poorly sorted outwash sand and gravel that was deposited as valley-train sediments during Wisconsinan glaciation, separated by till of variable thickness and lateral extent (Beaty and Clendenon, 1988, p. 16). The sand and gravel deposits range in total thickness from less than 10 ft to more than 100 ft thick, with most areas ranging from 25 to 75 ft thick (Beaty and Clendenon, 1988, p. 43). Similar deposits that correspond to the Whitewater Valley aquifer system in adjacent parts of Ohio along the East Fork Whitewater River are mapped as coarse-grained stratified Quaternary sediment, with thicknesses ranging 0 to 200 ft (Soller, 1998). The sand and gravel deposits abruptly contrast with the clay-rich till deposits of adjacent aquifer systems (the Wayne-Henry and Fayette-Union aquifer systems) outside the valleys of the Whitewater River and its tributaries (Beaty and Clendenon, 1988, p. 43 and plate 3). Water levels in the Whitewater Valley aquifer system typically are unconfined, with average static water levels in wells that range from 0 to 30 ft below land surface (Beaty and Clendenon, 1988, p. 43).

The aquifer system in the study area is in a north to south to southwest trending valley (the former glacial valley) (fig. 8). The former glacial valley contains outwash sand and gravel deposited by glacial meltwater (Gooding, 1957, p. 53–54) in the Champaign Sluice, a drainage channel for glacial meltwater during the retreat of Crawfordsville Phase ice during the Late Wisconsinan glaciation (approximately 19,000–20,000 years before present) (Franzi, 1980). The drainage channel was abandoned when glacial ice melted from the valleys of the East Fork Whitewater River and Middle Fork Whitewater River, exposing lower drainage outlets in those valleys (Gooding, 1957, p. 53–54).

The part of the Whitewater Valley aquifer system in the study area is divided into an upper, unconfined sand and gravel aquifer (the upper aquifer) and a lower, confined sand and gravel aquifer (the lower aquifer) by an intervening confining unit of till (figs. 9 and 10). The hydrogeologic setting in this study area has similar stratigraphy to other parts of the aquifer system. Because part of the public-water supply for Richmond is withdrawn from the upper aquifer, descriptions of local hydrogeology and interpretations of ground-water age, water quality, and vulnerability of ground water to contamination in this report focus primarily on the upper aquifer.

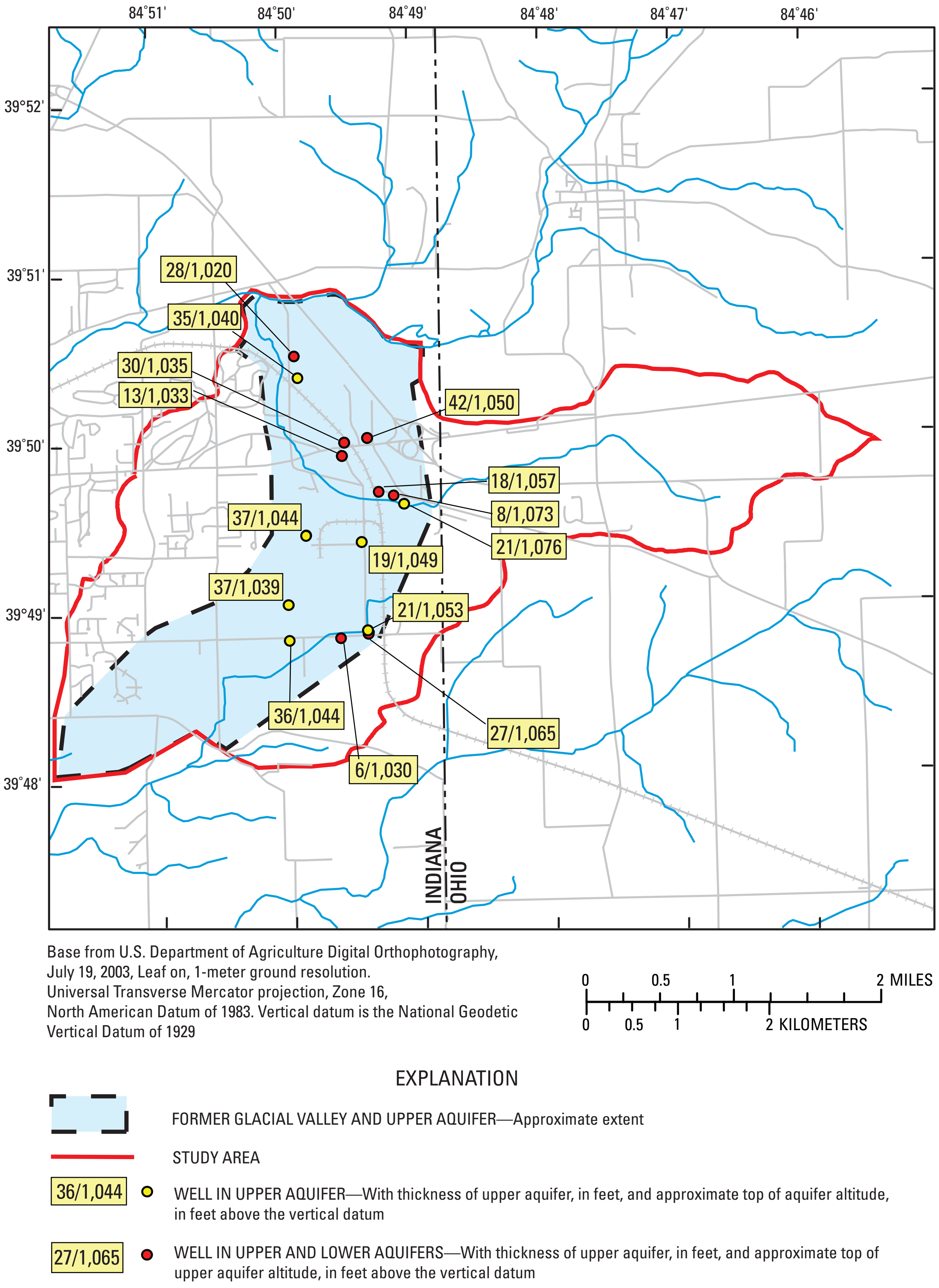
The maximum thickness of sediments of the upper aquifer, 55 ft at well 238964, was encountered near the northwestern part of the former glacial valley; however, only a 3-ft thickness was saturated (the well was not completed through the full aquifer thickness). The maximum thickness of the upper aquifer along mapped sections was about 42 ft along section A-A’ (well 238441, fig. 9) and about 36 ft along section B-B’ (well 3-38, fig. 10). The maximum saturated thickness of the upper aquifer was about 33 ft at well 3-38 near the south-central part of the valley (fig. 10). Based on drill cuttings and split-barrel core samples from wells 1-23, 2-26, and 3-38, the aquifer in the study area consists of a medium to coarse sand with some gravel. Logs from engineering borings reported that the aquifer consists of fine to coarse sand with traces of gravel and (or) silt in places (West and Bergman, 1973).

Gamma-radiation data from geophysical logs of aquifer sediments typically ranged from about 20 to 50 counts per second, indicating the generally low content of clay minerals in the valley-train sediments of the aquifer (fig. 11). Thin, alternating lenses of fine- and coarse-grained sediments less than 1 ft thick also were indicated by the gamma-radiation data in the 5 to 7 ft of the upper aquifer beneath the weathered till in wells 1-23 and 2-15 (fig. 11). The valley-train sediments and the thin alternating lenses of fine- and coarse-grained sediments were interpreted as part of the upper aquifer, as shown for wells 1-23 and 2-15 in sections A-A’ and B-B’ (figs. 9 and 10).

An x-ray diffraction analysis to determine the relative abundance of different minerals in upper-aquifer sediments was done on coarse sand that was recovered from auger flights during the drilling of well 2-26. The coarse sand consists of the following minerals, in decreasing abundance: quartz, dolomite, calcite, plagioclase feldspar, and orthoclase feldspar (Eurybiades Busenberg, U.S. Geological Survey, written commun., 2003). Sand and gravel deposits of Wisconsinan age (Crawfordsville Phase deposits) from adjacent areas of west-central Ohio typically also had abundant carbonate mineral content (between about 30 to 55 percent, most of which was dolomite), though some leached zones in those deposits had a lower abundance of carbonate minerals (Franzi, 1980, p. 50–68). Analysis of the silt and clay fraction of the sample from well 2-26 revealed traces of the clay minerals chlorite, kaolinite, and illite; undifferentiated smectite clays; and possible traces of gypsum. These same clay minerals also were reported in analyses of Wisconsinan sand and gravel deposits (Crawfordsville interphase deposits) from adjacent areas of west-central Ohio (Franzi, 1980, p. 68–82). Soils over the upper aquifer are from the Eldean-Ockley soil association (Blank, 1987, p. 154); they are nearly level, well-drained loam soils, 20 in. or more in thickness, derived from weathering of the underlying outwash and sand and gravel deposits (Blank, 1987, p. 5–6).

South of about US 40, the upper aquifer is underlain by a confining unit of till that ranged in thickness from about 27 ft at well 232888 (fig. 9) to about 60 ft at well 266388 (fig. 10). No wells drilled for this study penetrated the confining unit. The confining unit separating the upper and lower aquifer thins between wells 256056 and 238441 (fig. 9).

A second sand and gravel unit, the lower aquifer, underlies the till confining unit. The lower aquifer ranged in thickness from about 10 ft at wells 256056 (fig. 9) and 232946



Base from U.S. Department of Agriculture Digital Orthophotography,
July 19, 2003, Leaf on, 1-meter ground resolution.
Universal Transverse Mercator projection, Zone 16,
North American Datum of 1983. Vertical datum is the National Geodetic
Vertical Datum of 1929

Figure 8. Extent and thickness of the upper aquifer and selected wells that penetrate the upper aquifer near Richmond, Indiana.

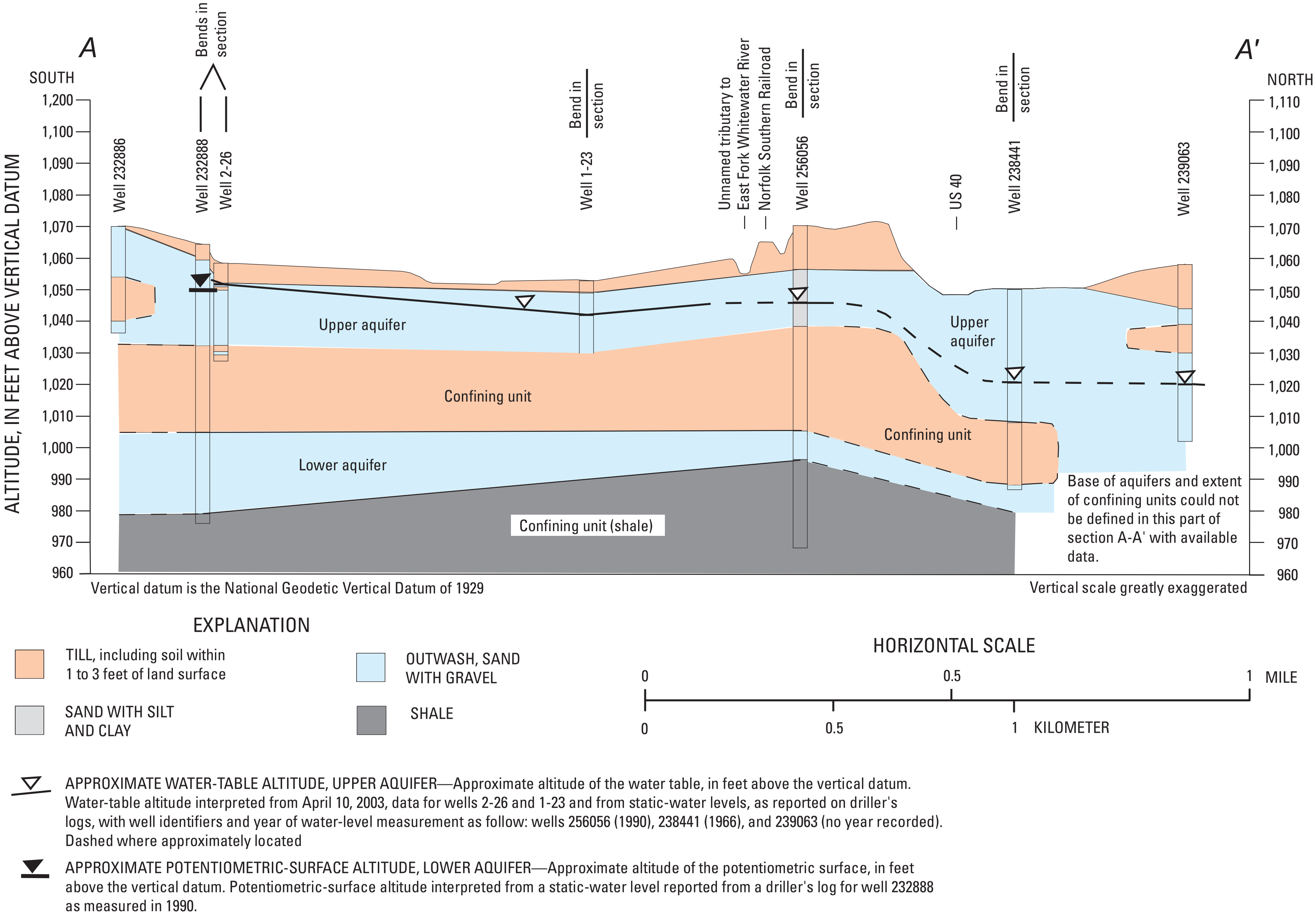
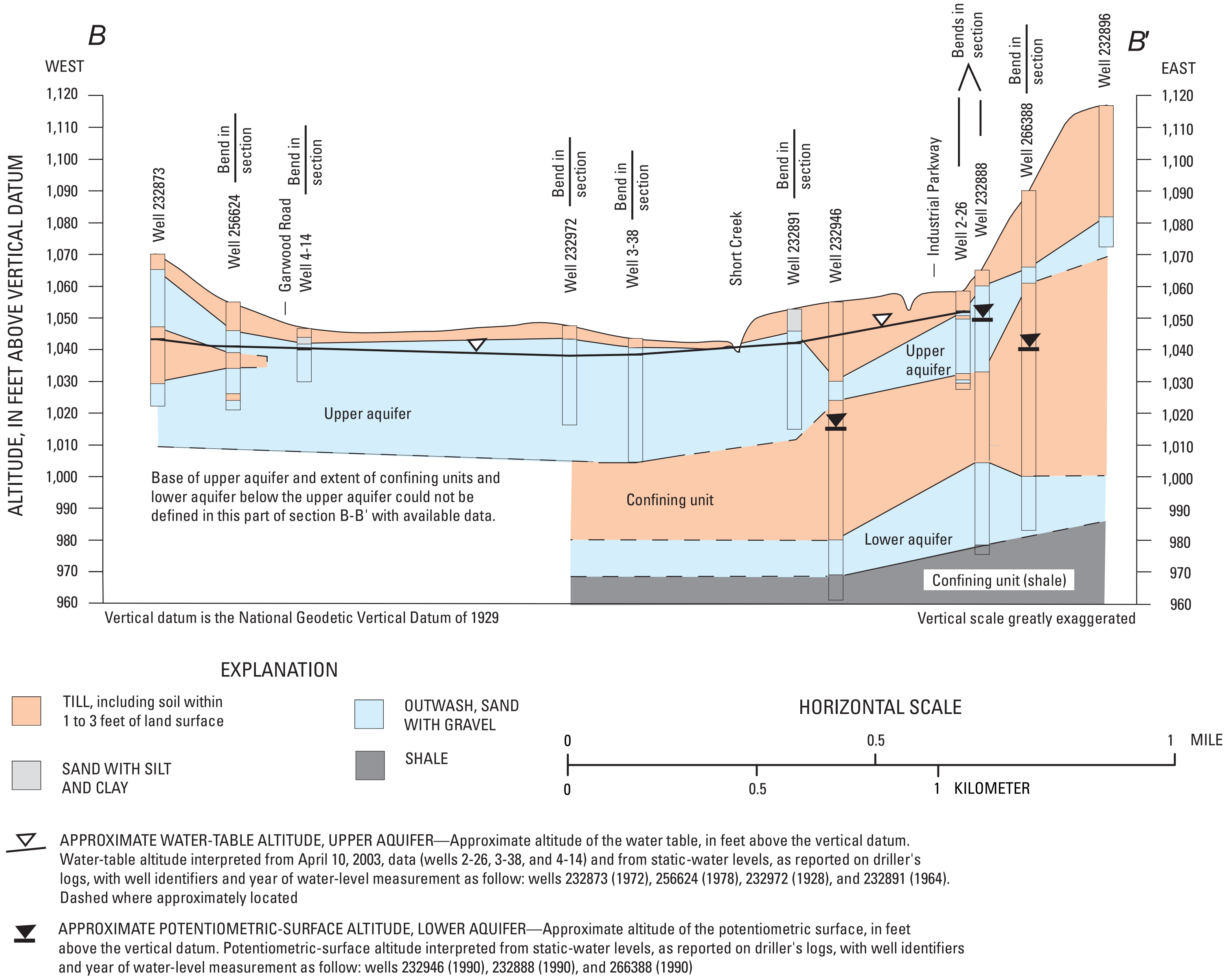


Figure 9. Hydrogeologic section A-A′, oriented south to north across the study area, showing the upper and lower aquifers, types of sediment and bedrock encountered, and approximate water-table and potentiometric-surface altitudes near Richmond, Indiana (line of section shown in fig. 6).



EXPLANATION

- 🟧 TILL, including soil within 1 to 3 feet of land surface
- ▨ SAND WITH SILT AND CLAY
- 🟦 OUTWASH, SAND WITH GRAVEL
- ⬛ SHALE

▽ APPROXIMATE WATER-TABLE ALTITUDE, UPPER AQUIFER—Approximate altitude of the water table, in feet above the vertical datum. Water-table altitude interpreted from April 10, 2003, data (wells 2-26, 3-38, and 4-14) and from static-water levels, as reported on driller's logs, with well identifiers and year of water-level measurement as follow: wells 232873 (1972), 256624 (1978), 232972 (1928), and 232891 (1964). Dashed where approximately located

▼ APPROXIMATE POTENTIOMETRIC-SURFACE ALTITUDE, LOWER AQUIFER—Approximate altitude of the potentiometric surface, in feet above the vertical datum. Potentiometric-surface altitude interpreted from static-water levels, as reported on driller's logs, with well identifiers and year of water-level measurement as follow: wells 232946 (1990), 232888 (1990), and 266388 (1990)

Figure 10. Hydrogeologic section B-B′, oriented west to east across the study area, showing the upper and lower aquifers, types of sediment and bedrock encountered, and approximate water-table and potentiometric-surface altitudes near Richmond, Indiana (line of section shown in fig. 6).

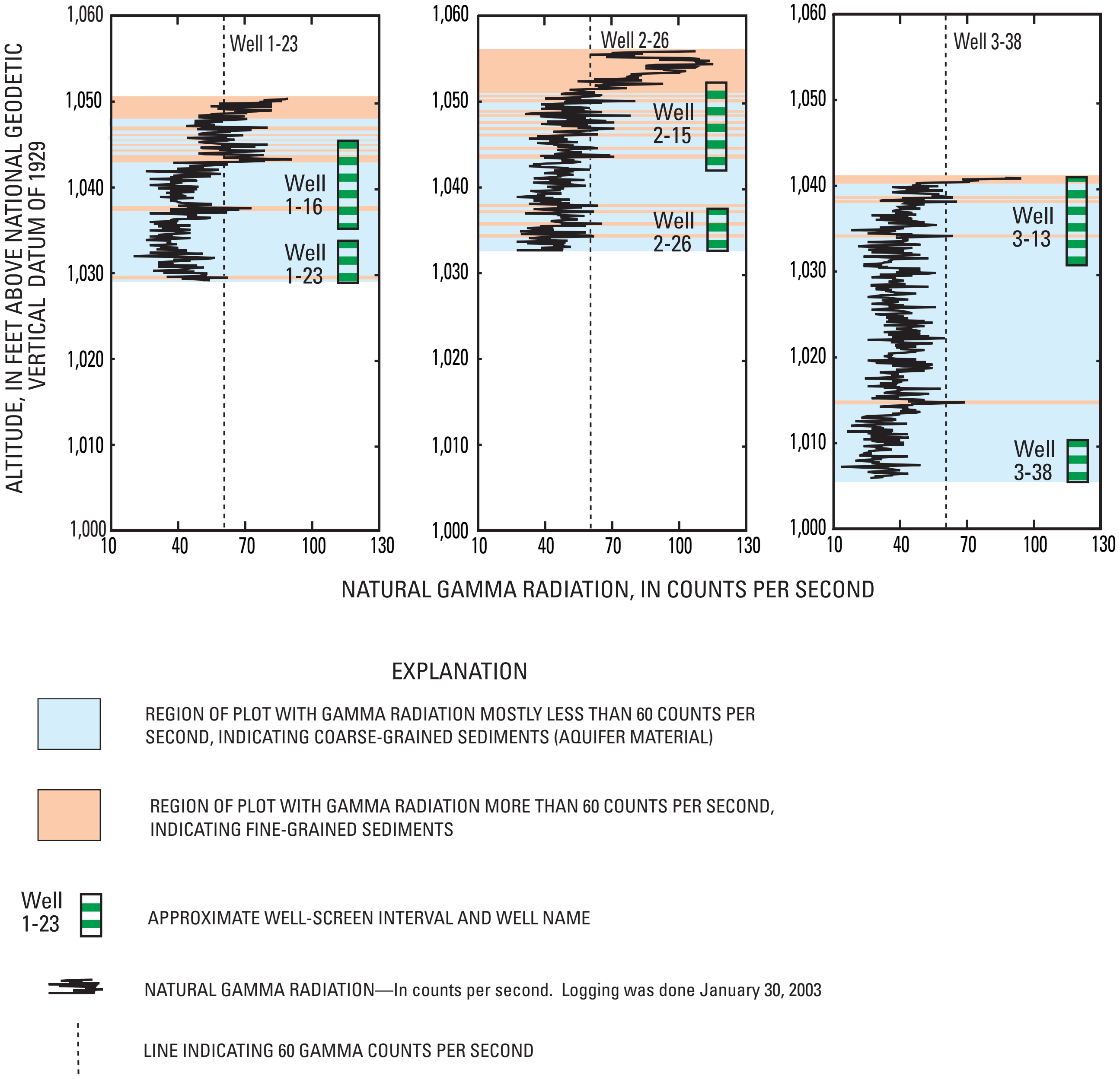


Figure 11. Borehole geophysical logs of natural gamma radiation from observation wells 1-23, 2-26, and 3-38; the distribution of fine- and coarse-grained sediments; and the altitude of well-screen intervals of these and selected nearby observation wells in the upper aquifer near Richmond, Indiana.

(fig. 10) to more than 28 ft at well 239063 (fig. 9). The base altitude of the lower aquifer ranged from about 970 ft above the vertical datum at well 232946 (fig. 10) to about 996 ft at well 256056 (fig. 9); the range is comparable to the altitude of the East Fork Whitewater River.

Ordovician shale of the Maquoketa Group (Rupp, 1991) is at the bedrock surface in the study area; these deposits underlay the lower aquifer and are considered to be a lower confining unit for the lower aquifer. The shale is exposed in the southwestern corner of the study area at an altitude of about 1,030 to 1,033 ft above the vertical datum where Wernle Road and Garwood Road intersect south of a former mill pond (fig. 6).

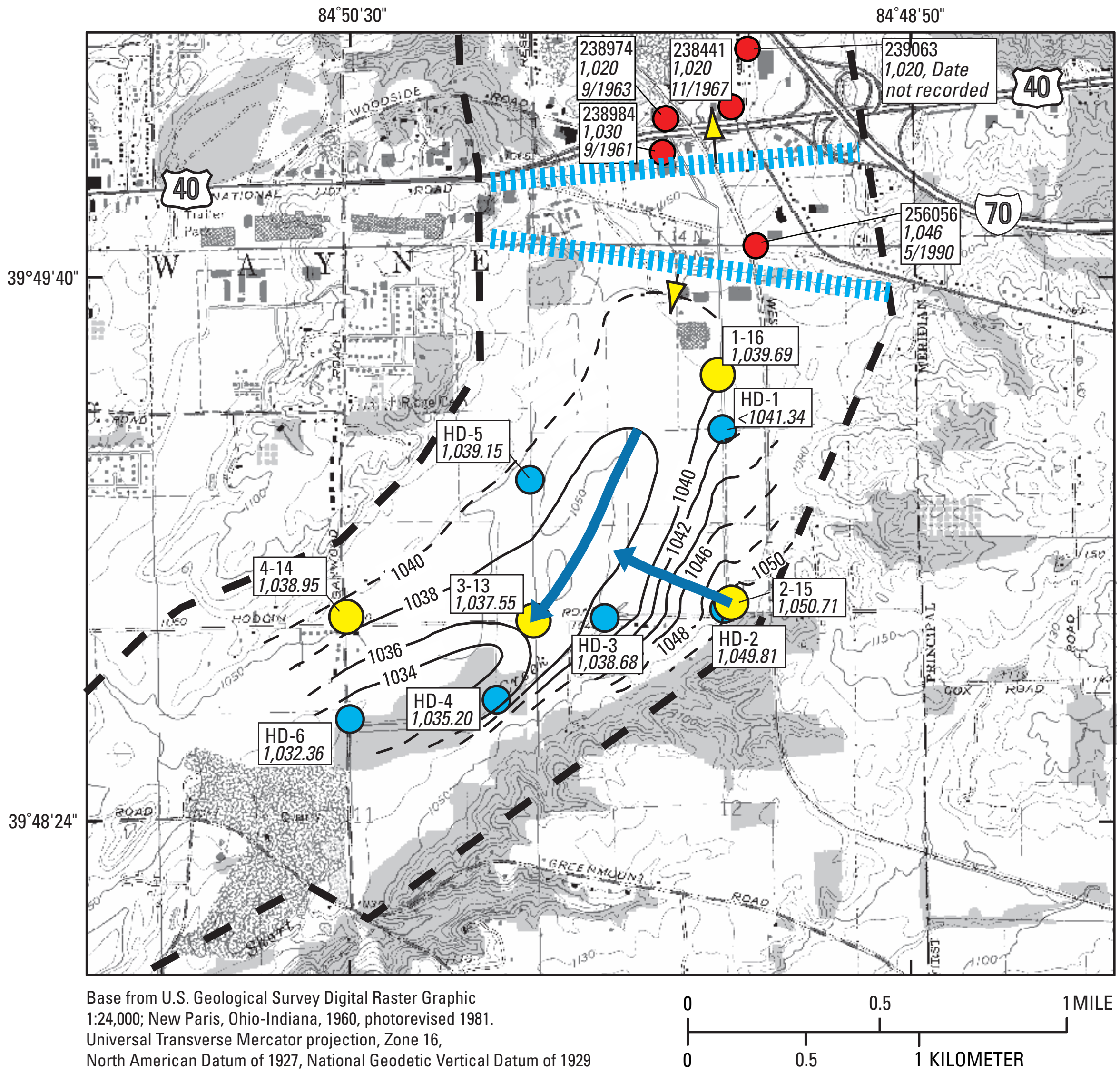
The ridges that flank the valley margins and the upstream parts of the watersheds of Short Creek and the unnamed tributary to the East Fork Whitewater River mostly consist of till. Aquifers in those areas are described as part of the Fayette-Union aquifer system by Beaty and Clendenon (1988). The Fayette-Union aquifer system contains thin sand and gravel units (less than 10 ft thick) within variably thick till sequences. Tills in these watersheds in adjacent parts of Ohio are described as containing coarse-grained stratified sediment of unspecified thickness and continuity (Soller, 1998). Ground water from these areas likely flows toward and discharges to streams or to the upper and lower aquifers of this study area. Soils on the ridges flanking the valley are from the Miami-Crosby-Strawn associations (Blank, 1987, p. 154). They are sloping, well-drained Miami soils; nearly level, poorly drained and clayey Crosby soils; and steep, well-drained, shallow, loamy Strawn soils on slopes (Blank, 1987, p. 7–8) over till.

Some of the weathered till along the valley margins was eroded and redeposited over the upper aquifer in parts of the valley, as indicated by the fine-grained sediments (gamma-radiation counts of about 60 to 110 counts per second) in the upper 5 to 8 ft of wells 1-23 and 2-26 (fig. 11). The development of ephemeral seeps on the hillside about 400 ft due west of wells 2-15 and 2-26 indicate that the redeposited till locally can restrict recharge to the upper aquifer. Elsewhere in the study area, the upper aquifer was immediately below the soil zone, as noted during the installation of wells 3-38 and 4-14. Through nearly its entire depth, well 3-38 had nearly uniform gamma-radiation counts that were similar to those observed for upper-aquifer sediments.

Water in the upper aquifer flows from the ridges along the valley margin toward the flatter parts of the valley center (figs. 12 and 13). Water levels measured for this study ranged in altitude from 1,032.36 ft on December 24, 2002, at well HD-6 to 1,052.49 ft on June 19, 2002, at well 2-26 (table 4, back of report). Depths to ground water from land surface in drilled wells that were measured for this study ranged from 4.75 ft at well 3-13 on June 20, 2002, to 13.32 ft at well 1-16 on December 24, 2002. Ground-water levels were above the streambed in hand-driven wells HD-2, HD-3, HD-4, and HD-6 in at least one of the two measurements made in these wells (table 4). Recharge to the aquifer likely occurs along the valley margins and across the valley floor through a thin veneer of permeable, loamy soils derived from weathered sediments; the estimated recharge rate for the Whitewater Valley aquifer system is about 10.5 in./yr (Beaty and Clendenon, 1988, p. 83, table 32). Additional recharge to the upper aquifer may originate from sand and gravel deposits in the till along the valley margin (Fayette-Union aquifer system) (Beaty and Clendenon, 1988, plate 3); an example of this sequence is shown on the eastern extent of hydrogeologic section B-B’ at wells 266388 and 232896 (fig. 10). The estimated recharge rate for the Fayette-Union aquifer system is about 2.1 in./yr, or about five times less than the Whitewater Valley aquifer system (Beaty and Clendenon, 1988, p. 83, table 32).

A local ground-water-flow divide was inferred by Beaty and Clendenon (1998, plate 2) to be about 0.25 mi north of well 1-16 (fig. 12) and near the northern boundary of the Aquifer Protection District (fig. 2) (City of Richmond, Indiana, 2006). The divide may be north of the mapped location; static-water altitudes reported in water-well logs indicate that the divide may be as much as about 0.25 mi farther north and may include areas near US 40. The static-water altitude in well 256056 at the time of drilling (about 1,046 ft in 1990) near the inferred divide was greater than water levels to the south at well 1-16 (ranging from 1,039.69 to 1,043.04, table 4). The static-water altitude in well 256056 at the time of drilling also was greater than static-water altitudes to the north near US 40 in wells 238411 (about 1,020 ft in 1967), 238974 (about 1,020 ft in 1963), 239063 (about 1,020 ft, no date recorded) and 238984 (about 1,030 ft in 1961) (Indiana Department of Natural Resources, 2005). These static-water-altitude data may not be sufficient to locate the divide because the measurements were made at different times and the land-surface altitudes at the wells are not known precisely. The location of the divide could be defined more precisely with additional synoptic water-level measurements made from new and existing wells during a range of hydrologic conditions. North of the divide, ground water flows north in the upper aquifer toward the East Fork Whitewater River. South of the divide, ground water flows principally south and southwest, where it discharges to Short Creek and its tributaries, to production wells, and possibly to the lower aquifer.

Water-table gradients along the valley margins are steeper than those along the valley floor. For example, from the water-table-altitude maps, the water-table gradient from the valley margin at well 2-15 to the valley floor near well HD-3 was about 0.0079 ft/ft on December 24, 2002 (fig. 12), and 0.0066 ft/ft on April 10, 2003 (fig. 13). By comparison, along the valley floor, the estimated water-table gradient from between wells 1-16 and HD-5 to well 3-13 was about 0.0001 ft/ft on December 24, 2002 (fig. 12), and from north of well 1-16 to just east of well 3-13 was 0.0007 ft/ft on April 10, 2003 (fig. 13). Estimates of horizontal ground-water-flow velocities were computed, using values of hydraulic conductivity from sand and gravel deposits in a Richmond-area quarry that ranged from about 8 to 159 ft/d (Acomb,



Base from U.S. Geological Survey Digital Raster Graphic
1:24,000; New Paris, Ohio-Indiana, 1960, photorevised 1981.
Universal Transverse Mercator projection, Zone 16,
North American Datum of 1927, National Geodetic Vertical Datum of 1929

EXPLANATION

– – 1040 —— WATER-TABLE CONTOUR—Approximate altitude of the water table in the upper aquifer, in feet above National Geodetic Vertical Datum of 1929. Dashed where approximately located. Contour interval 2 feet

▬ ▬ UPPER AQUIFER AND FORMER GLACIAL VALLEY—Approximate extent

▲ ▼ APPROXIMATE AREA OF GROUND-WATER-FLOW DIVIDE FOR THE UPPER AQUIFER—Estimated with the composite potentiometric surface of unconsolidated aquifers in the Whitewater River Basin, as mapped by Beaty and Clendenon (1988, plate 2), and modified with static-water-altitude data from driller's logs as shown on this figure. Arrows indicate general direction of ground-water flow away from the divide

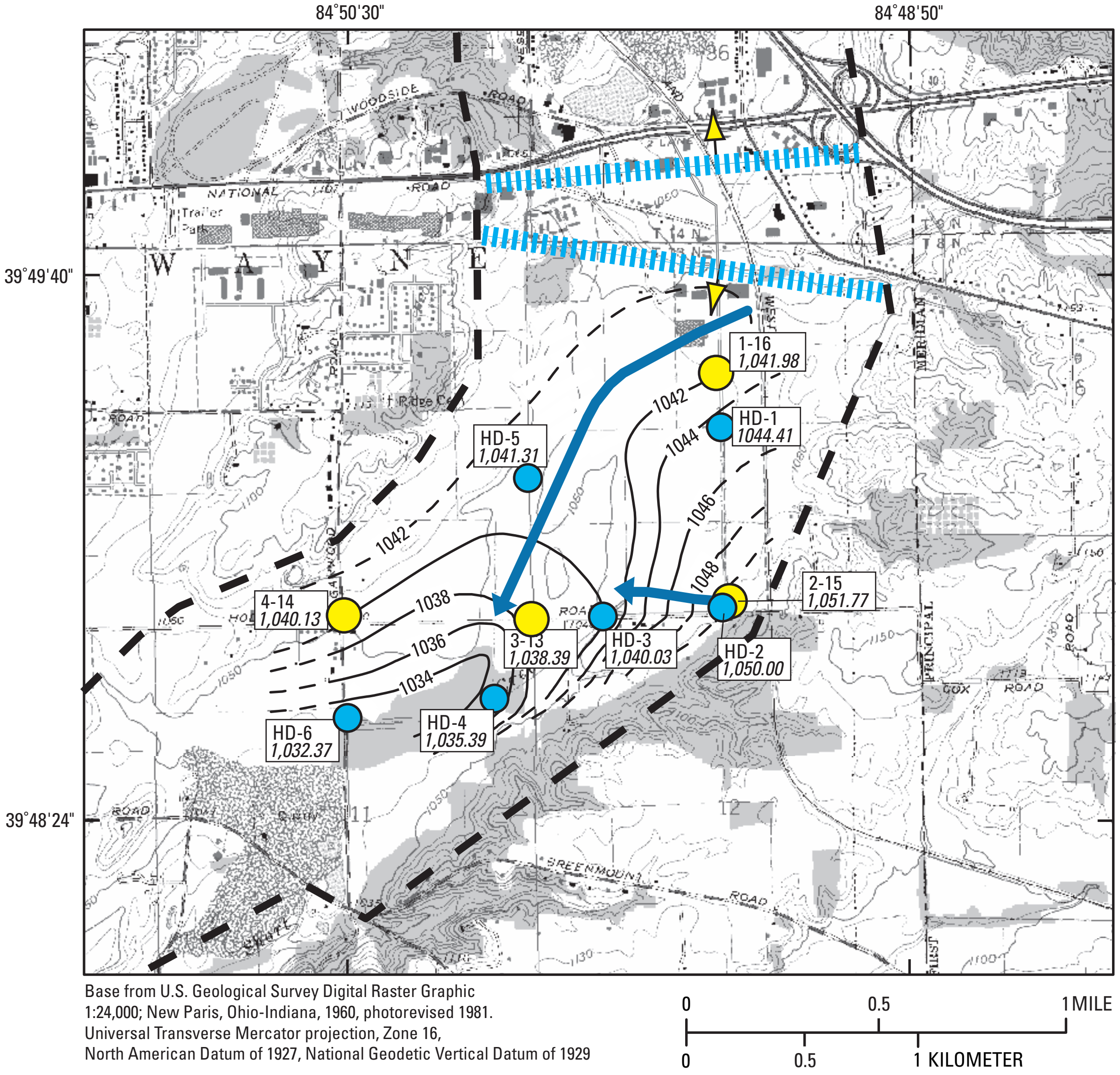
← FLOW PATH USED TO COMPUTE WATER-TABLE GRADIENT IN THE UPPER AQUIFER

4-14 1,038.95 ● SHALLOW DRILLED OBSERVATION WELL—With well name and water-table altitude, December 24, 2002

HD-6 1,032.36 ● HAND-DRIVEN OBSERVATION WELL—With well name and water-table altitude, December 24, 2002

256056 1,046 5/1990 ● OTHER WELL WITH WELL NAME, STATIC-WATER ALTITUDE, AND MONTH AND YEAR OF WELL COMPLETION FROM DRILLER'S LOG—Static-water altitude reported on driller's log is assumed to be from same month and year as well was completed

Figure 12. Altitude of the water table in the upper aquifer near Richmond, Indiana, December 24, 2002, relative to the approximate area of a ground-water-flow divide.



Base from U.S. Geological Survey Digital Raster Graphic
1:24,000; New Paris, Ohio-Indiana, 1960, photorevised 1981.
Universal Transverse Mercator projection, Zone 16,
North American Datum of 1927, National Geodetic Vertical Datum of 1929

EXPLANATION

— — 1040 —— WATER-TABLE CONTOUR—Approximate altitude of the water table in the upper aquifer, in feet above National Geodetic Vertical Datum of 1929. Dashed where approximately located. Contour interval 2 feet

▬ ▬ UPPER AQUIFER AND FORMER GLACIAL VALLEY—Approximate extent

▲ ▦ ▦ ▼ APPROXIMATE AREA OF GROUND-WATER-FLOW DIVIDE FOR THE UPPER AQUIFER—Estimated with the composite potentiometric surface of unconsolidated aquifers in the Whitewater River Basin, as mapped by Beaty and Clendenon (1988, plate 2), and modified with static-water-altitude data from driller's logs as shown on figure 10. Arrows indicate general direction of ground-water flow away from the divide

← FLOW PATH USED TO COMPUTE WATER-TABLE GRADIENT IN THE UPPER AQUIFER

4-14 1,040.13 ● SHALLOW DRILLED OBSERVATION WELL—With well name and water-table altitude, April 10, 2003

HD-6 1,032.37 ● HAND-DRIVEN OBSERVATION WELL—With well name and water-table altitude, April 10, 2003

Figure 13. Altitude of the water table in the upper aquifer near Richmond, Indiana, April 10, 2003, relative to the approximate area of a ground-water-flow divide.

1997). A similar hydraulic-conductivity value (144 ft/d) previously had been estimated by West and Bergman (1973) for a part of the upper aquifer near well 3-13. Porosity values measured for sand and gravel deposits in a Richmond-area quarry ranged from 0.25 to 0.41 (Acomb, 1997). If the typical porosity of the upper-aquifer material was assumed to fall within the above range, the average linear ground-water velocity (at the gradients referenced above) could be computed to range from about 0.002 to 0.44 ft/d along the valley floor and from about 0.13 to 5.0 ft/d along a flow path extending from the valley margin to the valley floor. More information about the range of hydraulic-conductivity values in the upper aquifer is needed to increase the precision of these estimates.

Vertical gradients in the upper aquifer ranged from downward on one measurement to upward during most water-level measurements at three pairs of shallow and deep wells (table 5, back of report). Vertical gradients between wells 1-16 and 1-23 ranged from 0.0014 ft/ft on April 10, 2003, to 0.0032 ft/ft on August 28, 2002; all three of the vertical-gradient measurements at this well pair were upward (positive gradient). Vertical gradients between wells 2-15 and 2-26 ranged from no gradient on August 5, 2002, to 0.0087 ft/ft on December 24, 2002; four of the five vertical-gradient measurements at this well pair were upward. Vertical gradients between wells 3-13 and 3-38 ranged from no gradient on August 20, 2002, and August 29, 2002, to 0.0011 ft/ft on April 10, 2003; two of the four vertical-gradient measurements at this well pair were upward. Vertical gradients were also upward from shallow wells HD-2, HD-4, and HD-6 into Short Creek. The upward gradients indicate that Short Creek is a discharge area for ground water near these wells. Vertical gradients were downward from Short Creek into the aquifer at well HD-3, indicating a possible local-recharge area for ground water. Downward vertical gradients also were indicated at wells HD-1 (April 10, 2003, only) and HD-5 when the adjacent tributaries to Short Creek were dry.

Vertical gradients are likely downward from the upper aquifer to the lower aquifer; discharge from the upper aquifer to the lower aquifer across the intervening confining unit is possible. Ground water in the lower aquifer is under confined conditions, except where the confining unit between the upper and lower aquifers is not present. Previous measurements of static-water altitudes reported for wells developed in the lower aquifer range from less than 1 to 30 ft lower than those measured for this study in the upper aquifer (figs. 9 and 10). This inference was made, using water levels measured in different years and under different hydrologic conditions, and should be verified with water levels collected from each aquifer during the same time.

Ground-Water-Age Dating

Estimates of ground-water age were developed from concentrations of CFCs, using excess air concentrations and recharge temperatures determined from dissolved-gas data (table 6). Dissolved-gas data also were used to evaluate oxidation-reduction conditions that could relate to possible microbial transformation of CFCs in ground water. Computations of ground-water ages also were made by assuming that recharge temperatures are equal to the average annual air temperature for the Richmond area (table 7). The most-reliable ground-water ages, computed with CFC-12 (or, for two wells, with CFC-113) concentrations, indicated that ground-water samples in the upper aquifer had recharged the aquifer from about 1973 to 1990, within about 13 to 30 years of this sampling (February and March 2003, table 7). Ground-water-age dating with sulfur hexafluoride was not possible for this study because concentrations of this compound were larger than what could be accounted for by atmospheric equilibrium.

Dissolved-Gas Concentrations and Estimated Average Recharge Temperatures

Estimated average recharge temperatures for water samples were derived by plotting the normalized concentrations of argon and nitrogen on a diamond-shaped plot of hypothetical concentrations of dissolved argon and dissolved nitrogen in water. The hypothetical concentrations were at the same pressure (760 mm of mercury); excess air concentrations ranged from 0 to 20 cm^3/kg of water. The estimated average recharge temperatures corresponded to the temperature and excess air, indicated by the point for each sample plotted on figure 14. Excess air concentrations in six wells ranged from 1.4 mg/L (well 1-23) to 8.2 mg/L (well 3-38); the excess air concentration in well 2-15 was a negative value (table 6, fig. 14). That value did not plot within the diamond-shaped plot of dissolved-nitrogen and dissolved-argon concentrations in figure 14. Ground-water-age computations for well 2-15 were made, using the average annual air temperature of 10.4°C as the estimated average recharge temperature, with no excess air assumed.

The dissolved-gas concentrations and resulting estimated average recharge temperatures in these samples are interpreted as affected by excess nitrogen from locally enriched airborne nitrogen concentrations or from denitrification. The amount of excess nitrogen from both processes was subtracted from the total excess air concentrations by extrapolating back to the “water in equilibrium with the atmosphere” line in figure 14 while holding the argon concentration constant (Rowe and others, 1999). This assumption is valid because addition of excess nitrogen from both processes would affect nitrogen concentrations and would not affect argon concentrations. The amount of excess nitrogen contributed to the samples was estimated to range from 0.8 mg/L in the sample from well 1-23 to 4.5 mg/L in the sample from well 3-38 (table 6).

Estimates of average recharge temperatures, after being adjusted for excess nitrogen, ranged from 5.6°C at well 3-38 to 13.3°C at well 1-16 (table 6). The highest estimated average recharge temperatures were from the shallow wells (table 6).

Table 6. Concentrations of selected dissolved gases in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.

[mm/dd/yy, month/day/year; hhmm, hours and minutes; mg/L, milligram per liter; mm, millimeter; cm^3/L, cubic centimeters of air per liter; °C, degrees Celsius; -- , not computed for quality-assurance sample]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Methane (mg/L)	Carbon dioxide (mg/L)	Oxygen (mg/L)	Argon (mg/L)	Nitrogen (mg/L)	Argon, normalized to 760 mm mercury (mg/L)	Nitrogen normalized to 760 mm mercury (mg/L)	Excess air concentration (cm^3/L)	Excess nitrogen concentration (mg/L)	Estimated average recharge temperature (°C)
Water samples												
Well 1-16	08/28/02	0900	0.0	82.6	5.2	0.62	17.8	0.64	18.5	2.5	1.3	13.3
Well 1-23	08/28/02	1345	.015	55.7	2.5	.65	17.9	.67	18.6	1.4	.8	11.1
Well 2-15	08/27/02	0915	.0021	58.6	5.5	.66	16.6	.69	17.2	Negative value	Estimated value used (1.0)	Average annual air temperature used (10.4)
Well 2-26	08/27/02	1500	.0040	66.5	1.9	.72	20.5	.75	21.3	2.6	1.5	6.3
Well 3-13	08/29/02	0900	.0	42.8	.071	.67	19.7	.69	20.4	3.5	2.0	9.6
Well 3-38	08/29/02	1330	.0	38.1	.064	.73	23.7	.75	24.7	8.2	4.5	5.6
Well 4-14	08/30/02	0930	.0	52.1	3.4	.65	18.6	.67	19.3	2.5	1.5	10.9
Quality-assurance samples (sequential duplicates)												
Well 1-16	08/28/02	0905	.0	83.2	4.4	.61	17.5	.63	18.2	2.3	--	--
Well 1-23	08/28/02	1350	.011	56.5	1.9	.65	18.4	.68	19.1	1.9	--	--
Well 2-26	08/27/02	1510	.0041	66.5	1.7	.71	19.7	.73	20.5	2.0	--	--
Well 3-13	08/29/02	0910	.0	42.9	.089	.67	19.8	.69	20.6	3.8	--	--
Well 3-38	08/29/02	1340	.0	38.3	.096	.72	23.6	.75	24.6	8.1	--	--
Well 4-14	08/30/02	0940	.0	52.0	3.3	.64	18.6	.67	19.3	2.6	--	--

Table 7. Concentrations of chlorofluorocarbon compounds and ground-water-age dates for water samples from the upper aquifer near Richmond, Indiana, 2003.

[The most-reliable ground-water-age dates are in **bold**; mm/dd/yyyy, month/day/year; hhmm, hours and minutes; °C, degrees Celsius; ft-VD, altitude in feet above vertical datum (National Geodetic Vertical Datum of 1929); pg/L, picogram per liter; CFC-11, trichlorofluoromethane; CFC-12, dichlorodifluoromethane; CFC-113, trichlorotrifluoroethane; pptv, part per trillion by volume; Contam., calculated atmospheric mixing ratio indicates chlorofluorocarbon concentration in water sample affected by addition of excess chlorofluorocarbon to that predicted to be in the atmosphere; Modern, apparent ground-water-age date within 0 to 4 years of sample collection; ND, not detected in sample; < , less than]

Well name	Date sampled (mm/dd/yyyy)	Time sampled (hhmm)	Estimated recharge temperature (°C)	Estimated recharge altitude (ft-VD)	Sample vial	Concentration in water sample			Calculated atmospheric mixing ratio			Ground-water-age dates, no mixing assumed			Median ground-water-age since recharge (years)
						CFC-11 (pg/L)	CFC-12 (pg/L)	CFC-113 (pg/L)	CFC-11 (pptv)	CFC-12 (pptv)	CFC-113 (pptv)	CFC-11	CFC-12	CFC-113	
Ground-water-age dates computed, using recharge temperature derived from dissolved-gas data															
Well 1-16	02/07/2003	1030	13.3	1,040	2	540.1	362.6	62.7	233.9	674.5	65.6	1986.5	Contam.	**1988**	15
					4	542.0	346.9	62.7	234.8	645.3	65.6	1986.5	Contam.	**1988**	
					5	541.8	385.3	63.3	234.6	716.7	66.2	1986.5	Contam.	**1988.5**	
Well 1-23	02/07/2003	1235	11.1	1,060	2	1,764.9	1,748.9	18.2	680.2	2,931.2	16.7	Contam.	Contam.	**1977.5**	25
					4	1,760.6	1,620.4	24.7	678.5	2,716.0	22.7	Contam.	Contam.	**1979.5**	
					5	1,727.1	1,690.2	19.3	665.7	2,832.9	17.8	Contam.	Contam.	**1978**	
Well 2-15	02/13/2003	1255	10.4	1,050	2	792.7	337.8	49.6	262.6	494.4	38.7	1989	**1990.5**	1984	13.5
					4	814.5	328.8	50.9	269.8	481.3	39.7	1990.5	**1989.5**	1984	
					5	802.7	328.3	48.6	265.9	480.6	37.9	1989.5	**1989.5**	1984	
Well 2-26	02/13/2003	1110	6.3	1,060	2	470.6	337.6	8.3	137.9	442.9	5.7	1976.5	**1987.5**	1969.5	16
					4	462.6	336.0	17.8	135.6	440.8	12.1	1976	**1987**	1975	
					5	460.7	317.8	10.0	135.0	416.9	6.8	1976	**1986.5**	1971	
Well 3-13	03/07/2003	1355	9.6	1,038	2	172.0	246.1	15.0	61.0	382.7	12.6	1970	**1984.5**	1975.5	18.5
					4	177.7	247.9	16.6	63.0	385.5	13.9	1970	**1984.5**	1976	
					5	175.6	245.7	16.0	62.2	382.0	13.4	1970	**1984.5**	1976	
Well 3-38	03/07/2003	1525	5.6	1,060	2	4.8	147.8	ND	1.3	186.8	ND	1952	**1973**	pre-1957	30
					4	8.3	141.1	ND	2.3	178.4	ND	1953.5	**1972.5**	pre-1957	
					5	12.0	147.4	ND	3.4	186.2	ND	1954.5	**1973**	pre-1957	
Well 4-14	02/13/2003	1530	10.9	1,040	2	529.5	288.0	54.3	201.7	477.7	49.3	1983.5	**1989.5**	1986	13
					4	535.2	293.4	56.1	203.9	486.5	51.0	1984	**1990**	1986	
					5	541.4	300.2	55.5	206.3	497.9	50.4	1984	**1991**	1986	

Table 7. Concentrations of chlorofluorocarbon compounds and ground-water-age dates for water samples from the upper aquifer near Richmond, Indiana, 2003.—Continued

[The most-reliable ground-water-age dates are in **bold**; mm/dd/yyyy, month/day/year; hhmm, hours and minutes; ºC, degrees Celsius; ft-VD, altitude in feet above vertical datum (National Geodetic Vertical Datum of 1929); pg/L, picogram per liter; CFC-11, trichlorofluoromethane; CFC-12, dichlorodifluoromethane; CFC-113, trichlorotrifluoroethane; pptv, part per trillion by volume; Contam., calculated atmospheric mixing ratio indicates chlorofluorocarbon concentration in water sample affected by addition of excess chlorofluorocarbon to that predicted to be in the atmosphere; Modern, apparent ground-water-age date within 0 to 4 years of sample collection; ND, not detected in sample; <, less than]

Well name	Date sampled (mm/dd/yyyy)	Time sampled (hhmm)	Estimated recharge temperature (°C)	Estimated recharge altitude (ft-VD)	Sample vial	Concentration in water sample			Calculated atmospheric mixing ratio			Ground-water-age dates, no mixing assumed			Median ground-water-age since recharge (years)
						CFC-11 (pg/L)	CFC-12 (pg/L)	CFC-113 (pg/L)	CFC-11 (pptv)	CFC-12 (pptv)	CFC-113 (pptv)	CFC-11	CFC-12	CFC-113	
Ground-water-age dates computed, using recharge temperature equal to average annual air temperature (10.4°C)															
Well 1-16	02/07/2003	1030	10.4	1,040	2	540.1	362.6	62.7	200.2	586.8	55.3	1983.5	Contam.	**1987**	16
					4	542.0	346.9	62.7	200.9	561.3	55.3	1983.5	Modern	**1987**	
					5	541.8	385.3	63.3	200.8	623.4	55.8	1983.5	Contam.	**1987**	
Well 1-23	02/07/2003	1235	10.4	1,060	2	1,764.9	1,748.9	18.2	654.6	2,832.2	16.0	Contam.	Contam.	**1977**	25.5
					4	1,760.6	1,620.4	24.7	653.0	2,624.3	21.8	Contam.	Contam.	**1979.5**	
					5	1,727.1	1,690.2	19.3	640.6	2,737.2	17.0	Contam.	Contam.	**1977.5**	
Well 2-15	02/13/2003	1255	10.4	1,050	2	792.7	337.8	49.6	293.9	546.8	43.8	Modern	Modern	1985	5
					4	814.5	328.8	50.9	302.0	532.3	44.9	Contam.	**1997.5**	1985	
					5	802.7	328.3	48.6	297.6	531.5	42.8	Contam.	**1997**	1984.5	
Well 2-26	02/13/2003	1110	10.4	1,060	2	470.6	337.6	8.3	174.5	546.7	7.3	1980.5	**Modern**	1971.5	<5
					4	462.6	336.0	17.8	171.6	544.1	15.7	1980	**Modern**	1977	
					5	460.7	317.8	10.0	170.9	514.6	8.9	1980	**1992.5**	1973	
Well 3-13	03/07/2003	1355	10.4	1,038	2	172.0	246.1	15.0	63.7	398.2	13.2	1970.5	**1985.5**	1975.5	17.5
					4	177.7	247.9	16.6	65.8	401.2	14.6	1970.5	**1985.5**	1976.5	
					5	175.6	245.7	16.0	65.1	397.5	14.1	1970.5	**1985.5**	1976	
Well 3-38	03/07/2003	1525	10.4	1,060	2	4.8	147.8	ND	1.8	239.4	ND	1952.5	**1975.5**	pre-1957	27.5
					4	8.3	141.1	ND	3.1	228.6	ND	1954.5	**1975**	pre-1957	
					5	12.0	147.4	ND	4.5	238.6	ND	1955.5	**1975.5**	pre-1957	
Well 4-14	02/13/2003	1530	10.4	1,040	2	529.5	288.0	54.3	196.2	466.1	47.8	1983	**1988.5**	1985.5	14
					4	535.2	293.4	56.1	198.4	474.7	49.5	1983	**1989**	1986	
					5	541.4	300.2	55.5	200.2	586.8	55.3	1983.5	**1990**	1986	

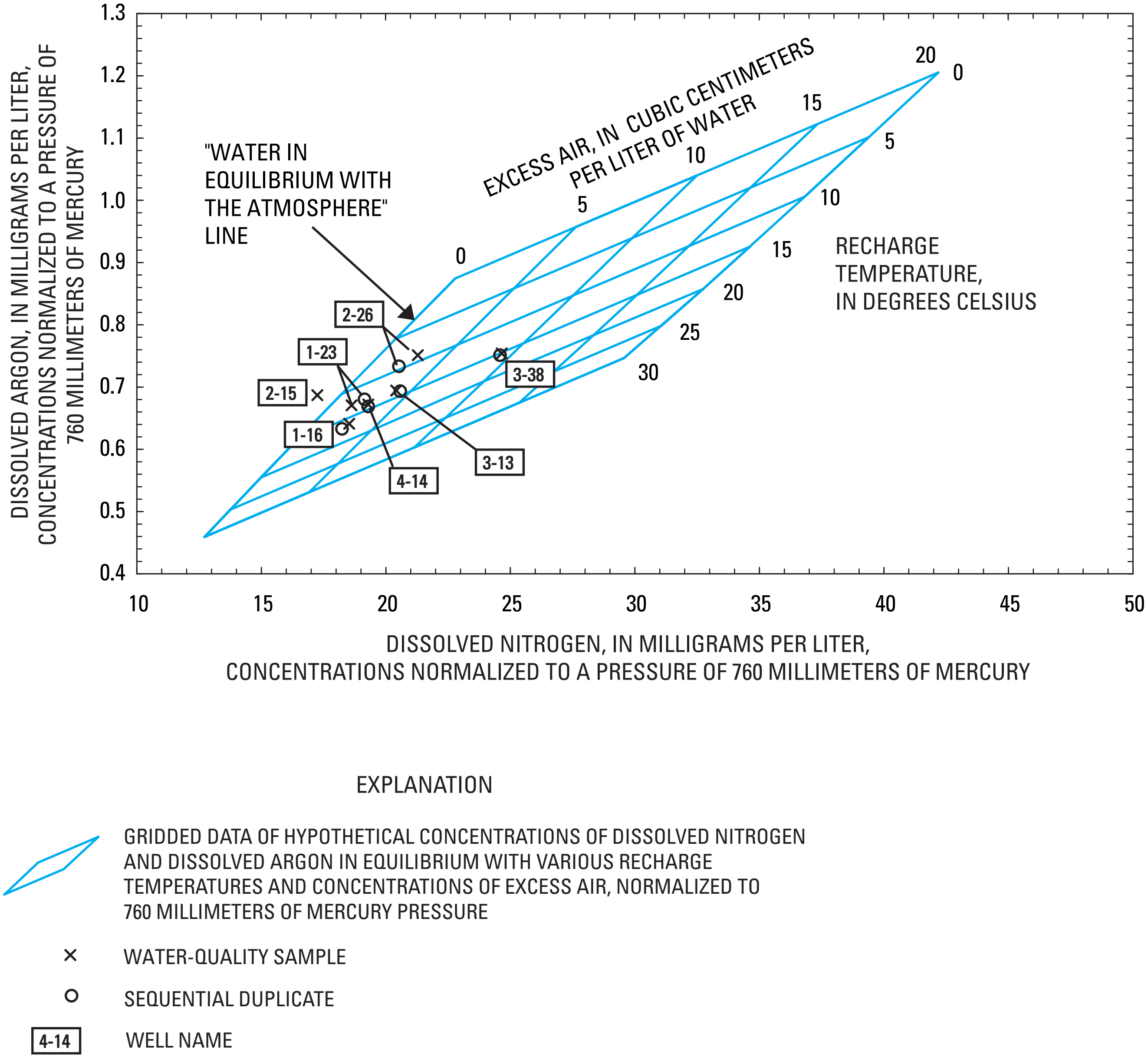


Figure 14. Concentrations of dissolved nitrogen and dissolved argon in water samples and sequential duplicates from the upper aquifer near Richmond, Indiana, 2002 data, plotted on a grid with hypothetical concentrations of dissolved nitrogen and dissolved argon at various recharge temperatures and concentrations of excess air in water samples. Gridded data of hypothetical concentrations of dissolved nitrogen and dissolved argon (Julian Wayland, U.S. Geological Survey, written commun., 2003) as computed, using methods from Weiss, 1970.

The estimated average recharge temperatures for water from wells 1-23, 3-13, and 4-14 were similar to the average annual air temperature of 10.4°C for Richmond between 1971 and 2000 (Midwestern Regional Climatic Center, 2005a). The estimated average recharge temperatures for water from the deep wells 2-26 and 3-38 were 6.3°C and 5.6°C, substantially less than the average annual air temperature. The low recharge temperatures for wells 2-26 and 3-38 are consistent with the observation by Rowe and others (1999) that most recharge to a similar glacial aquifer about 35 mi to the east occurs during the cooler fall and winter months.

Chlorofluorocarbon-Based Ground-Water Ages

Ground water in samples collected for this study from the upper aquifer had infiltrated to the water table within about 13 to 30 years of this sampling (February and March 2003, table 7). These ground-water ages were computed with CFC-12 data (or CFC-113 data for wells 1-16 and 1-23), recharge temperatures computed from dissolved-gas data (except at well 2-15), and with the assumption of no appreciable mixing between different-aged waters. Ground-water ages based on CFC-11 and CFC-113 generally were older than the CFC-12-based ground-water ages for all samples for which dates could be computed; an exception was the sample from well 2-15 (table 7). CFC-12 is less affected by microbial processes that degrade CFC-11 and CFC-113 (Rowe and others, 1999); therefore, the CFC-12-based age dates are likely the more-accurate estimates. Ground-water ages were youngest in shallow wells along the former glacial-valley margins at about 13 to 15 years since recharge (from about 1988 to 1990). The oldest ground-water age was about 30 years since recharge (1973) at the base of the upper aquifer at well 3-38. The oldest ground-water age from a shallow well was about 18.5 years since recharge (1984.5) in water from well 3-13. The range in ground-water ages includes the post-1972 period when industrial and commercial development replaced agricultural and airfield development in some parts of the study area that were south of the ground-water-flow divide.

CFC-113 was used to estimate ground-water ages for samples from wells 1-16 and 1-23 where contamination of samples with excess CFC-12 (and in one case excess CFC-11) was detected (table 7). The CFC-113-based ground-water ages were about 15 years (1988) before sampling from near the water table at well 1-16 and about 25 years (1978) before sampling from the base of the aquifer at well 1-23. Concentrations of CFC-12 in water from wells 1-16 and 1-23 and of CFC-11 from well 1-23 are considered contaminated because the CFC concentrations were higher than could be explained by equilibration with atmospheric values. Wells 1-16 and 1-23 are in an industrial area (fig. 4). It is possible that local manufacturing operations may have used CFC-12 at some time before the phase-out of CFC refrigerants during the 1990s.

Ground-water ages at the base of the upper aquifer were older than the ages of ground water near the water table (table 7). For example, ground water at well 1-23 is estimated to have recharged the aquifer about 10 years before water from the shallow well at the same site (well 1-16). Ground water sampled from the deep well 3-38 recharged the aquifer about 11.5 years before water sampled from the shallow well (3-13) at the same site. The ground-water age for water from the base of the aquifer at well 2-26 was about 2.5 years older (about 16 years since recharge or 1987) than water sampled from near the water table at well 2-15 (about 13.5 years since recharge or 1989.5).

Ground-water ages determined for shallow wells ranged from about 13 to 18.5 years since recharge (table 7). This result was not anticipated because the samples were collected within about 5 to 10 ft below the water table where very modern water ages might be expected. This result may reflect imprecision in the dating technique or mixing of very recent vertical recharge with lateral flow of older ground water. Upward hydraulic gradients measured at all paired shallow and deep wells during most water-level measurements (table 5) indicate that the ground-water ages for samples from the shallow wells 1-16, 2-15, and 3-13 were affected by mixing of shallow with older deep ground water.

Ground-water ages estimated with the average annual air temperature as the recharge temperature were similar to but slightly younger than the ages estimated with recharge temperatures derived from dissolved-gas data (table 7). CFC-12-based ground-water ages for water from wells 2-15 and 2-26 were the most sensitive to the use of a different temperature for the age computation. Estimates of ground-water ages for these wells were about 5 years since recharge when the average annual air temperature was used as the recharge temperature; they were about 13 and 15 years since recharge when the recharge temperatures derived from dissolved-gas data were used.

Ground-water ages computed from CFC concentrations are minimum ages (some contamination by introduction of these gases from the atmosphere during sampling of ground water was possible). Such contamination would most affect samples with older age dates because those samples would have had the lowest CFC concentrations. Sorption and microbial transformation of CFCs and mixing of older and younger ground water within the saturated zone can affect the accuracy of age estimates. Estimated ground-water ages also may be affected by matrix diffusion, hydrodynamic dispersion, and complex mixing in the aquifer or the well screen during sampling (Plummer and Busenberg, 1999).

Sulfur Hexafluoride Data

Sulfur-hexafluoride (SF_6) concentrations were not used in this study to estimate ground-water age because SF_6 concentrations in ground water from the upper aquifer (table 8, back of report) were higher than those reported for the atmosphere (fig. 7). SF_6 concentrations in ground water, after adjustments for recharge temperature and excess air concentration, ranged from 5.6 pptv in a sample from well 3-38 to 10.0 pptv in a sample from well 3-13. By comparison, reconstructed annual averages of atmospheric concentrations of SF_6 range from near zero in 1953 to about 4.8 pptv in 2000 (fig. 7) (Busenberg and Plummer, 2000). The higher concentrations of SF_6 in ground water from the upper aquifer indicate a possible natural or a local human-influenced source of SF_6. The USGS Dissolved Gas Laboratory reported that some SF_6 leakage may have occurred because of loose caps on sample bottles collected from wells 3-13 and 3-38. No such potential interferences were reported for the other samples.

A solid-phase analysis of upper-aquifer sediments revealed a relatively large abundance of carbonate minerals and traces of gypsum. Busenberg and Plummer (2000) indicated large contributions of natural SF_6 can arise from some but not all carbonate rocks and may interfere with ground-water-age dating with SF_6. Contributions of natural SF_6 to water samples collected from carbonate and siliciclastic aquifers also previously have been noted in Lindsey and others (2003). There are no known local SF_6 uses that would have created the elevated concentrations reported for ground water from the upper aquifer. Data from this study indicate that SF_6 should be used with caution when dating ground water in clastic aquifers that contain substantial carbonate mineral content.

Ground-Water Quality

Water-quality data (tables 9–11; tables 12–15, back of report) were interpreted relative to the results of quality-assurance analyses (tables 16 and 17), comparisons with data ranges from other parts of the Whitewater Valley aquifer system (Beaty and Clendenon, 1988) (table 18), and comparisons with State and applicable Federal water-quality standards (table 19) as published by the Indiana Administrative Code (2006) and the U.S. Environmental Protection Agency (1992, 2002a, 2004). Except as discussed in this section, all major cations and anions, several nutrients, and most trace elements were detected in ground-water samples (tables 10–11). Most pesticides, VOCs, SVOCs, and wastewater-related organic compounds generally were not detected in ground-water samples or were detected only in trace quantities (tables 12–15, back of report).

Evaluation of Quality-Assurance Data

Equipment-cleaning procedures between samples were sufficient for most water-quality characteristics and constituents to limit carryover of contaminants from one water sample to the next. This conclusion was reached for each constituent that was not detected in the equipment blank or was not detected in the water samples, although various constituents (including calcium, sodium, silica, cobalt, and strontium) were detected in an equipment blank (table 16). Concentrations of these constituents in water samples were more than 10 times the corresponding concentration in the equipment blank; therefore, no apparent interference was identified.

Comparisons of chemical analyses of water samples and equipment blanks indicated possible equipment or cleaning interferences related to detections of submicrogram per liter concentrations of the trace elements antimony, lead, manganese, molybdenum, nickel, thallium and the organic compounds chloroform, toluene, and N,N-diethyl-meta-toluamide (DEET). Concentrations of these constituents were detected in some water samples at levels less than 10 times the concentrations in the corresponding equipment blank. These interferences were near the threshold of detection for these substances. DEET is a commonly used insect repellent; none was used during water-sample collection for this study. Fugitive DEET residues from previous uses near the sampling vehicle or equipment still may be present in the sampling environment and unintentionally may have been added to the samples. Concentrations of antimony, lead, manganese, thallium (table 11), chloroform and toluene (table 13), DEET and isophorone (table 15) in water samples that were within 10 times the concentration in the corresponding equipment blank were flagged as estimated to indicate a possible sampling-related interference.

For most constituents and water-quality characteristics, sample-collection procedures and water-quality analyses produced reproducible results for the two sets of water samples and sequential duplicates (table 17). The RPDs between analyses of water samples and sequential duplicates for most constituents were less than 10 percent or could not be computed because both analyses had concentrations that were less than the detection limit. The RPDs of analyses that had concentrations near (dissolved solids) or greater than (nitrite plus nitrate) the corresponding drinking-water standard were less than 3 percent, indicating that those results were not affected by sampling-related error.

The RPDs of several constituents that had concentrations at or near the reporting limits (aluminum, antimony, molybdenum, and zinc) were greater than 25 percent (table 17). Analytical precision typically is least for chemical analyses near the limit of detection and the limit of quantitation of a constituent (Taylor, 1987, p. 79–82); the limit of quantitation is referred to in this report as the reporting limit. RPDs for the organic compounds toluene and DEET were greater than 25 percent between a water sample and a sequential duplicate. RPDs for one of two sets of manganese concentrations and for the one set of boron concentrations were greater than 25 percent; the manganese and boron concentrations in the water sample and a sequential duplicate from well 1-23 (table 17) were greater than their reporting limits (table 3, back of report). The latter data indicate that concentrations of manganese that are less than about 3 μg/L and of boron that are less than about 40 μg/L may have reduced analytical precision.

Table 9. Values of field-determined water-quality characteristics in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002–03.

[USGS, U.S. Geological Survey; mm/dd/yy, month/day/year; hhmm, hours and minutes; mm Hg, millimeters of mercury; µS/cm, microsiemen per centimeter; ºC, degrees Celsius; mg/L, milligram per liter; NTU, nephelometric turbidity unit; --, not measured or determined]

USGS station-identification number	Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Barometric pressure (mm Hg)	pH (standard units)	Specific conductance (µS/cm)	Water temperature (°C)	Dissolved oxygen (mg/L)	Turbidity (NTU)
				Water samples					
394924084492501	Well 1-16	08/28/02	0900	744	6.7	1,540	16.9	5.5	0.9
		02/06/03	1230	--	6.9	880	12.5	--	--
394924084492502	Well 1-23	08/28/02	1345	744	6.8	1,500	15.9	3.3	1.8
		02/06/03	1240	--	6.9	1,640	14.3	--	--
394852084492501	Well 2-15	08/27/02	0915	737	6.8	1,000	17.5	6.5	70
		02/13/03	1255	--	7.0	830	10.8	--	--
394852084492502	Well 2-26	08/27/02	1400	737	6.8	1,200	18.2	5.5	28
		02/13/03	1110	--	6.8	1,026	12.5	--	--
394851084500001	Well 3-13	08/29/02	0900	740	6.8	737	18.6	.4	1.8
		03/07/03	1350	--	7.0	823	7.3	--	--
394851084500002	Well 3-38	08/29/02	1330	--	6.6	727	13.1	.1	.7
		09/05/02	1030	738	6.9	719	12.9	.1	.4
		03/07/03	1525	--	7.0	726	11.1	--	--
394852084503301	Well 4-14	08/30/02	0930	746	7.1	900	16.8	4.6	2.1
		02/13/03	1530	--	6.9	856	9.7	--	--

Table 10. Concentrations of major cations and anions, alkalinity, dissolved solids, and nutrients in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.

[mm/dd/yy, month/day/year; hhmm, hours and minutes; mg/L, milligram per liter; $CaCO_3$, calcium carbonate; CO_3, carbonate ion; HCO_3, bicarbonate ion; < , less than; -- , not measured or determined; E, estimated value below reporting limit; N, nitrogen; P, phosphorus; all concentrations reported are as dissolved constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Calcium (mg/L)	Magnesium (mg/L)	Potassium (mg/L)	Sodium (mg/L)	Alkalinity (mg/L as $CaCO_3$)	Carbonate alkalinity (mg/L as CO_3)	Bicarbonate alkalinity (mg/L as HCO_3)
Water samples									
Well 1-16	08/28/02	0900	163	45.9	2.95	81.8	384	<1	467
Well 1-23	08/28/02	1345	120	36.7	2.32	124	333	<1	406
Well 2-15	08/27/02	0915	107	29.5	3.12	65.3	378	<1	460
Well 2-26	08/27/02	1400	134	39.6	5.02	57.2	411	<1	500
Well 3-13	08/29/02	0900	101	31.6	2.35	4.35	306	<1	372
Well 3-38	09/05/02	1030	99.3	33.5	1.49	4.83	309	<1	376
Well 4-14	08/30/02	0930	103	30.2	3.44	37.0	334	<1	407
Quality-assurance samples									
Well 3-13 (Sequential duplicate)	08/29/02	0930	100	31.0	2.37	4.49	--	--	--
Well 2-15 (Equipment blank)	08/26/02	1800	.016	<.008	<.1	E.06	--	--	--

Table 10. Concentrations of major cations and anions, alkalinity, dissolved solids, and nutrients in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; mg/L, milligram per liter; $CaCO_3$, calcium carbonate; CO_3, carbonate ion; HCO_3, bicarbonate ion; < , less than; -- , not measured or determined; E, estimated value below reporting limit; N, nitrogen; P, phosphorus; all concentrations reported are as dissolved constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Bromide (mg/L)	Chloride (mg/L)	Fluoride (mg/L)	Silica (mg/L)	Sulfate (mg/L)	Dissolved solids (total residue, 180 degrees Celsius) (mg/L)
				Water samples				
Well 1-16	08/28/02	0900	0.0575	256	<0.10	9.73	19.8	893
Well 1-23	08/28/02	1345	.0594	247	E.09	11.4	29.1	723
Well 2-15	08/27/02	0915	E.0249	75.4	.17	13.0	20.5	570
Well 2-26	08/27/02	1400	.0367	117	.13	13.3	45.9	682
Well 3-13	08/29/02	0900	E.0167	13.3	.15	10.6	29.3	433
Well 3-38	09/05/02	1030	E.0203	14.2	.15	11.7	38.4	426
Well 4-14	08/30/02	0930	E.0245	67.9	.14	10.1	26.1	411
				Quality-assurance samples				
Well 3-13 (Sequential duplicate)	08/29/02	0930	E.016	13.8	.14	10.5	29.6	443
Well 2-15 (Equipment blank)	08/26/02	1800	<.03	<.3	<.1	E.09	<.1	<10

Table 10. Concentrations of major cations and anions, alkalinity, dissolved solids, and nutrients in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; mg/L, milligram per liter; $CaCO_3$, calcium carbonate; CO_3, carbonate ion; HCO_3, bicarbonate ion; < , less than; -- , not measured or determined; E, estimated value below reporting limit; N, nitrogen; P, phosphorus; all concentrations reported are as dissolved constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Ammonia (mg/L as N)	Ammonia plus organic nitrogen, (mg/L as N)	Nitrite plus nitrate (mg/L as N)	Nitrite (mg/L as N)	Nitrate[1] (mg/L as N)	Orthophosphate (mg/L as P)
				Water samples				
Well 1-16	08/28/02	0900	<0.04	<0.10	1.18	<0.008	1.18	<0.02
Well 1-23	08/28/02	1345	<.04	E.05	2.62	<.008	2.62	<.02
Well 2-15	08/27/02	0915	<.04	E.06	3.67	<.008	3.67	E.01
Well 2-26	08/27/02	1400	<.04	E.07	6.64	<.008	6.64	<.02
Well 3-13	08/29/02	0900	<.04	.12	11.0	E.005	11.0	<.02
Well 3-38	09/05/02	1030	<.04	E.06	5.12	.035	5.08	<.02
Well 4-14	08/30/02	0930	<.04	E.07	2.80	<.008	2.80	<.02
				Quality-assurance samples				
Well 3-13 (Sequential duplicate)	08/29/02	0930	<.04	E.10	11.1	<.008	11.1	<.02
Well 2-15 (Equipment blank)	08/26/02	1800	<.04	<.1	<.05	<.008	Could not be computed	<.02

[1] Nitrate concentration was computed according to the following method:

[Nitrate] =[Nitrite plus nitrate] - [Nitrite]

for cases where either nitrite or nitrite plus nitrate concentrations were less than the reporting limit, their concentrations were set equal to zero for the above computation. This convention is followed by Nolan and Hitt (2002) and reflects that the potential variability of nitrite concentrations below the reporting limit (from not detected to 0.008 mg/L as N) would not affect the computed nitrate concentration.

Table 11. Concentrations of trace elements in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.

[mm/dd/yy, month/day/year; hhmm, hours and minutes; µg/L, microgram per liter; E, estimated value below reporting limit; < , less than; Q, concentration estimated because relative percent difference between environmental and sequential duplicate samples was more than 25 percent; -- , not measured or determined; all concentrations are reported as dissolved constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Aluminum (µg/L)	Antimony (µg/L)	Arsenic (µg/L)	Barium (µg/L)	Beryllium (µg/L)	Boron (µg/L)	Cadmium (µg/L)	Chromium (µg/L)
Water samples										
Well 1-16	08/28/02	0900	5	[1]0.05	E0.1	77	<0.06	31	<0.04	E0.6
Well 1-23	08/28/02	1345	Q7	[1]Q.06	<.2	78	<.06	Q38	<.04	<.8
Well 2-15	08/27/02	0915	8	[1].08	.3	80	<.06	67	<.04	E.7
Well 2-26	08/27/02	1400	6	[1].13	.2	135	<.06	56	.05	E.5
Well 3-13	08/29/02	0900	5	[1].28	.3	77	<.06	38	E.02	<.8
Well 3-38	09/05/02	1030	<1	[1].30	E.1	95	<.06	28	E.02	<.8
Well 4-14	08/30/02	0930	<1	[1]E.03	.3	77	<.06	35	<.04	<.8
Quality-assurance samples										
Well 1-23 (Sequential duplicate)	08/28/02	1415	<1	<.05	<.2	77	<.06	21	<.04	<.8
Well 3-13 (Sequential duplicate)	08/29/02	0930	--	--	--	--	--	--	--	--
Well 2-15 (Equipment blank)	08/26/02	1800	<1	.079	<.2	<1	<.06	<7	<.04	<.8

Table 11. Concentrations of trace elements in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; µg/L, microgram per liter; E, estimated value below reporting limit; < , less than; Q, concentration estimated because relative percent difference between environmental and sequential duplicate samples was more than 25 percent; -- , not measured or determined; all concentrations are reported as dissolved constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Cobalt (µg/L)	Copper (µg/L)	Iron (µg/L)	Lead (µg/L)	Lithium (µg/L)	Manganese (µg/L)	Molybdenum (µg/L)	Nickel (µg/L)
					Water samples					
Well 1-16	08/28/02	0900	0.30	0.6	<10	<0.08	1.3	[1]1.0	[1]0.3	[1]1.93
Well 1-23	08/28/02	1345	.25	.6	<10	[1]E.05	2.1	Q2.3	[1]Q.6	5
Well 2-15	08/27/02	0915	.24	.5	<10	<.08	2.8	9.0	1.6	[1]1.36
Well 2-26	08/27/02	1400	.52	.7	E7	<.08	4.1	82.1	2.0	[1]2.03
Well 3-13	08/29/02	0900	.22	1.0	<10	<.08	2.6	3.0	2.7	[1]1.24
Well 3-38	09/05/02	1030	1.40	.7	<10	<.08	2.8	93.5	3.9	[1]3.22
Well 4-14	08/30/02	0930	.24	.7	<10	<.08	1.3	1.2	[1].9	[1]1.04
					Quality-assurance samples					
Well 1-23 (Sequential duplicate)	08/28/02	1415	.28	.7	--	[1]E.04	1.8	4.7	[1].4	5
Well 3-13 (Sequential duplicate)	08/29/02	0930	--	--	E6	--	--	E2.9	--	--
Well 2-15 (Equipment blank)	08/26/02	1800	.018	<.2	<10	E.041	<.3	.186	E.134	.385

Table 11. Concentrations of trace elements in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; µg/L, microgram per liter; E, estimated value below reporting limit; < , less than; Q, concentration estimated because relative percent difference between environmental and sequential duplicate samples was more than 25 percent; -- , not measured or determined; all concentrations are reported as dissolved constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Selenium (µg/L)	Silver (µg/L)	Strontium (µg/L)	Thallium (µg/L)	Uranium (µg/L)	Vanadium (µg/L)	Zinc (µg/L)
Water samples									
Well 1-16	08/28/02	0900	0.4	<1	152	<0.04	0.39	3.4	<1
Well 1-23	08/28/02	1345	.5	<1	114	<.04	.39	<.2	Q<1
Well 2-15	08/27/02	0915	.7	<1	123	<.04	.89	6.2	<1
Well 2-26	08/27/02	1400	.7	<1	177	<.04	1.7	4.1	1
Well 3-13	08/29/02	0900	2.2	<1	150	[1].11	2.9	1.2	1
Well 3-38	09/05/02	1030	1.2	<1	366	[1].16	1.3	1.1	3
Well 4-14	08/30/02	0930	1.0	<1	128	<.04	1.1	.9	<1
Quality-assurance samples									
Well 1-23 (Sequential duplicate)	08/28/02	1415	.6	<1	114	<.04	.39	<.2	1
Well 3-13 (Sequential duplicate)	08/29/02	0930	--	--	--	--	--	--	--
Well 2-15 (Equipment blank)	08/26/02	1800	<.3	<1	.081	.063	<.02	<.2	<1

[1] Reported concentrations in this analysis represent a potential sampling-related interference.

Table 16. Comparison of concentrations of selected constituents in equipment blanks to the range of concentrations of those constituents in water samples from the upper aquifer near Richmond, Indiana, 2002.

[mg/L, milligram per liter; < , less than; E, estimated concentration below reporting limit; N, nitrogen; P, phosphorus; µg/L, microgram per liter]

Constituent name	Reporting unit	Concentration in equipment blank(s)	Concentration range in water samples		Comment[1]	Well name where potential interference was detected
			Minimum	Maximum		
Major cations and anions and a water-quality characteristic						
Calcium	mg/L	0.016	99.3	163	2	Not applicable.
Magnesium	mg/L	<.008	29.5	45.9	1	Not applicable.
Potassium	mg/L	<.1	1.49	5.02	1	Not applicable.
Sodium	mg/L	E.06	4.35	124	2	Not applicable.
Bromide	mg/L	<.03	E.0167	.0594	1	Not applicable.
Chloride	mg/L	<.3	13.3	256	1	Not applicable.
Fluoride	mg/L	<.1	E.09	.17	1	Not applicable.
Silica	mg/L	E.09	9.73	13.3	2	Not applicable.
Sulfate	mg/L	<.1	19.8	45.9	1	Not applicable.
Dissolved solids (total residue, 180 degrees Celsius)	mg/L	<10	411	893	1	Not applicable.
Nutrients						
Nitrogen, ammonia	mg/L as N	<.04	<.04	<.04	1	Not applicable.
Nitrogen, ammonia plus organic	mg/L as N	<.1	E.05	.12	1	Not applicable.
Nitrogen, nitrite plus nitrate	mg/L as N	<.05	1.18	11.0	1	Not applicable.
Nitrogen, nitrite	mg/L as N	<.008	E.005	.035	1	Not applicable.
Phosphorus, phosphate, ortho	mg/L as P	<.02	E.01	<.02	1	Not applicable.

Table 16. Comparison of concentrations of selected constituents in equipment blanks to the range of concentrations of those constituents in water samples from the upper aquifer near Richmond, Indiana, 2002.—Continued

[mg/L, milligram per liter; < , less than; E, estimated concentration below reporting limit; N, nitrogen; P, phosphorus; µg/L, microgram per liter]

Constituent name	Reporting unit	Concentration in equipment blank(s)	Concentration range in water samples		Comment[1]	Well name where potential interference was detected
			Minimum	Maximum		
			Trace elements			
Aluminum	µg/L	<1	<1	8	1	Not applicable.
Antimony	µg/L	.079	E.03	.30	3	Wells 1-16, 1-23, 2-15, 2-26, and 4-14.
Arsenic	µg/L	<.2	E.1	.3	1	Not applicable.
Barium	µg/L	<1	77	135	1	Not applicable.
Beryllium	µg/L	<.06	<.06	<.06	1	Not applicable.
Boron	µg/L	<7	28	67	1	Not applicable.
Cadmium	µg/L	<.04	E.02	.05	1	Not applicable
Chromium	µg/L	<.8	E.5	<.8	1	Not applicable
Cobalt	µg/L	.018	.22	1.40	2	Not applicable.
Copper	µg/L	<.2	.5	1.0	1	Not applicable.
Iron	µg/L	<10	E7	<10	1	Not applicable.
Lead	µg/L	E.041	<.08	E.05	3	Well 1-23.
Lithium	µg/L	<.3	1.3	4.1	1	Not applicable.
Manganese	µg/L	.186	.2	93.5	3	Wells 1-16 and 4-14.
Molybdenum	µg/L	E.134	.3	3.9	3	Wells 1-16, 1-23, and 4-14.
Nickel	µg/L	.385	1.04	3.22	3	Wells 1-16, 2-15, 2-26, 3-13, 3-38, and 4-14.
Selenium	µg/L	<.3	.4	2.2	1	Not applicable.
Silver	µg/L	<1	<1	<1	1	Not applicable.
Strontium	µg/L	.081	114	366	2	Not applicable.
Thallium	µg/L	.063	<.04	.16	3	Wells 3-13 and 3-38.
Uranium	µg/L	<.02	.39	2.9	1	Not applicable.
Vanadium	µg/L	<.2	<.2	6.2	1	Not applicable.
Zinc	µg/L	<1	<1	3	1	Not applicable.

Table 16. Comparison of concentrations of selected constituents in equipment blanks to the range of concentrations of those constituents in water samples from the upper aquifer near Richmond, Indiana, 2002.—Continued

[mg/L, milligram per liter; < , less than; E, estimated concentration below reporting limit; N, nitrogen; P, phosphorus; µg/L, microgram per liter]

Constituent name	Reporting unit	Concentration in equipment blank(s)	Concentration range in water samples		Comment[1]	Well name where potential interference was detected
			Minimum	Maximum		
		Volatile organic compounds—Detected in equipment blank				
Chloroform	µg/L	E.02; <0.02	E0.01	E0.04	3	Well 1-23.
Methyl ethyl ketone	µg/L	E4.2; <5.0	<5.0	<5.0	1	Not applicable.
Styrene	µg/L	E.02; E.05	<.04	<.04	1	Not applicable.
Toluene	µg/L	E.01; <.05	<.05	.17	3	Well 1-23.
		Wastewater-related compounds—Detected in equipment blank				
N,N-diethyl-meta-toluamide (DEET)	µg/L	E.38	E.1	E.2	3	All sampled wells.
Isophorone	µg/L	E.2	<.2	E.2	3	Well 3-38.
Triphenyl phosphate	µg/L	E.004	<.5	<.5	1	Not applicable.
Tris(dichlorisopropyl) phosphate	µg/L	E.02	<.5	<.5	1	Not applicable.

[1] Comments: 1, no equipment interference; constituent not detected in equipment blank or not detected in water samples. 2, no apparent equipment interference; constituent concentration in one or more water samples is more than 10 times the concentration detected in equipment blank.
3, potential interference; constituent concentration in a subsequent water sample is within 10 times the concentration detected in equipment blank.

Table 17. Comparison of concentrations of selected constituents detected in water samples from the upper aquifer near Richmond, Indiana, or in sequential duplicates, 2002.

[RPD, relative percent difference; mg/L, milligram per liter; -- , estimate not needed to compute relative percent difference statistic; E, estimated concentration below reporting limit or estimated relative percent difference statistic; < , less than; µg/L, microgram per liter; **bold** value indicates relative percent difference statistic greater than 25 percent]

Constituent name	Reporting units	Well name	Water sample		Sequential duplicate[1]		RPD (precision) between replicates[3]
			Reported concentration	Concentration used to compute estimated RPD[2]	Reported concentration	Concentration used to compute estimated RPD[2]	
Major cations and anions and a water-quality characteristic							
Calcium	mg/L	Well 3-13	101	--	100	--	1.00
Magnesium	mg/L	Well 3-13	31.6	--	31.0	--	1.92
Potassium	mg/L	Well 3-13	2.35	--	2.37	--	.85
Sodium	mg/L	Well 3-13	4.35	--	4.49	--	3.17
Bromide	mg/L	Well 3-13	E.0167	.0167	E.0160	.0160	E4.28
Chloride	mg/L	Well 3-13	13.3	--	13.8	--	3.69
Fluoride	mg/L	Well 3-13	.15	--	.14	--	6.90
Silica	mg/L	Well 3-13	10.6	--	10.5	--	.95
Sulfate	mg/L	Well 3-13	29.3	--	29.6	--	1.02
Dissolved solids (total residue, 180 degrees Celsius)	mg/L	Well 3-13	433	--	443	--	2.28
Nutrients							
Ammonia plus organic nitrogen	mg/L as N	Well 3-13	.12	--	E.097	.097	E21.20
Nitrite plus nitrate	mg/L as N	Well 3-13	11	--	11.1	--	.90
Nitrite	mg/L as N	Well 3-13	.005	--	<.008	.004	E22.22
Trace elements							
Aluminum	µg/L	Well 1-23	7	--	<1	.5	**E173.33**
Antimony	µg/L	Well 1-23	.06	--	<.05	.025	**E82.35**
Barium	µg/L	Well 1-23	78	--	77	--	1.29
Boron	µg/L	Well 1-23	38	--	21	--	**57.63**
Cobalt	µg/L	Well 1-23	.25	--	.28	--	11.32
Copper	µg/L	Well 1-23	.6	--	.7	--	15.38
Iron	µg/L	Well 3-13	<10	5	E6	6	E18.18
Lead	µg/L	Well 1-23	E.05	.05	E.04	.04	E22.22
Lithium	µg/L	Well 1-23	2.1	--	1.8	--	15.38

Table 17. Comparison of concentrations of selected constituents detected in water samples from the upper aquifer near Richmond, Indiana, or in sequential duplicates, 2002.—Continued

[RPD, relative percent difference; mg/L, milligram per liter; -- , estimate not needed to compute relative percent difference statistic; E, estimated concentration below reporting limit or estimated relative percent difference statistic; < , less than; µg/L, microgram per liter; **bold** value indicates relative percent difference statistic greater than 25 percent]

Constituent name	Reporting units	Well name	Water sample		Sequential duplicate[1]		RPD (precision) between replicates[3]
			Reported concentration	Concentration used to compute estimated RPD[2]	Reported concentration	Concentration used to compute estimated RPD[2]	
			Trace elements—Continued				
Manganese	µg/L	Well 1-23	2.3	--	4.7	--	**68.57**
		Well 3-13	3.0	--	E2.9	2.9	E3.39
Molybdenum	µg/L	Well 1-23	.6	--	.4	--	**40.00**
Nickel	µg/L	Well 1-23	5	--	5	--	.00
Selenium	µg/L	Well 1-23	.5	--	.6	--	18.18
Strontium	µg/L	Well 1-23	114	--	114	--	.00
Uranium	µg/L	Well 1-23	.39	--	.39	--	.00
Zinc	µg/L	Well 1-23	<1	.5	1	--	**E66.67**
			Pesticides and pesticide transformation product				
Atrazine	µg/L	Well 3-13	E.006	.006	E.006	.006	E.00
Deethylatrazine (2-Chloro-4-isopropylamino-6-amino-s-triazine)	µg/L	Well 3-13	E.015	.015	E.012	.012	E22.22
Flumetsulam	µg/L	Well 3-13	E.02	.02	E.02	.02	E.00
Tebuthiron	µg/L	Well 3-13	E.01	.01	E.01	.01	E.00
			Volatile organic compound				
Toluene	µg/L	Well 1-23	E.05	.05	.17	--	**E109.09**
			Wastewater-related organic compounds				
N,N-diethyl-meta-toluamide (DEET)	µg/L	Well 1-23	E.07	.07	E.03	.03	**E80.00**

[1] A sequential duplicate is a second sample of water collected immediately after the first sample (the water sample). The water sample and sequential duplicate were shipped, processed, and analyzed in the same manner.

[2] Sample concentrations that were reported as estimated (with a magnitude less than the method or lower reporting limit) were set equal to the estimated concentration for computation of statistics. Sample concentrations used for computation were unrounded values from the U.S. Geological Survey, National Water-Quality Information System database. Statistics reported in this table were rounded to two decimal places.

[3] Absolute relative percent differences (RPD) were computed as:

$$RPD = |(SD-WS)/((SD+WS)/2)| \times 100$$

where,

RPD is the relative percent difference
SD is the sequential duplicate
WS is the water sample

This statistic is used to summarize the percent difference in concentration between two samples that should be identical composition and that were identical in their handling and analysis.

Table 18. Statistical summary of water-quality characteristics and concentrations of selected major cations, major anions, nitrate and trace elements in water samples from the Whitewater Valley aquifer aystem, Indiana, 1978 and 1985 data, and from the upper aquifer, 2002–03.

[mg/L, milligram per liter; < , less than; N, Nitrogen; µg/L, microgram per liter; E, estimated value below reporting limit]

		Water samples from Whitewater Valley aquifer system[1]						Water samples from upper aquifer		
Characteristic or constituent name	Reporting units	Number of samples	Minimum	Percentage of samples in which values are less than or equal to that shown			Maximum	Number of samples	Minimum	Maximum
				25th percentile	Median	75th percentile				
Major cations and anions and a water-quality characteristic										
pH	Standard units	42	6.1	7.1	7.4	7.6	8.3	15	6.7	7.1
Calcium	mg/L	43	72	82	93	97	129	7	99.3	163
Magnesium	mg/L	43	13.9	27	30	33	40.6	7	29.5	45.9
Potassium	mg/L	41	.4	.9	1.6	2	5	7	1.49	5.2
Sodium	mg/L	41	3	4.6	5.6	10	39	7	4.35	124
Chloride	mg/L	43	4	10	16	24	105	7	13.3	256
Fluoride	mg/L	41	.1	.2	.2	.4	4.7	7	<.1	.17
Sulfate	mg/L	43	8	35	44	53	95	7	19.8	45.9
Dissolved solids	mg/L	41	438	529	572	609	816	7	411	893
Nutrient										
Nitrate	mg/L as N	36	<.1	1.1	2.5	4.2	22	7	1.18	11.0
Trace elements										
Iron	µg/L	40	<100	<100	<100	500	5,900	7	<10	E7
Manganese	µg/L	40	<.1	<.1	<.1	.03	.5	7	.02	93.5

[1] Data reference: Beaty and Clendenon (1988).

Table 19. State of Indiana standards for indicator levels of chloride, sulfate, and dissolved solids and maximum permissible levels of selected nutrients, trace elements, pesticides, and volatile and semivolatile organic compounds in drinking-water-class ground water.

[mg/L, milligram per liter; --, no standard established; N, nitrogen; µg/L, microgram per liter]

Name of constituent or characteristic (constituent or characteristic name used in this report in brackets)	Reporting units for constituent or characteristic	Indicator level of a constituent or characteristic in drinking-water-class ground water[1]	Maximum permissible level of a constituent or characteristic in drinking-water-class ground water[1]
Major cations and anions			
Chloride	mg/L	250	--
Fluoride	mg/L	--	4
Sulfate	mg/L	250	--
Dissolved solids (total residue, 180 degrees Celsius)	mg/L	500	--
Nutrients			
Nitrate	mg/L as N	--	10
Nitrite	mg/L as N	--	1
Trace elements			
Antimony	µg/L	--	6
Arsenic	µg/L	--	50
Barium	µg/L	--	2,000
Beryllium	µg/L	--	4
Cadmium	µg/L	--	5
Chromium (total)	µg/L	--	100
Lead	µg/L	--	15
Selenium	µg/L	--	50
Thallium	µg/L	--	2
Pesticides			
2,4-D	µg/L	--	70
Alachlor	µg/L	--	2
Atrazine	µg/L	--	3
Carbofuran	µg/L	--	40
Di(2-ethylhexyl)adipate	µg/L	--	400
Dinoseb	µg/L	--	7
Glyphosate	µg/L	--	700

Table 19. State of Indiana standards for indicator levels of chloride, sulfate, and dissolved solids and maximum permissible levels of selected nutrients, trace elements, pesticides, and volatile and semivolatile organic compounds in drinking-water-class ground water.—Continued

[mg/L, milligram per liter; --, no standard established; N, nitrogen; µg/L, microgram per liter]

Name of constituent or characteristic (constituent or characteristic name used in this report in brackets)	Reporting units for constituent or characteristic	Indicator level of a constituent or characteristic in drinking-water-class ground water[1]	Maximum permissible level of a constituent or characteristic in drinking-water-class ground water[1]
Pesticides—Continued			
Lindane	µg/L	--	0.2
Oxamyl	µg/L	--	200
Picloram	µg/L	--	500
Simazine	µg/L	--	4
Volatile organic compounds			
Trichloroethane, 1,1,1-	µg/L	--	200
Trichloroethane, 1,1,2-	µg/L	--	5
Dichloroethylene, 1,1-	µg/L	--	7
Dichloroethane, 1,2-	µg/L	--	5
Dichloropropane, 1,2-	µg/L	--	5
Dichloroethylene, trans-1,2-	µg/L	--	100
Trichlorobenzene, 1,2,4-	µg/L	--	70
Dichlorobenzene, 1,2-	µg/L	--	600
Dichlorobenzene, 1,4-	µg/L	--	75
Benzene	µg/L	--	5
Carbon tetrachloride	µg/L	--	5
Chlorobenzene	µg/L	--	100
Dibromochloropropane [1,2-Dibromo-3-chloropropane]	µg/L	--	.2
Ethylbenzene	µg/L	--	700
Methylene chloride	µg/L	--	5
Xylenes (total)	µg/L	--	10,000
Styrene	µg/L	--	100
Tetrachloroethylene	µg/L	--	5
Toluene	µg/L	--	1,000
Trichloroethylene	µg/L	--	5
Vinyl chloride	µg/L	--	2

Table 19. State of Indiana standards for indicator levels of chloride, sulfate, and dissolved solids and maximum permissible levels of selected nutrients, trace elements, pesticides, and volatile and semivolatile organic compounds in drinking-water-class ground water.—Continued

[mg/L, milligram per liter; --, no standard established; N, nitrogen; µg/L, microgram per liter]

Name of constituent or characteristic (constituent or characteristic name used in this report in brackets)	Reporting units for constituent or characteristic	Indicator level of a constituent or characteristic in drinking-water-class ground water[1]	Maximum permissible level of a constituent or characteristic in drinking-water-class ground water[1]
Semivolatile organic compounds			
Benzo(a)pyrene	µg/L	--	0.2
Di(2-ethylhexyl)phthalate [Bis(2-ethylhexyl) phthalate]	µg/L	--	6
Hexachlorocyclopentadiene	µg/L	--	50
Hexachlorobenzene	µg/L	--	1
Pentachlorophenol	µg/L	--	1

[1] Indiana Administrative Code, 2006.

General Ground-Water Chemistry, Major Cations and Anions, and Alkalinity

The pH values of the seven water samples from the upper aquifer were near neutral (table 9). The pH of ground water in the study area ranged from 6.7 at well 1-16 in August 2002 to 7.1 at well 4-14 in August 2002; the median value was 6.8. No trends in pH with depth or across the study area were noted. By comparison, pH values measured in 42 ground-water samples from other parts of the Whitewater Valley aquifer system (table 18) ranged from 6.1 to 8.3. Ground water from the upper aquifer had a lower pH that was less than or equal to about 75 percent of samples from other parts of the Whitewater Valley aquifer system (table 18).

Field measurements (table 9) and laboratory analyses (table 6) of dissolved oxygen indicated that ground water was more oxygenated near the valley margins and was more oxygen depleted at wells near the valley center. Field-measured dissolved oxygen values in ground water ranged from 0.1 mg/L at well 3-38 in August and September 2002 to 6.5 mg/L at well 2-15 in August 2002. In each case, water from the shallow well at paired sites contained more dissolved oxygen than water from the deeper well. Field-measured concentrations of dissolved oxygen were higher than laboratory-determined concentrations (tables 6 and 9) by differences that ranged from 0.036 mg/L higher in water from well 3-38 to 3.6 mg/L higher in water from well 2-26. Those data indicate that some dissolved oxygen in the laboratory-analyzed samples was consumed between sampling and analysis.

Specific conductance (SC) values in ground water measured during 2002 and 2003 were highest in samples from well 1-23 (1,640 µS/cm in February 2003 and 1,500 µS/cm in August 2002), well 1-16 (1,540 µS/cm in August 2002), and well 2-26 (1,200 µS/cm in August 2002) along the valley margin (table 9). SC measures the fluid electrical conductivity; SC values relate to the types and quantities of dissolved substances in water, but there is no universal linear relation between dissolved-solids concentrations and SC (Radtke and others, 1998). The lowest SC values were measured in samples from the valley center at wells 3-38 and 3-13; SC values at these wells ranged from 719 to 823 µS/cm. SC values decreased between the 2002 and 2003 sampling of wells 1-16, 2-15, 2-26, and 4-14 and increased during the same period at wells 1-23 and 3-13 (table 9).

The analyses of the field parameters specific conductance, temperature, dissolved oxygen, and turbidity were comparable from the August and September 2002 samplings of well 3-38. Values of pH were higher in the September sampling (6.9) than in the August sampling (6.6). A set of water samples collected from well 3-38 in August 2002 was mishandled during shipping; the samples arrived at the laboratory at an unacceptably high temperature that could compromise the accuracy of the analyses. Well 3-38 was resampled in September 2002 as soon as possible after notification of the unacceptable delivery so that samples from all the wells would be comparable. The field-parameter data indicate the results from the September sampling of well 3-38 were similar to conditions during the August sampling of the other six wells.

Dissolved-solids concentrations were higher (table 10) in water from the same wells that had higher SC values (table 9). Dissolved-solids concentrations in water from wells 1-16 (893 mg/L), 1-23 (723 mg/L), 2-15 (570 mg/L), and 2-26 (682 mg/L) exceeded the State of Indiana standard for dissolved solids in drinking-water-class ground water (500 mg/L) (table 19). By comparison, dissolved-solids concentrations in water from wells 3-13, 3-38, and 4-14 ranged from 411 to 433 mg/L. Calculated dissolved-solids concentrations in 41 ground-water samples from other parts of the Whitewater Valley aquifer system ranged from 438 to 816 mg/L (table 18).

Concentrations of dissolved solids in water from wells 2-15, 2-26, 3-13, 3-38, and 4-14 principally consist of calcium and bicarbonate (fig. 15). Equivalent concentrations of bicarbonate alkalinity in water from the five wells were more than 50 percent of the equivalent concentrations of all major anions (chloride, fluoride, nitrate, and sulfate) in the samples. The equivalent concentrations of calcium in water from six wells (1-16, 2-15, 2-26, 3-13, 3-38, and 4-14) were more than 50 percent of the sum of the equivalent concentrations of all major cations (calcium, magnesium, potassium, and sodium) in the samples (fig. 15). The computation of equivalent concentrations of cations and anions is explained in figure 15. The proportions of calcium and bicarbonate alkalinity in all seven water samples (fig. 15) may relate to the abundance of carbonate minerals (calcite and dolomite) within the upper aquifer. The water sample from well 1-23 had no predominant cation or anion, and the water sample from well 1-16 had no predominant anion.

The chloride concentration in the August 2002 water sample from well 1-16 (256 mg/L) (table 10) was higher than the State of Indiana standard for indicator levels of chloride in drinking-water-class ground water (250 mg/L, table 19). The chloride concentration in the August 2002 water sample from well 1-23 (247 mg/L) was slightly lower than that standard. Chloride concentrations in all other wells ranged from 13.3 to 117 mg/L and were considerably lower than the State of Indiana chloride standard. Chloride concentrations in water from wells 1-16, 1-23, 2-15 (75.4 mg/L), 2-26 (117 mg/L) and 4-14 (67.9 mg/L) were higher, however, than the 75th percentile of chloride concentrations from other parts of the Whitewater Valley aquifer system (24 mg/L) (table 18). Stated another way, 25 percent of chloride concentrations in water from previous sampling of the Whitewater Valley aquifer system were higher than 24 mg/L, and five of the seven water samples collected for this study from the upper aquifer also had chloride concentrations higher than 24 mg/L. Chloride concentrations in 43 ground-water samples from other parts of the Whitewater Valley aquifer system ranged from 4 to 105 mg/L (table 18).

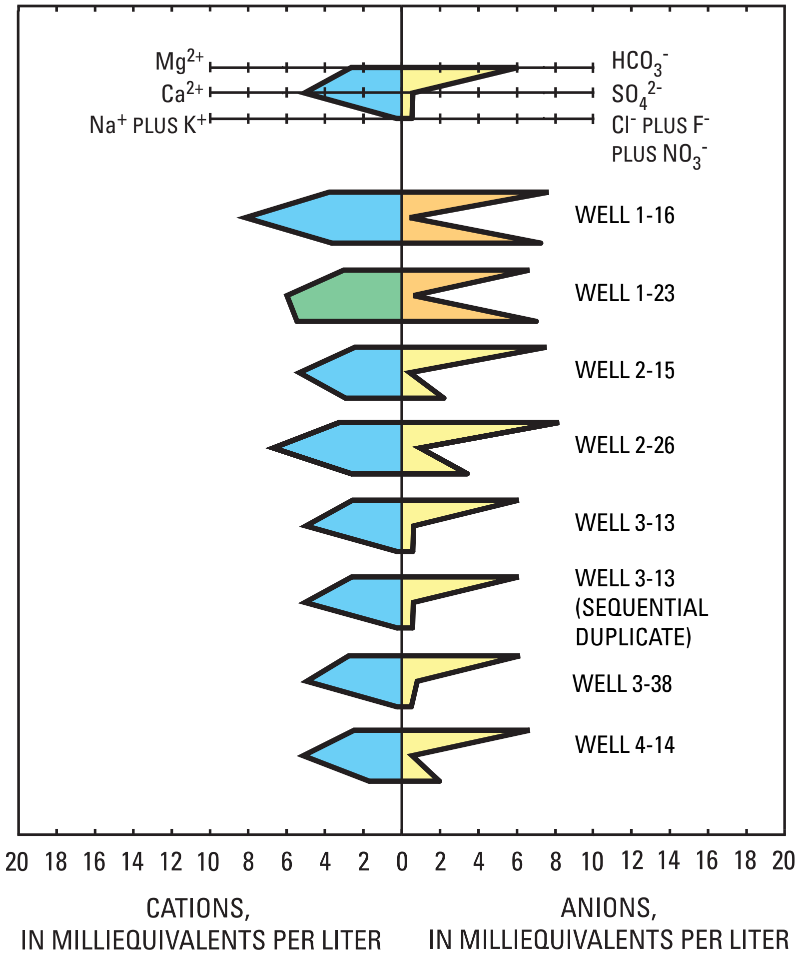
Sodium concentrations (table 10) in water from five of the seven wells were greater than the U.S. Environmental Protection Agency (USEPA) drinking-water equivalency level (DWEL) for sodium in drinking water (20 mg/L) (U.S. Environmental Protection Agency, 2002a). Sodium concentrations in ground water ranged from 4.35 mg/L at well 3-13 to 124 mg/L at well 1-23 (table 18). Sodium concentrations in water from wells 1-16 (81.8 mg/L), 1-23, 2-15 (65.3 mg/L), 2-26 (57.2 mg/L) and 4-14 (37.0 mg/L) ranged from slightly less than the maximum concentration of sodium in water from other parts of the Whitewater Valley aquifer system (39 mg/L, table 18) to about 2.1 times that value. By comparison, sodium concentrations in water from wells 3-13 (4.35 mg/L) and 3-38 (4.83 mg/L) were more similar to the minimum concentration of sodium in other parts of the Whitewater Valley aquifer system (3 mg/L) (table 18). The DWEL for sodium was established for health reasons. The USEPA reference for the DWEL stated that, given current knowledge, this level is probably low and may be revised upward (U.S. Environmental Protection Agency, 2002a). For those persons whose total sodium intake is restricted to 500 mg/d, adverse health effects may occur if they regularly consume water with sodium concentrations greater than 20 mg/L (National Research Council, 1977, p. 402).

Sulfate concentrations in water samples collected in 2002 from all wells ranged from 19.8 to 45.9 and were all less than the State of Indiana standard for indicator levels of sulfate in drinking-water-class ground water (250 mg/L, table 19). By comparison, sulfate concentrations in 43 ground-water samples from other parts of the Whitewater Valley aquifer system ranged from 8 to 95 mg/L (table 18).

Fluoride concentrations in water samples collected in 2002 from all wells ranged from < 0.1 mg/L in water from well 1-16 to 0.17 mg/L in water from well 2-15 (table 10). Fluoride concentrations in the water samples collected for this study were lower than 75 percent of the samples from other parts of the Whitewater Valley aquifer system (0.2 mg/L) (table 18). Bromide concentrations in water samples ranged from an estimated concentration of 0.0167 mg/L in water from well 3-13 to 0.0594 mg/L in water from well 1-23 (table 10). Silica concentrations in water samples collected in 2002 from all wells ranged from 9.73 mg/L in water from well 1-16 to 13.3 mg/L in water from well 2-15 (table 10). This range was within that reported for silica concentrations in 13 ground-water samples from glacial aquifers in Ohio and Indiana (11 to 22 mg/L) (Eberts and George, 2000, p. C61).

Nutrients

Nitrate, reported as the difference between nitrite plus nitrate and nitrite concentrations, was the principal nutrient constituent detected in water from the upper aquifer (table 10). Nutrients, as discussed in this report, include nitrogen-containing constituents (ammonium, nitrate, nitrite, nitrite plus nitrate, and organic nitrogen) and orthophosphate. These constituents are considered to be nutrients for plant growth and nutrition. Concentrations of nitrite plus nitrate in water samples ranged from 1.18 mg/L as N from well 1-16 to 11.0 mg/L



EXPLANATION

STIFF DIAGRAM—Cation and anion concentrations are plotted as points and connected by lines into a closed pattern. The pattern indicates predominant cations and anions in a water-quality analysis. The width of the pattern approximately indicates the dissolved-solids content of the water. Cations include calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), and potassium (K^+). Anions include bicarbonate (HCO_3^-), sulfate (SO_4^{2-}), chloride (Cl^-), fluoride (F^-), and nitrate (NO_3^-).

A milliequivalent is defined as a weight of a chemical substance divided by the formula weight of its composition elements and the assumed charge of the species. For example, calcium and magnesium have assumed charges of 2, and sodium and potassium have assumed charges of 1.

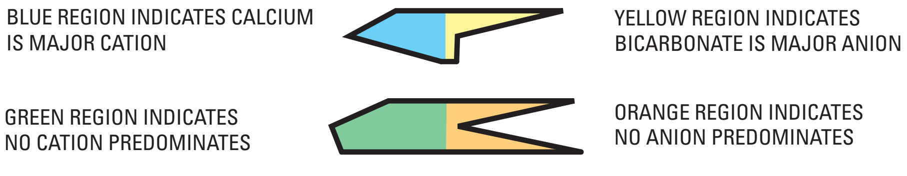


Figure 15. Stiff diagrams showing the relation of concentrations of major cations and anions in water-quality samples from the upper aquifer near Richmond, Indiana, and in a sequential duplicate, 2002 data (well locations shown on fig. 6).

as N from well 3-13. Nearly all of the nitrite plus nitrate in water samples was present as nitrate (table 10). Nitrite was not detected in water samples from five wells but was detected in water samples from wells 3-38 (0.035 mg/L as N) and 3-13 (estimated concentration of 0.005 mg/L as N). By comparison, nitrate concentrations in 36 ground-water samples from other parts of the Whitewater Valley aquifer system ranged from less than the reporting limit (0.02 mg/L as N or 0.1 mg/L as N) to 22 mg/L as N (table 18). Nitrate concentrations in water from three wells—2-26 (6.64 mg/L as N), 3-13 (11.0 mg/L as N), and 3-38 (5.08 mg/L as N)—were higher than the 75th percentile of nitrate concentrations in samples from other parts of the Whitewater Valley aquifer system (4.2 mg/L as N, table 18). These three wells are in or downgradient from land used for cultivated agriculture (fig. 4). Nitrate concentrations were lowest at the valley edges near an industrial area (wells 1-16 and 1-23) and near cultivated agricultural and residential areas (well 4-14).

Detectable concentrations of ammonia plus organic nitrogen in water samples ranged from 0.05 mg/L as N (estimated concentration) from well 1-23 to 0.12 mg/L as N from well 3-13. No ammonia was detected; all the nitrogen in the analyses of ammonia plus organic nitrogen was present as organic nitrogen. Of the seven wells sampled, orthophosphate was detected in one water sample from well 2-15 (estimated concentration of 0.01 mg/L as phosphorus).

The nitrate concentration in a water sample from well 3-13 (11.0 mg/L as N, August 2002) was greater than the State of Indiana standard for concentrations of nitrate in drinking-water-class ground water (10 mg/L as N, table 19). Water from adjacent well 3-38 at the base of the aquifer contained less nitrate (5.08 mg/L as N, August 2002). Nitrate concentrations in drinking water that exceed 10 mg/L as N may cause methemoglobinemia in small children and have been associated with six miscarriages in a part of northeastern Indiana (U.S. Water News, 1996).

Trace Elements

Of the 23 trace elements analyzed, 21 were detected in one or more of the water samples (table 11). The 18 trace elements detected in one or more water samples with no sampling-related interference were

aluminum
arsenic
barium
boron
cadmium
chromium
cobalt
copper
iron
lithium
manganese
molybdenum
nickel
selenium
strontium
uranium
vanadium
zinc

Concentrations of aluminum, cobalt, iron, lithium, molybdenum, nickel, selenium, uranium, vanadium, and zinc were less than or equal to 8 μg/L; concentrations of arsenic, cadmium, chromium, and copper were less than or equal to 1 μg/L. Beryllium and silver were not detected in any water samples.

Strontium, barium, and boron were detected in the highest concentrations of the trace elements in water samples (table 11). Concentrations of strontium in water samples ranged from 114 μg/L from well 1-23 to 366 μg/L from well 3-38. Concentrations of barium in water samples ranged from 77 μg/L from wells 1-16, 3-13, and 4-14 to 135 μg/L from well 2-26. Strontium and, to a lesser extent, barium concentrations in ground water may originate from the dissolution of carbonate minerals; strontium and barium are common trace substitutes for calcium in carbonate minerals such as calcite and dolomite (Hem, 1989, p. 135–6). Boron concentrations in water samples ranged from 28 μg/L from well 3-38 to 67 μg/L from well 2-15 (table 11); traces of boron are present in most natural waters (Hem, 1989, p. 129).

The highest manganese concentrations in water samples (82.1 μg/L from well 2-26 and 93.5 μg/L from well 3-38) exceeded the 50 μg/L USEPA National Secondary Drinking Water Regulation (NSDWR) for manganese. The NSDWR is a nonenforceable guideline that regulates manganese concentrations because of possible aesthetic effects on the taste, odor, or color of drinking water (U.S. Environmental Protection Agency, 1992). Manganese concentrations were less than 10 μg/L in water samples from the other five sampled wells. Iron concentrations, by comparison, were less than 10 μg/L in all water samples. Concentrations of all other trace elements detected in ground water from the upper aquifer were less than the corresponding drinking-water standard (tables 11 and 19). State of Indiana standards for drinking-water-class ground water are established for the trace elements antimony, arsenic, barium, beryllium, cadmium, chromium (total), lead, selenium, and thallium.

This study was not able to characterize the extent to which trace-element concentrations were from natural sources or were human influenced. Resampling over time would be needed to establish time-related trends or to determine whether these concentrations represent background conditions. The detections of very small concentrations of most trace elements analyzed by this study could be used with additional data as a baseline to compare whether changes in land-use practices correlate with changes in their concentrations in water from the upper aquifer.

Pesticides and Organic Compounds

Concentrations of all pesticides detected in samples collected for this study were less than 0.1 μg/L. Detections of atrazine and some of its transformation products (deethylatrazine [DEA], deisopropyldeethylatrazine, deisopropylatrazine, and 2-hydroxyatrazine) were reported in water from the upper aquifer from wells near the water table (wells 1-16, 2-15, 3-13, and 4-14) and in one deep well near the glacial-valley margin (well 1-23) (table 12). Atrazine concentrations detected in water samples ranged from an estimated concentration of 0.003 μg/L from well 1-23 to 0.036 μg/L from well 4-14. Concentrations of atrazine detected in water samples were at least

83 times below the corresponding State of Indiana standard for drinking-water-class ground water (3 µg/L) (table 19). Concentrations of DEA detected in water samples ranged from an estimated concentration of 0.005 µg/L from well 1-23 to an estimated concentration of 0.096 µg/L from well 4-14. The highest concentrations of all atrazine transformation products were in the water sample from well 4-14. Wells 3-13 and 4-14 are in or adjacent to cultivated agricultural land; wells 1-16 and 2-15 are downgradient from cultivated agricultural land.

Other pesticides detected in water samples included flumetsulam (well 3-13, estimated concentration of 0.02 µg/L), prometon (well 1-16, 0.04 µg/L; well 1-23, estimated concentration of 0.01 µg/L; and well 4-14, detected but not quantified), simazine (well 4-14, estimated concentration of 0.003 µg/L), and tebuthiron (well 3-13, estimated concentration of 0.01 µg/L) (table 12). All other pesticides analyzed were not detected in water samples collected for this study (table 12). The concentration of simazine detected in the water sample from well 4-14 was about 1,333 times less than its corresponding State of Indiana standard for drinking-water-class ground water (4 µg/L) (table 19). The other detected pesticides do not have State of Indiana standards for drinking-water-class ground water (Indiana Administrative Code, 2006).

Concentrations of all volatile organic compounds detected in samples collected for this study were less than 0.1 µg/L. Volatile organic compounds (table 13) detected in ground-water samples were carbon disulfide (well 2-26, estimated concentration of 0.02 µg/L), chloroform (well 4-14, estimated concentration of 0.04 µg/L; well 1-16, estimated concentration of 0.01 µg/L), and toluene (well 1-23, estimated concentration of 0.05 µg/L). Carbon disulfide is produced naturally in soils and marshes by plants and the weathering of sulfide minerals. It also may result from human-influenced processes such as natural-gas production and the manufacture of viscose fiber (rayon) and cellophane film (Newhook and others, 2002). Water from well 2-26 also contained a trace concentration of methane (0.004 µg/L) (table 6), indicating the possibility that the trace of carbon disulfide in this water sample was of natural origin. Chloroform concentrations reported in water samples were of similar magnitude to those reported in the equipment blank, indicating that the concentrations may not be present in ground water. Chloroform in ground water also may relate to recharge of chlorinated public-supply water from lawn sprinklers, leaking water or sewer lines, septic systems, and (in concentrations less than about 0.1 µg/L) from infiltrating precipitation (Fenelon and Moore, 1996). A toluene concentration of 0.17 µg/L was reported for the sequential duplicate collected from well 1-23 (table 13). That reported concentration did not have an obvious source; however, the well is within an industrial area and within the area of the former East Richmond Airport (fig. 4).

One semivolatile organic compound, Bis(2-ethylhexyl) phthalate, was detected in a water sample from well 2-26 at an estimated concentration of 4 µg/L (table 14). The compound is a plasticizer (Kolpin and others, 2002), indicating that well-construction materials or sample contact with plastic materials are possible sources. No other semivolatile organic compounds were detected during this study.

Wastewater-related organic compounds (table 15) detected in water samples were isophorone (well 3-38, estimated concentration of 0.2 µg/L), phenol (well 3-38, 0.5 µg/L), and tetrachloroethene (well 3-38, estimated concentration of 0.1 µg/L). Isophorone is a solvent used in paints, inks, coatings, and adhesives for plastics and in some pesticide formulations; it occurs naturally in cranberries (Agency for Toxic Substances and Disease Registry, 1989, p. 61). The isophorone detection may relate to local pesticide use. The trace detection of tetrachloroethene by the analytical method used for wastewater-related organic compounds was not reproduced by the analytical method used for VOCs at the lower reporting limit of 0.03 µg/L. The tetrachloroethene detection therefore is considered to be tentative; additional sampling would be necessary to verify its presence in ground water.

Vulnerability of Ground Water to Contamination

Results of hydrogeologic interpretations, ground-water-age dating, and water-quality analyses indicate that although ground water in the upper aquifer is vulnerable to contamination, its vulnerability to specific types of contaminants is variable. By conventional measures related to hydrogeology and the detection of contaminants and indicators of human activity in ground water, the upper aquifer is vulnerable to contamination. Ground-water-age dates indicate that residence times of ground water in the aquifer are less than or equal to about 30 years. The short residence times indicate the potential for rapid contamination and, conversely, rapid restoration of impaired water quality when contaminant sources are eliminated. Several geochemical measures indicate that microbial activity and oxidation-reduction processes that transform potential contaminants such as nitrate, atrazine, and some halogenated organic compounds may limit the vulnerability of ground water to similar types of contamination.

Hydrogeologic and cultural information compiled for this study indicate that the upper aquifer is vulnerable to contamination. The upper aquifer is unconfined and has a shallow depth to the water table (from about 4.75 to 14 ft below land surface). Low permeability sediments in the unsaturated zone above the upper aquifer in the flatter parts of the glacial valley are less than 10 ft thick (figs. 9–11). Estimated ground-water-flow rates through the upper aquifer are relatively rapid (the highest estimated rates ranged from 0.44 ft/d to about 5.0 ft/d). Industrial, commercial, transportation, residential, and agricultural land uses over the upper aquifer and surface-water runoff from adjacent areas in the watershed with similar land uses are potential sources of contaminants to the aquifer. Similar characteristics also are present in other parts of the Whitewater

Valley aquifer system (Beaty and Clendenon, 1988) and in other sand and gravel aquifers in Indiana (Fenelon and Moore, 1996; Kay and others, 2002).

Concentrations of chloride, sodium, and bromide detected in sampled ground water indicate the vulnerability of the upper aquifer to contamination by road deicing. For example, water from wells 1-16, 1-23, 2-15, 2-26, and 4-14 had higher concentrations of sodium and chloride relative to water from wells 3-13 and 3-38 (fig. 15). Ratios of chloride to bromide in water samples from these same wells were similar to water chemistries cited in the literature as affected by road-deicer salt (table 20). Ratios of chloride to bromide concentrations (by weight) were computed, using the following equation

$$\text{Chloride/bromide weight ratio} = [\text{chloride, in mg/L}]/[\text{bromide, in mg/L}] \qquad (3)$$

Chloride/bromide weight ratios for water from wells 1-16 (4,452) and 1-23 (4,158) were in the range of those of deicer-affected water (Risch and Robinson, 2001, p. 18); chloride/bromide weight ratios for water from wells 2-15 (3,028), 2-26 (3,188), and 4-14 (2,771) were within the ranges of a hypothetical mixture of deicer-affected water and unaffected ground water at a research site in northwestern Indiana (Watson and others, 2002, fig. 12, p. 32).

Ground-water-age estimates ranged from 13.5 to 25 years for water from wells affected by road-deicer contamination (1-16, 1-23, 2-15, 2-26, and 4-14) (table 7), indicating road-deicer use near or upgradient from those wells within that time. Road-deicer application was observed on streets adjacent to wells 1-16 and 1-23 during the February 2003 sampling. It is also likely that road salt was applied along Industrial Parkway and along Garwood Road or Hodgin Road, based on the ground-water-age estimates and the similarity of the chloride/bromide ratios to deicer-affected water. Areas along US 40 and I-70 also received seasonal road-deicer application and may have contributed runoff and recharge to the upper aquifer. The potential for deicer-affected runoff from areas along US 40 and I-70 to recharge the upper aquifer, however, depends on the location of the ground-water-flow divide (figs. 12 and 13).

Geochemical and hydrodynamic processes that limit the vulnerability of ground water to sodium and chloride from road deicing generally involve cation exchange (sodium only) and hydrodynamic dispersion (Watson and others, 2002). In a study of contaminant effects on a sand aquifer near a deicer-treated roadway, hydrodynamic dispersion (mixing with uncontaminated water) was the main process that caused concentrations of chloride and sodium to decrease with distance from the roadway (Watson and others, 2002). Cation exchange was deemed less important in affecting transport of sodium because cation-exchange capacities reported for glacial-aquifer sands were relatively small (0.2 to 0.7 milliequivalents per liter) (Watson and others, 2002, p. 52).

Concentrations of nitrite plus nitrate in five of seven water samples from the upper aquifer were in the range that indicated water that potentially was affected by human influences. Nitrate concentrations in water from wells 3-38 (5.08 mg/L as N), 2-15 (3.67 mg/L as N), and 2-26 (6.64 mg/L as N) were greater than the median nitrate-concentration range from hydrogeologically vulnerable aquifers (mainly coarse-textured or fractured deposits) beneath undeveloped rangeland (1.4 to 2.7 mg/L as N) (Nolan and Hitt, 2003, table 3, p. 9) (table 21). The concentrations of nitrate reported in this study were largest in water samples from wells near or downgradient from cultivated agricultural land (wells 2-15, 2-26, 3-13, and 3-38); ground-water ages in samples from those wells ranged from 13 to 30 years. Cultivated agricultural land in the study area predates the oldest estimated ground-water age of 30 years. Nitrate contamination in the upper aquifer therefore may have occurred for an unknown time before 1972.

Denitrification-related transformations of nitrate to nitrite and nitrogen gas may decrease the vulnerability of the upper aquifer to contamination by nitrate. Denitrification was indicated in water samples from wells 3-13 and 3-38 by the higher concentrations of nitrogen gas and lower concentrations of oxygen relative to other dissolved-gas samples collected for this study (table 6) and by the concentrations of nitrite in water samples from those wells (table 10). Relatively high concentrations of nitrogen gas in association with oxygen-depleted conditions in ground water have been identified as evidence of denitrification processes (Vogel and others, 1981). The concentrations of nitrogen gas in water samples from wells 3-13 and 3-38 were 19.7 mg/L and 23.7 mg/L, the third-largest and largest concentrations detected for this study (table 6). Nitrite, a common intermediate product of denitrification (Vogel and others, 1981), also was detected in water samples from well 3-13 (estimated concentration of 0.05 mg/L as N) and well 3-38 (0.035 mg/L as N). Concentrations of dissolved oxygen in water samples from these wells were less than 0.1 mg/L (table 6), sufficiently low to indicate oxygen-depleted conditions and the possibility of denitrification. Denitrification can take place only under anaerobic conditions, a key aspect of the nitrogen cycle (Chapelle, 1993, p. 247). The capacity of denitrification to decrease nitrate concentrations may be reduced by factors that limit microbial activity in ground water, such as a lack of nutrients for bacterial growth, a lack of a reactive organic-carbon substrate in the aquifer sediments, competition with other organisms for these components, and the rates of denitrification reactions relative to ground-water residence times (Chapelle, 1993; Puckett and Hughes, 2005); these conditions were not evaluated for this study.

By comparison, water samples from other wells, with the exception of well 2-26, had lower nitrite plus nitrate concentrations, no detectable nitrite (table 10), lower concentrations of nitrogen gas (ranging from 16.6 mg/L to 18.6 mg/L), and more than 1 mg/L of dissolved oxygen (table 6). The water sample from well 2-26 had the second highest nitrogen-gas (20.5 mg/L, table 6) and nitrate concentrations (6.64 mg/L as N, table 10) but had detectable dissolved oxygen (1.9 mg/L, table 6) and no detectable nitrite (<0.008 mg/L, table 10). Concentrations of excess nitrogen in most other dissolved-gas samples (table 6), however, indicated minor amounts of

Table 20. Classification of chloride source in water samples from the upper aquifer near Richmond, Indiana, 2002, based on published chloride/bromide weight ratios.

Potential chloride source	Well name and ratio values of water samples with similar chloride/bromide weight ratios (milligrams/milligrams)	Ranges of chloride/bromide weight ratios for potential chloride sources (milligrams/milligrams)
Atmospheric deposition	None	[1]50- 150
Urban runoff, summer	None	[1]10- 100
Uncontaminated ground water	None	[1]100- 200 [2]173- 293
Domestic sewage	None	[1]300- 600 [2]150- 540
Halite road-deicer salts	None	[3]8,320- 8,440
Deicer-affected ground water near Valparaiso, Indiana	Wells 1-23 (4,158) and 1-16 (4,452)	[4]3,570-11,200
Mixture of deicer-affected water and background ground water from near Porter, Indiana	Wells 4-14 (2,771), 2-15 (3,028), and 2-26 (3,188)	[5]1,100- 7,727
No referenced sources in range	Wells 3-38 (700), 3-13 (796)	--

[1] Davis and others (1998).

[2] Vengosh and Pankratov (1998).

[3] Howard and Beck (1986).

[4] Risch and Robinson (2001, table 2, p. 18).

[5] Watson and others (2002, fig. 12, p. 32 and table 11, p. 70–122). The lowest chloride/bromide ratio in this range is from the December 21, 1994, sample of unaffected ground water from well 1-UG-3. The highest chloride/bromide ratio in this range is from the March 28, 1995, sample of deicer-affected ground water from well 1-DG-WT.

Table 21. Classification of human-influenced nitrate concentrations in water samples from the upper aquifer near Richmond, Indiana, 2002.

[mg/L, milligram per liter; N, nitrogen; USEPA, U.S. Environmental Protection Agency]

Range of nitrate or nitrite plus nitrate concentrations	Well name with nitrate concentrations in water samples in concentration ranges	Nitrate-source classification[1]
Less than 2.7 mg/L as N	None	Assumed to represent natural background conditions.
Greater than 2.7 mg/L as N	Wells 2-15, 2-26, 3-13, 3-38, and 4-14	Concentrations exceed range found beneath undeveloped range land in aquifers vulnerable to contamination. May indicate potential human influence on ground-water quality.
Greater than 10 mg/L as N	Well 3-13	Concentration exceeds public-health drinking-water standard (USEPA maximum contaminant level for nitrate).

[1] Nolan and Hitt (2003).

denitrification had occurred. This apparent contradiction may be explained by the coexistence of anaerobic and aerobic oxidation-reduction conditions in parts of the upper aquifer. Traces of methane were detected in three of five water samples that had dissolved-oxygen concentrations greater than 1 mg/L (wells 1-23, 2-15, and 2-26) (table 6). The detection of methane in ground water may indicate reduced zones within the aquifer where organic carbon in aquifer sediments is oxidized by methanogenic bacteria (Chapelle, 1993, p. 238–9). The coexistence of methane and dissolved oxygen in these wells indicates that water from reduced and oxidized zones of the aquifer were produced during sampling. Denitrification also would be possible within those reduced, methanogenic zones.

Microbial processes also may limit the vulnerability of ground water to small inputs of halogenated aliphatic compounds, as indicated by the apparent microbial transformation of CFC-11 and CFC-113 relative to CFC-12. Ground-water ages computed with CFC-11 and CFC-113 at wells 2-26, 3-13, 3-38, and 4-14 generally were consistent with each other but were older than the corresponding CFC-12-based ground-water ages (table 7). The older ground-water ages computed with CFC-11 and CFC-113 likely indicate some degree of microbial transformation of those compounds relative to CFC-12. The existence of local methanogenic conditions in the upper aquifer indicates conditions favorable for reductive dehalogenation of CFC-11 and CFC-113 relative to CFC-12 (Plummer and Busenberg, 1999) and some other chlorinated aliphatic and monocyclic aromatic compounds (Chapelle, 1993, p. 369).

Although the upper aquifer is vulnerable to contamination by atrazine, as indicated by the detection of that compound at wells 1-16, 1-23, 2-15, 3-13, and 4-14, the atrazine also partially had been transformed to other compounds (table 22). The large molar ratio of the atrazine transformation product deethylatrazine to its parent compound atrazine indicates that biotransforming processes in the soil or aquifer can decrease concentrations of some potential contaminants. The molar ratio of DEA to atrazine (DAR) is defined as:

$$\text{DAR} = [\text{deethylatrazine, in micromoles/L}] / [\text{atrazine, in micromoles/L}] \qquad (4)$$

The DAR has been used as a measure of soil interactions affecting atrazine as it infiltrates through the vadose zone and migrates through the aquifer (Adams and Thurman, 1991). Adams and Thurman (1991) suggest that the presence of increased DEA concentrations in ground water relates to a large number of microbes, high organic carbon content, and warm soil temperatures during infiltration. DAR values for water samples from the upper aquifer range from 1.3 to 3.1 (table 22). These values indicate that transformation of atrazine had occurred by the time water had reached the sampled depths within the upper aquifer. Atrazine and its transformation products were detected in water samples from the upper aquifer (table 22) from wells with the youngest ground-water ages, less than about 24 years since recharge (1979) (table 7). Morrow (2003) identified a correlation between detections of atrazine and its transformation products in water samples and ground-water ages that were younger than about 28 years (1975) in a shallow glacial-aquifer system in an urbanizing area west and north of Chicago, Illinois.

Table 22. Detection summary of atrazine and atrazine transformation products in water samples from the upper aquifer near Richmond, Indiana, 2002.

[µg/L, microgram per liter; DEA, deethylatrazine; DAR, DEA/atrazine molar ratio; E, estimated concentration; < , less than; -- , not computed]

Well where compound was detected	Atrazine (µg/L)	DEA (µg/L)	DAR[1]	Deisopropyl-deethyl-atrazine (µg/L)	Deisopropyl-atrazine (µg/L)	2-Hydroxy-atrazine (µg/L)	DEA/ 2-Hydroxy-atrazine molar ratio
Well 1-16	0.011	E0.017	1.8	E0.003	<0.04	E0.016	1.1
Well 1-23	E.003	E.005	1.9	<.01	<.04	E.004	1.3
Well 2-15	E.006	E.007	1.3	<.01	<.04	E.010	.7
Well 3-13	E.006	E.015	2.9	<.01	<.04	<.008	--
Well 4-14	.036	E.096	3.1	E.01	E.01	E.020	5.0

[1] The molar concentration of a substance is computed by dividing its concentration, in micrograms per liter, by its molecular weight in grams. The molecular weights of the substances in this table are as follows: atrazine, 215.68 grams; deethylatrazine, 187.63 grams; deisopropyldeethylatrazine, 145.55 grams; deisopropylatrazine, 173.60 grams; 2-hydroxyatrazine, 197.24 grams (National Center for Biotechnology Information, 2006).

In three of the five wells, 2-hydroxyatrazine was detected in concentrations similar to DEA. The molar ratio of DEA to 2-hydroxyatrazine in water samples ranged from 0.7 in the sample from well 2-15 to 5.0 in the sample from well 4-14 (table 22). Formed through abiotic hydrolysis of atrazine (Adams and Thurman, 1991), 2-hydroxyatrazine is sorbed more strongly than DEA by soils (Panshin and others, 2000). The results indicate that local soils and the aquifer sediments may be less capable of sorbing 2-hydroxyatrazine and decreasing its concentration, relative to DEA, near wells 1-16, 1-23, and 2-15 and more capable of sorbing 2-hydroxyatrazine nearest to well 4-14. These results also indicate the general lack of sufficient organic matter in local soils and upper aquifer sediments that would sorb and retard 2-hydroxyatrazine relative to the more weakly sorbed DEA.

Transformation of an organic compound does not necessarily reduce its risk to consumers of drinking water because its transformation products may have their own toxicity. For example, the USEPA includes several transformation products of atrazine in its risk-based computation of an allowable concentration of atrazine and its byproducts in drinking water; each product has a potential health risk associated with consumption in food and water (U.S. Environmental Protection Agency, 2002b). The toxicity of transformation products therefore must be considered when evaluating whether natural processes reduce the vulnerability to contamination by specific compounds.

If contamination were to become established in the upper aquifer, it may require decades to be removed by natural ground-water-flow processes, as indicated by the ground-water-age dates reported for this study. This interpretation is made by assuming advective flow of ground water; it does not account for processes that would limit contamination, such as biotransformation or sorption, or a process that would extend the duration of low-level contamination, such as desorption or presence of a continual source of contaminants. For example, Watson and others (2002) identified a carryover into subsequent years of deicer-related chloride contamination of ground water. The carryover was caused by incomplete annual flushing of deicing salt from the thin unsaturated zone (less than 5 ft thick) of a sand aquifer (about 30 ft thick). That sand aquifer in the study by Watson and others (2002) was similar in hydrogeologic characteristics to the upper aquifer of this study.

The lower aquifer, although not sampled for this study, appears to be more hydraulically isolated than the upper aquifer from sources of contamination at the land surface and likely may be less vulnerable to contamination. More information would be needed to establish the extent and directions of ground-water flow within the lower aquifer, vertical gradients across the confining unit that separates the lower aquifer from the upper aquifer, and ground-water-age dates and the quality of water within the lower aquifer as indicators of its vulnerability.

Summary and Conclusions

The Federal Safe Drinking Water Act Amendments of 1996 mandated the assessment of water sources used by public-water systems and their vulnerability to contamination. The USGS has identified ground-water-age dating; detailed water-quality analyses of nitrate, pesticides, trace elements, and wastewater-related organic compounds; and assessed natural processes that affect those constituents as potential, unique improvements to existing methods of vulnerability assessment. To evaluate these methods, in 2002 and 2003, the U.S. Geological Survey, in cooperation with the City of Richmond, Indiana, compiled hydrogeologic data and chemically analyzed water samples from seven wells to investigate the hydrogeologic setting and to describe ground-water flow; ground-water ages; baseline water quality; and hydrogeologic, hydrochemical, and biological processes that affect the vulnerability of ground water in a part of the Whitewater Valley aquifer system in a former glacial valley near Richmond, Indiana. The study was done to provide water-resource managers with methods and examples of the types of baseline data needed to implement effective assessments of the vulnerability of ground water to contamination in this and in other parts of the Whitewater Valley aquifer system and in other shallow aquifers in similar hydrogeologic settings throughout the glaciated midwestern United States.

Richmond obtains some of its drinking water from wells in an upper, unconfined part of the Whitewater Valley aquifer system (the upper aquifer) in a former glacial valley. Data from previously drilled wells and geologic and geophysical data from this study were used to define the extent of the upper aquifer and identify an underlying till confining unit and a lower confined sand and gravel aquifer. Seven observation wells were drilled to enable sampling of ground-water quality at the water table and near the base of the upper aquifer. Six temporary wells were installed in the streambeds of Short Creek and its tributaries to enable measurement of additional water levels at the water table in the upper aquifer and to measure surface-water stage. Water in the upper aquifer flows from the valley-margin ridges toward the flatter parts of the valley center. A ground-water-flow divide was inferred to be about 0.25 to 0.5 mi north of well 1-16, near the northern boundary of the aquifer protection area and possibly including areas near US 40. North of this divide, water in the upper aquifer flows north toward the East Fork Whitewater River. South of the divide, water in the upper aquifer flows south and southwest, where it discharges to Short Creek and its tributaries, production wells, and possibly through the confining unit to the lower aquifer.

Seven ground-water samples collected for this study during February and March 2003 from the upper aquifer were estimated to have recharged the aquifer within about 13 to 30 years, using CFC-113-based ground-water ages from wells 1-16 and 1-23 and CFC-12-based ground-water ages from all other wells. Ground-water ages were youngest in shallow wells along the valley margins (from about 13 to 15 years since recharge) and in a shallow well near the valley center (well 3-13, about 18.5 years since recharge). These results were not anticipated because the water samples were collected within a few feet below the water table where modern water ages might be expected. Ground-water-age dates from the shallow wells may be affected by mixing of recent recharge to the water table with older ground water from deeper in the aquifer, as was indicated by upward hydraulic gradients measured at the paired shallow and deep wells during most water-level measurements. Ground-water age was oldest at the base of the upper aquifer near the valley center (well 3-38, about 30 years since recharge). The range in ground-water ages includes the post-1972 period when industrial and commercial development replaced agricultural and airfield development in some parts of the study area that were south of the ground-water-flow divide.

State of Indiana water-quality standards were exceeded for chloride, dissolved solids, and nitrate at several wells. The chloride concentration in the August 2002 water sample from well 1-16 (256 mg/L) was greater than the State of Indiana standard for indicator levels of chloride in drinking-water-class ground water (250 mg/L). Dissolved-solids concentrations in water samples from wells 1-16 (893 mg/L), 1-23 (723 mg/L), 2-15 (570 mg/L), and 2-26 (682 mg/L) exceeded the State of Indiana standard for dissolved solids in drinking-water-class ground water (500 mg/L). The nitrate concentration in the August 2002 water sample from well 3-13 (11.0 mg/L as N) was greater than the State of Indiana standard for concentrations of nitrate in drinking-water-class ground water (10 mg/L as N).

Dissolved solids in water from five of seven wells sampled for this study were principally calcium and bicarbonate. The abundance of calcium and bicarbonate alkalinity may relate to the large abundance of carbonate minerals (calcite and dolomite) within the upper aquifer. Concentrations of chloride, sodium, and nitrate were generally larger in ground water from the upper aquifer than in other parts of the Whitewater Valley aquifer system. Chloride concentrations in water from five of seven wells sampled for this study—wells 1-16 (256 mg/L), 1-23 (247 mg/L), 2-15 (75.4 mg/L), 2-26 (117 mg/L), and 4-14 (67.9 mg/L)—were higher than the 75th-percentile concentration of data from other parts of the Whitewater Valley aquifer system (24 mg/L). Sodium concentrations in water from these same wells—1-16 (81.8 mg/L), 1-23, 2-15 (65.3 mg/L), 2-26 (57.2 mg/L), and 4-14 (37.0 mg/L)—ranged from slightly less than the maximum concentration of sodium in water from other parts of the Whitewater Valley aquifer system (39 mg/L) to about 2.1 times that value. The largest concentrations of nitrate in ground water from the upper aquifer were from three wells 2-26 (6.64 mg/L as N), 3-13 (11.0 mg/L as N), and 3-38 (5.08 mg/L as N) that were in or downgradient from cultivated agricultural land. Nitrate concentrations in water from those three wells were higher than the 75th percentile of nitrate concentrations in samples from other parts of the Whitewater Valley aquifer system (4.2 mg/L as N).

Eighteen trace elements were detected in one or more water samples with no potential sampling-related interference: aluminum, arsenic, barium, boron, cadmium, chromium, cobalt, copper, iron, lithium, manganese, molybdenum, nickel, selenium, strontium, uranium, vanadium, and zinc. The largest manganese concentrations in water samples from the upper aquifer (82.1 µg/L from well 2-26 and 93.5 µg/L from well 3-38) exceeded the USEPA National Secondary Drinking Water Regulation aesthetic standard for manganese (50 µg/L). Concentrations of aluminum, cobalt, iron, lithium, molybdenum, nickel, selenium, uranium, vanadium, and zinc were less than or equal to 8 µg/L; concentrations of arsenic, cadmium, chromium, and copper were less than or equal to 1 µg/L.

Atrazine and its transformation products, deethylatrazine, deisopropyldeethylatrazine, deisopropylatrazine, and 2-hydroxyatrazine, were detected in water samples in 2002 from all shallow wells and one deep well (1-23). Other pesticides detected in water samples included flumetsulam (well 3-13, estimated concentration of 0.02 µg/L), prometon (well 1-16, 0.04 µg/L; well 1-23, estimated concentration of 0.01 µg/L; and well 4-14, detected but not quantified), simazine (well 4-14, estimated concentration of 0.003 µg/L), and tebuthiron (well 3-13, estimated concentration of 0.01 µg/L). Few volatile, semivolatile, or wastewater-related organic compounds were detected in water samples collected for this study: carbon disulfide (well 2-26, estimated concentration of 0.02 µg/L), chloroform (well 4-14, estimated concentration of 0.04 µg/L; well 1-16, estimated concentration of 0.01 µg/L), and toluene (well 1-23, estimated concentration of 0.05 µg/L). Bis(2-ethylhexyl) phthalate was the only semivolatile organic compound detected by the sampling (well 2-26, estimated concentration of 4 µg/L). Wastewater-related organic compounds detected in water samples were isophorone (well 3-38, estimated concentration of 0.2 µg/L), phenol (well 3-38, 0.5 µg/L), and tetrachloroethene (well 3-38, estimated concentration of 0.1 µg/L). The detections of very small concentrations of most trace elements analyzed by this study could be used with additional detailed analyses of ground-water quality as a baseline to compare whether changes in land-use practices correlate with changes in the concentrations of these elements and compounds in water from the upper aquifer.

Several hydrogeologic and cultural measures indicate that the upper aquifer is vulnerable to contamination. The upper aquifer is unconfined and has a shallow depth to the water table (from about 4.75 to 14 ft below land surface). Low-permeability sediments in the unsaturated zone are thinnest (less than 10 ft thick) in the flatter parts of the former glacial valley. Estimated ground-water-flow rates through the upper aquifer are rapid (the highest estimated rates ranged from 0.44 ft/d to about 5.0 ft/d). Industrial, commercial, transportation, residential, and agricultural land uses over the upper aquifer and surface-water runoff from adjacent areas in the watershed with similar land uses are potential sources of contaminants to aquifer recharge. These hydrogeologic and cultural measures define, for the upper aquifer, the coexistence of potential sources of contamination and possible mechanisms for the rapid transport of contaminants in recharge through the unsaturated zone and through ground-water flow to production wells. Similar characteristics are present in other unconfined parts of the Whitewater Valley aquifer system and in other shallow sand and gravel aquifers in Indiana. The lower aquifer, although not sampled for this study, appears to be more hydraulically isolated than the upper aquifer from sources of contamination at the land surface and may be less vulnerable to contamination.

Concentrations of chloride and sodium and chloride/bromide ratios detected in sampled ground water from four shallow wells and one deep well indicated the vulnerability of the upper aquifer to road-deicer contamination. Ground-water-age estimates ranged from 13.5 to 25 years for water from wells affected by road-deicer contamination (wells 1-16, 1-23, 2-15, 2-26, and 4-14), indicating road-deicer use near or upgradient from those wells within that time. The amount of road deicer applied and the amount of hydrodynamic dispersion likely would be the main factors that affect the extent of deicer contamination in the upper aquifer.

Concentrations of nitrite plus nitrate in five of seven water samples from the upper aquifer were in the range that indicated water potentially affected by human influences. Concentrations of nitrate were largest in wells near or downgradient from cultivated agricultural areas; ground-water ages in water samples from those wells ranged from 13.5 to 30 years. Cultivation of land in the study area predates the oldest estimated ground-water age of 30 years; therefore, nitrate contamination in the upper aquifer also may predate the ages of most ground water in the upper aquifer. The vulnerability of ground water to nitrate contamination apparently is limited by denitrification of nitrate to nitrite and nitrogen gas. Denitrification is indicated in water from wells 3-13 and 3-38 by the association of higher concentrations of nitrogen gas, lower concentrations of oxygen, and the detection of nitrite in water samples from those wells. Concentrations of excess nitrogen in most dissolved-gas samples, however, indicated minor amounts of denitrification elsewhere in the aquifer where dissolved oxygen also was detected by sampling. This apparent contradiction may be explained by the apparent coexistence of anaerobic and aerobic oxidation-reduction conditions in parts of the upper aquifer, as indicated by traces of methane in three of five water samples with dissolved-oxygen concentrations greater than 1 mg/L (wells 1-23, 2-15, and 2-26).

Detection of from one to four atrazine transformation products in water samples from the upper aquifer indicate biological and hydrochemical processes that may limit the vulnerability of the ground water to atrazine contamination. Transformation of atrazine had occurred by the time water had reached the sampled depths, as indicated by the large molar ratio of the atrazine transformation product deethylatrazine (DEA) to its parent compound (range from 1.2 to 2.7) in five water samples. Atrazine and its transformation products were detected in water samples from wells with the youngest ground-water ages, about 24 years or less since recharge. A transformation product of atrazine hydrolysis, 2-hydroxyatrazine, was detected in concentrations similar to DEA in three water samples, indicating that local soils and upper-aquifer sediments may lack sufficient organic matter to sorb and retard 2-hydroxyatrazine relative to the more weakly sorbed DEA. Transformation of atrazine does not necessarily reduce its risk to consumers of drinking water because its transformation products may have their own toxicity.

The apparent degradation of CFC-11 and CFC-113 in several water samples also indicate the possibility that microbial processes may limit the vulnerability of ground water to small inputs of other halogenated aliphatic compounds. The older ground-water ages computed with CFC-11 and CFC-113 in water from wells 2-26, 3-13, 3-38, and 4-14, relative to the age computed using CFC-12, indicate microbial transformation of those compounds relative to CFC-12. The existence of locally methanogenic conditions within the aquifer also indicates the potential for reductive dehalogenation of CFC-11, CFC-113, and some other halogenated organic compounds.

The application of ground-water-age dating, dissolved-gas analyses, and detailed water-quality analyses enhanced the types of vulnerability assessment made by this study. For example, the ground-water-age data indicate there would be a quantitative lag time between changes in potential contaminant inputs from greenfield development, the detection of development-related contaminants in the upper aquifer, and the flushing of previous contaminants from the aquifer. Ground-water-age dates also provided information regarding appropriate sampling strategies for any future ground-water-quality monitoring. For example, monitoring for the effects of greenfield-development-related sources of potential contamination could be done most appropriately in wells that produce ground water whose age indicates recharge after that development. Evidence of denitrification and transformations of atrazine and chlorofluorocarbon compounds was provided by ground-water-age dating, dissolved-gas analyses, and detailed water-quality analyses. These interpretations would have been unlikely through conventional vulnerability-assessment methods.

These results also have implications for the vulnerability of shallow ground-water quality in other parts of the Whitewater Valley aquifer system. Those parts of the Whitewater Valley aquifer system where the aquifer is as thin as the upper aquifer in this study area could be expected to have similarly young ground-water ages and residence times. The vulnerability of ground water to contamination in other parts of the aquifer system may be mitigated somewhat by processes such as hydrodynamic dispersion and biologically mediated transformations of nitrate, pesticides, and some organic compounds. The distribution of coarse-grained glacial deposits in the midwestern United States and the common presence of particulate organic matter and methanogenic conditions in those deposits indicate that vulnerability-assessment methods used in this study could be applied to other hydrogeologically similar shallow aquifers.

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Tables 3 through 5

Table 8

Tables 12 through 15

Table 3. Laboratory analytical constituents and reporting limits for water samples collected during August and September 2002 from observation wells in the upper aquifer near Richmond, Indiana.

[USGS, U.S. Geological Survey; mg/L, milligram per liter; lrl, laboratory reporting limit; mrl, method reporting limit; N, nitrogen; P, phosphorus; µg/L, microgram per liter]

Constituent name	USGS parameter code	Chemical Abstracts Service identification number	Reporting-limit magnitude	Reporting-limit unit	Reporting-limit type
Major cations and anions and a property—Filtered samples					
Calcium	00915	7440-70-2	0.012	mg/L	lrl
Magnesium	00925	7439-95-4	.008	mg/L	lrl
Potassium	00935	7440-09-7	.11	mg/L	lrl
Sodium	00930	7440-23-5	.09	mg/L	lrl
Bromide	71870	24959-67-9	.029	mg/L	lrl
Chloride	00940	16887-00-6	.33	mg/L	lrl
Fluoride	00950	16984-48-8	.11	mg/L	lrl
Silica	00955	7631-86-9	.13	mg/L	lrl
Sulfate	00945	14808-79-8	.11	mg/L	lrl
Total residue, 180 degrees Celsius	70300	None	10	mg/L	mrl
Nutrients—Filtered samples					
Ammonia	00608	7664-41-7	.041	mg/L as N	lrl
Ammonia plus organic nitrogen	00623	17778-88-0	.1	mg/L as N	lrl
Nitrite plus nitrate	00631	None	.047	mg/L as N	lrl
Nitrite	00613	14797-65-0	.008	mg/L as N	lrl
Orthophosphate	00671	14265-44-2	.018	mg/L as P	lrl
Trace elements—Filtered samples					
Aluminum	01106	7429-90-5	1	µg/L	mrl
Antimony	01095	7440-36-0	.048	µg/L	lrl
Arsenic	01000	7440-38-2	.8	µg/L	lrl
Barium	01005	7440-39-3	1	µg/L	mrl
Beryllium	01010	7440-41-7	.06	µg/L	lrl
Boron	01020	7440-42-8	7	µg/L	lrl
Cadmium	01025	7440-43-9	.04	µg/L	lrl

Table 3. Laboratory analytical constituents and reporting limits for water samples collected during August and September 2002 from observation wells in the upper aquifer near Richmond, Indiana.—Continued

[USGS, U.S. Geological Survey; mg/L, milligram per liter; lrl, laboratory reporting limit; mrl, method reporting limit; N, nitrogen; P, phosphorus; µg/L, microgram per liter]

Constituent name	USGS parameter code	Chemical Abstracts Service identification number	Reporting-limit magnitude	Reporting-limit unit	Reporting-limit type
Trace elements—Filtered samples—Continued					
Chromium	01030	7440-47-3	0.8	µg/L	lrl
Cobalt	01035	7440-48-4	.015	µg/L	lrl
Copper	01040	7440-50-8	.23	µg/L	lrl
Iron	01046	7439-89-6	10	µg/L	lrl
Lead	01049	7439-92-1	.08	µg/L	lrl
Lithium	01130	7439-93-2	.3	µg/L	lrl
Manganese	01056	7439-96-5	.1	µg/L	lrl
Molybdenum	01060	7439-98-7	.2	µg/L	lrl
Nickel	01065	7440-02-0	.06	µg/L	lrl
Selenium	01145	7782-49-2	.33	µg/L	lrl
Silver	01075	7440-22-4	1	µg/L	mrl
Strontium	01080	7440-24-6	.08	µg/L	lrl
Thallium	01057	7440-28-0	.041	µg/L	lrl
Uranium	22703	7440-61-1	.018	µg/L	lrl
Vanadium	01085	7440-62-2	.21	µg/L	lrl
Zinc	01090	7440-66-6	1	µg/L	mrl
Pesticides and pesticide transformation products—Unfiltered samples					
2,4-D	39732	94-75-7	.0218	µg/L	mrl
2,4-D methyl ester	50470	1928-38-7	.0086	µg/L	mrl
2,4-DB	38746	94-82-6	.016	µg/L	mrl
2,6-Diethylaniline	82660	579-66-8	.006	µg/L	lrl
3-Hydroxycarbofuran	49308	16655-82-6	.0058	µg/L	mrl
3-Ketocarbofuran	50285	16709-30-1	1.5	µg/L	mrl
Acetochlor	49206	34256-82-1	.006	µg/L	lrl
Acifluorfen	49315	50594-66-6	.0066	µg/L	mrl
Alachlor	46342	15972-60-8	.0045	µg/L	lrl

Table 3. Laboratory analytical constituents and reporting limits for water samples collected during August and September 2002 from observation wells in the upper aquifer near Richmond, Indiana.—Continued

[USGS, U.S. Geological Survey; mg/L, milligram per liter; lrl, laboratory reporting limit; mrl, method reporting limit; N, nitrogen; P, phosphorus; µg/L, microgram per liter]

Constituent name	USGS parameter code	Chemical Abstracts Service identification number	Reporting-limit magnitude	Reporting-limit unit	Reporting-limit type
Pesticides and pesticide transformation products—Unfiltered samples—Continued					
Aldicarb	49312	116-06-3	0.04	µg/L	mrl
Aldicarb sulfone	49313	1646-88-4	.02	µg/L	mrl
Aldicarb sulfoxide	49314	1646-87-3	.0082	µg/L	mrl
alpha-HCH	34253	319-84-6	.0046	µg/L	lrl
Atrazine	39632	1912-24-9	.007	µg/L	lrl
Azinphos-methyl	82686	86-50-0	.050	µg/L	lrl
Bendiocarb	50299	22781-23-3	.0252	µg/L	mrl
Benfluralin	82673	1861-40-1	.010	µg/L	lrl
Benomyl	50300	17804-35-2	.0038	µg/L	mrl
Bensulfuron-methyl	61693	83055-99-6	.0158	µg/L	mrl
Bentazon	38711	25057-89-0	.011	µg/L	mrl
Bromacil	04029	314-40-9	.033	µg/L	mrl
Bromoxynil	49311	1689-84-5	.017	µg/L	mrl
Butylate	04028	2008-41-5	.002	µg/L	lrl
Caffeine	50305	58-08-2	.010; .5 (wastewater method)	µg/L	mrl
Carbaryl	49310	63-25-2	.041	µg/L	mrl
Carbofuran	49309	1563-66-2	.0056	µg/L	mrl
Chloramben, methyl ester	61188	7286-84-2	.018	µg/L	mrl
Chlorimuron-ethyl	50306	90982-32-4	.0096	µg/L	mrl
Chlorothalonil	49306	1897-45-6	.035	µg/L	mrl
Chlorpyrifos	38933	2921-88-2	.005	µg/L	lrl
Clopyralid	49305	1702-17-6	.0138	µg/L	mrl
Cyanazine	04041	21725-46-2	.018	µg/L	lrl
Cycloate	04031	1134-23-2	.013	µg/L	mrl
Dacthal monoacid	49301	887-54-7	.0116	µg/L	mrl

Table 3. Laboratory analytical constituents and reporting limits for water samples collected during August and September 2002 from observation wells in the upper aquifer near Richmond, Indiana.—Continued

[USGS, U.S. Geological Survey; mg/L, milligram per liter; lrl, laboratory reporting limit; mrl, method reporting limit; N, nitrogen; P, phosphorus; µg/L, microgram per liter]

Constituent name	USGS parameter code	Chemical Abstracts Service identification number	Reporting-limit magnitude	Reporting-limit unit	Reporting-limit type
Pesticides and pesticide transformation products—Unfiltered samples—Continued					
Dacthal (DCPA)	82682	1861-32-1	0.003	µg/L	lrl
Deethylatrazine (2-Chloro-4-isopropylamino-6-amino-s-triazine)	04040	6190-65-4	.006	µg/L	lrl
Deisopropyldeethylatrazine (Chlordiamino-s-triazine)	04039	3397-62-4	.01	µg/L	mrl
Deisopropylatrazine (2-Chloro-6-ethylamino-4-amino-s-triazine)	04038	1007-28-9	.044	µg/L	mrl
Diazinon	39572	333-41-5	.005	µg/L	lrl
Dicamba	38442	1918-00-9	.0128	µg/L	mrl
Dichlorprop	49302	120-36-5	.0138	µg/L	mrl
Dieldrin	39381	60-57-1	.0048	µg/L	lrl
Dinoseb	49301	88-85-7	.012	µg/L	mrl
Diphenamid	04033	957-51-7	.0264	µg/L	mrl
Disulfoton	82677	298-04-4	.021	µg/L	lrl
Diuron	49300	330-54-1	.015	µg/L	mrl
EPTC	82668	759-94-4	.002	µg/L	lrl
Ethalfluralin	82663	55283-68-6	.009	µg/L	lrl
Ethoprophos	82672	13194-48-4	.005	µg/L	lrl
Fenuron	49297	101-42-8	.0316	µg/L	mrl
Flumetsulam	61694	98967-40-9	.011	µg/L	mrl
Fluometuron	38811	2164-17-2	.031	µg/L	mrl
Fonofos	04095	944-22-9	.0027	µg/L	lrl
2-Hydroxyatrazine (2-Hydroxy-4-isopropylamino-6-ethylamino-s-triazine)	50355	2163-68-0	.008	µg/L	mrl
Imazaquin	50356	81335-37-7	.016	µg/L	mrl
Imazethapyr	50407	81335-77-5	.017	µg/L	mrl
Imidacloprid	61695	138261-41-3	.0068	µg/L	mrl
Lindane	39341	58-89-9	.004	µg/L	lrl
Linuron	82666	330-55-2	.035	µg/L	lrl

Table 3. Laboratory analytical constituents and reporting limits for water samples collected during August and September 2002 from observation wells in the upper aquifer near Richmond, Indiana.—Continued

[USGS, U.S. Geological Survey; mg/L, milligram per liter; lrl, laboratory reporting limit; mrl, method reporting limit; N, nitrogen; P, phosphorus; µg/L, microgram per liter]

Constituent name	USGS parameter code	Chemical Abstracts Service identification number	Reporting-limit magnitude	Reporting-limit unit	Reporting-limit type
Pesticides and pesticide transformation products—Unfiltered samples—Continued					
Malathion	39532	121-75-5	0.027	µg/L	lrl
MCPA	38482	94-74-6	.0162	µg/L	mrl
MCPB	38487	94-81-5	.015	µg/L	mrl
Metalaxyl	50359	57837-19-1	.02	µg/L	mrl
Methiocarb	38501	2032-65-7	.008	µg/L	mrl
Methomyl	49296	16752-77-5	.0044	µg/L	mrl
Methyl parathion	82667	298-00-0	.006	µg/L	lrl
Metolachlor	39415	51218-45-2	.013	µg/L	lrl
Metribuzin	82630	21087-64-9	.006	µg/L	lrl
Metsulfuron methyl	61697	74223-64-6	.025	µg/L	mrl
Molinate	82671	2212-67-1	.0016	µg/L	lrl
Napropamide	82684	15299-99-7	.007	µg/L	lrl
Neburon	49294	555-37-3	.012	µg/L	mrl
Nicosulfuron	50364	111991-09-4	.013	µg/L	mrl
Norflurazon	49293	27314-13-2	.016	µg/L	mrl
Oryzalin	49292	19044-88-3	.0176	µg/L	mrl
Oxamyl	38866	23135-22-0	.0122	µg/L	mrl
p,p’-DDE	34653	72-55-9	.0025	µg/L	lrl
Parathion	39542	56-38-2	.010	µg/L	lrl
Pebulate	82669	1114-71-2	.0041	µg/L	lrl
Pendimethalin	82683	40487-42-1	.022	µg/L	lrl
cis-Permethrin	82687	54774-45-7	.006	µg/L	lrl
Phorate	82664	298-02-2	.011	µg/L	lrl
Picloram	49291	1918-02-1	.0198	µg/L	mrl
Prometon	04037	1610-18-0	.015	µg/L	lrl
Pronamide (Propyzamide)	82676	23950-58-5	.0041	µg/L	lrl
Propachlor	04024	1918-16-7	.01	µg/L	lrl

Table 3. Laboratory analytical constituents and reporting limits for water samples collected during August and September 2002 from observation wells in the upper aquifer near Richmond, Indiana.—Continued

[USGS, U.S. Geological Survey; mg/L, milligram per liter; lrl, laboratory reporting limit; mrl, method reporting limit; N, nitrogen; P, phosphorus; µg/L, microgram per liter]

Constituent name	USGS parameter code	Chemical Abstracts Service identification number	Reporting-limit magnitude	Reporting-limit unit	Reporting-limit type
Pesticides and pesticide transformation products—Unfiltered samples—Continued					
Propanil	82679	709-98-8	0.011	µg/L	lrl
Propargite	82685	2312-35-8	.023	µg/L	lrl
Propham	49236	122-42-9	.0096	µg/L	mrl
Propiconazole	50471	60207-90-1	.021	µg/L	mrl
Propoxur	38538	114-26-1	.008	µg/L	mrl
Siduron	38548	1982-49-6	.0168	µg/L	mrl
Simazine	04035	122-34-9	.005	µg/L	lrl
Sulfometuron-methyl	50337	74222-97-2	.0088	µg/L	mrl
Tebuthiuron	82670	34014-18-1	.016	µg/L	lrl
Terbacil	04032	5902-51-2	.0098	µg/L	mrl
Terbufos	82675	13071-79-9	.017	µg/L	lrl
Thiobencarb	82681	28249-77-6	.0048	µg/L	lrl
Tri-allate	82678	2303-17-5	.0023	µg/L	lrl
Triclopyr	49235	55335-06-3	.0224	µg/L	mrl
Trifluralin	82661	1582-09-8	.009	µg/L	lrl
3(4-Chlorophenyl)-1-methyl urea	61692	5352-88-5	.0242	µg/L	mrl
Volatile organic compounds—Unfiltered samples					
1,1,1-Trichloroethane	34506	71-55-6	.032	µg/L	lrl
1,1,2-Trichloroethane	34511	79-00-5	.064	µg/L	lrl
1,1-Dichloroethane	34496	75-34-3	.035	µg/L	lrl
1,1-Dichloroethene	34501	75-35-4	.044	µg/L	lrl
1,1-Dichloropropene	77168	563-58-6	.05	µg/L	lrl
1,2,3-Trichloropropane	77443	96-18-4	.16	µg/L	lrl
1,2-Dibromoethane	77651	106-93-4	.036	µg/L	lrl
1,2-Dichloroethane	32103	107-06-2	.13	µg/L	lrl
1,2-Dichloropropane	34541	78-87-5	.029	µg/L	lrl
trans-1,2-Dichloroethylene	34546	156-60-5	.032	µg/L	lrl

Table 3. Laboratory analytical constituents and reporting limits for water samples collected during August and September 2002 from observation wells in the upper aquifer near Richmond, Indiana.—Continued

[USGS, U.S. Geological Survey; mg/L, milligram per liter; lrl, laboratory reporting limit; mrl, method reporting limit; N, nitrogen; P, phosphorus; µg/L, microgram per liter]

Constituent name	USGS parameter code	Chemical Abstracts Service identification number	Reporting-limit magnitude	Reporting-limit unit	Reporting-limit type
Volatile organic compounds—Unfiltered samples—Continued					
2,2-Dichloropropane	77170	594-20-7	0.05	µg/L	lrl
trans-1,4-Dichloro-2-butene	73547	110-57-6	.70	µg/L	lrl
2-Hexanone	77103	591-78-6	.7	µg/L	lrl
Acetone	81552	67-64-1	7	µg/L	lrl
Acrylonitrile	34215	107-13-1	1.2	µg/L	lrl
1,2,3-Trichlorobenzene	77613	87-61-6	.27	µg/L	lrl
1,2,3-Trimethylbenzene	77221	526-73-8	.12	µg/L	lrl
1,2,4-Trichlorobenzene	34551	120-82-1	.07	µg/L	lrl
1,2,4-Trimethylbenzene	77222	95-63-6	.056	µg/L	lrl
1,3,5-Trimethylbenzene	77226	108-67-8	.044	µg/L	lrl
1,2-Dichlorobenzene	34536	95-50-1	.031	µg/L	lrl
1,3-Dichlorobenzene	34566	541-73-1	.03	µg/L	lrl
1,4-Dichlorobenzene	34571	106-46-7	.05	µg/L	lrl
Isopropylbenzene	77223	98-82-8	.06	µg/L	lrl
n-Butylbenzene	77342	104-51-8	.19	µg/L	lrl
n-Propylbenzene	77224	103-65-1	.042	µg/L	lrl
sec-Butylbenzene	77350	135-98-8	.032	µg/L	lrl
tert-Butylbenzene	77353	98-06-6	.048	µg/L	lrl
Benzene	34030	71-43-2	.035	µg/L	lrl
Bromobenzene	81555	108-86-1	.036	µg/L	lrl
Bromoethene	50002	593-60-2	.11	µg/L	lrl
Bromoform	32104	75-25-2	.06	µg/L	lrl
Carbon disulfide	77041	75-15-0	.075	µg/L	lrl
Carbon tetrachloride (Tetrachloromethane)	32102	56-23-5	.06	µg/L	lrl
Chlorobenzene	34301	108-90-7	.028	µg/L	lrl
Dibromochloromethane	32105	124-48-1	.18	µg/L	lrl
Chloroethane	34311	75-00-3	.12	µg/L	lrl

Table 3. Laboratory analytical constituents and reporting limits for water samples collected during August and September 2002 from observation wells in the upper aquifer near Richmond, Indiana.—Continued

[USGS, U.S. Geological Survey; mg/L, milligram per liter; lrl, laboratory reporting limit; mrl, method reporting limit; N, nitrogen; P, phosphorus; µg/L, microgram per liter]

Constituent name	USGS parameter code	Chemical Abstracts Service identification number	Reporting-limit magnitude	Reporting-limit unit	Reporting-limit type
Volatile organic compounds—Unfiltered samples—Continued					
Chloroform	32106	67-66-3	0.024	µg/L	lrl
cis-1,2-Dichloroethene	77093	156-59-2	.038	µg/L	lrl
cis-1,3-Dichloropropene	34704	10061-01-5	.09	µg/L	lrl
1,2-Dibromo-3-chloropropane	82625	96-12-8	.5	µg/L	mrl
Dibromomethane	30217	74-95-3	.05	µg/L	lrl
Bromodichloromethane	32101	75-27-4	.048	µg/L	lrl
Dichlorodifluoromethane	34668	75-71-8	.18	µg/L	lrl
Diisopropyl ether	81577	108-20-3	.10	µg/L	lrl
1,1,1,2-Tetrachloroethane	77562	630-20-6	.030	µg/L	lrl
1,1,2,2-Tetrachloroethane	34561	79-34-5	.09	µg/L	lrl
Hexachloroethane	34396	67-72-1	.19	µg/L	lrl
Ethylbenzene	34371	100-41-4	.03	µg/L	lrl
Diethyl ether	81576	60-29-7	.17	µg/L	lrl
Ethyl tert-butyl ether	50004	637-92-3	.054	µg/L	lrl
tert-Pentyl methyl ether	50005	994-05-8	.08	µg/L	lrl
Freon-113 (1,1,2-Trichlorotrifluoroethane)	77652	76-13-1	.06	µg/L	lrl
Tetrahydrofuran	81607	109-99-9	2.2	µg/L	lrl
Hexachlorobutadiene	39702	87-68-3	.14	µg/L	lrl
1,2,3,5-Tetramethylbenzene (Isodurene)	50000	527-53-7	.2	µg/L	lrl
Ethyl methacrylate	73570	97-63-2	.18	µg/L	lrl
Methyl methacrylate	81597	80-62-6	.35	µg/L	lrl
Methyl acrylonitrile	81593	126-98-7	.57	µg/L	lrl
Bromochloromethane	77297	74-97-5	.07	µg/L	lrl
Methyl acrylate	49991	96-33-3	2.0	µg/L	mrl
Methyl iodide	77424	74-88-4	.25	µg/L	lrl
Methyl tert-Butyl ether	78032	1634-04-4	.17	µg/L	lrl

Table 3. Laboratory analytical constituents and reporting limits for water samples collected during August and September 2002 from observation wells in the upper aquifer near Richmond, Indiana.—Continued

[USGS, U.S. Geological Survey; mg/L, milligram per liter; lrl, laboratory reporting limit; mrl, method reporting limit; N, nitrogen; P, phosphorus; µg/L, microgram per liter]

Constituent name	USGS parameter code	Chemical Abstracts Service identification number	Reporting-limit magnitude	Reporting-limit unit	Reporting-limit type
Volatile organic compounds—Unfiltered samples—Continued					
Bromomethane (Methyl bromide)	34413	74-83-9	0.26	µg/L	lrl
Chloromethane (Methyl chloride)	34418	74-87-3	.17	µg/L	lrl
Dichloromethane	34423	75-09-2	.16	µg/L	lrl
Methyl ethyl ketone (2-Butanone)	81595	78-93-3	5.0	µg/L	mrl
Methyl isobutyl ketone (4-Methyl-2-pentanone)	78133	108-10-1	.37	µg/L	lrl
m- and p-Xylene	85795	108-38-3 (m-Xylene); 106-42-3 (p-Xylene)	.06	µg/L	lrl
Naphthalene	34696	91-20-3	.5	µg/L	mrl
2-Chlorotoluene	77375	95-49-8	.026	µg/L	lrl
o-Xylene	77135	95-47-6	.07	µg/L	lrl
p-Isopropyl toluene (4-Isopropyl-1-methyl-benzene)	77356	99-87-6	.07	µg/L	lrl
1,2,3,4-Tetramethylbenzene	49999	488-23-3	.23	µg/L	lrl
1,3-Dichloropropane	77173	142-28-9	.12	µg/L	lrl
3-Chloropropene	78109	107-05-1	.07	µg/L	lrl
Styrene	77128	100-42-5	.042	µg/L	lrl
Tetrachloroethene	34475	127-18-4	.027	µg/L	lrl
o-Ethyl toluene	77220	611-14-3	.06	µg/L	lrl
4-Chlorotoluene	77277	106-43-4	.05	µg/L	lrl
Toluene	34010	108-88-3	.05	µg/L	lrl
trans-1,3-Dichloropropene	34699	10061-02-6	.09	µg/L	lrl
Trichloroethene	39180	79-01-6	.038	µg/L	lrl
Trichlorofluoromethane	34488	75-69-4	.09	µg/L	lrl
Vinyl chloride	39175	75-01-4	.11	µg/L	lrl

Table 3. Laboratory analytical constituents and reporting limits for water samples collected during August and September 2002 from observation wells in the upper aquifer near Richmond, Indiana.—Continued

[USGS, U.S. Geological Survey; mg/L, milligram per liter; lrl, laboratory reporting limit; mrl, method reporting limit; N, nitrogen; P, phosphorus; µg/L, microgram per liter]

Constituent name	USGS parameter code	Chemical Abstracts Service identification number	Reporting-limit magnitude	Reporting-limit unit	Reporting-limit type
Semivolatile organic compounds—Unfiltered samples					
Dibenz[a,h]anthracene (1,2,5,6-Dibenzanthracene)	34556	53-70-3	3.4	µg/L	lrl
1,2-Diphenylhydrazine	82626	122-66-7	2.1	µg/L	lrl
2,4,6-Trichlorophenol	34621	88-06-2	2.8	µg/L	lrl
2,4-Dimethylphenol	34606	105-67-9	.7	µg/L	lrl
2,4-Dichlorophenol	34601	120-83-2	2.9	µg/L	lrl
2,4-Dinitrophenol	34616	51-28-5	3.3	µg/L	lrl
2,4-Dinitrotoluene	34611	121-14-2	2.6	µg/L	lrl
2,6-Dinitrotoluene	34626	606-20-2	2.3	µg/L	lrl
2-Chloronaphthalene	34581	91-58-7	1.9	µg/L	lrl
2-Chlorophenol	34586	95-57-8	2.4	µg/L	lrl
2-Nitrophenol	34591	88-75-5	1.4	µg/L	lrl
3,3'-Dichlorobenzidine	34631	91-94-1	5.0	µg/L	lrl
4,6-Dinitro-o-cresol (4,6-Dinitro-2-methylphenol)	34657	534-52-1	3.2	µg/L	lrl
4-Bromophenyl phenyl ether	34636	101-55-3	2.1	µg/L	lrl
4-Chlorophenyl phenyl ether	34641	7005-72-3	2.2	µg/L	lrl
4-Nitrophenol	34646	100-02-7	2.6	µg/L	lrl
Acenaphthene	34205	83-32-9	1.8	µg/L	lrl
Acenaphthylene	34200	208-96-8	2.4	µg/L	lrl
Acrylonitrile	34215	107-13-1	1.2	µg/L	lrl
Anthracene, unfiltered	34220	120-12-7	2.0	µg/L	lrl
Nitrobenzene	34447	98-95-3	2.0	µg/L	lrl
Benzidine	39120	92-87-5	40	µg/L	mrl
Benzo[a]pyrene,unfiltered	34247	50-32-8	1.3	µg/L	lrl
Benzo[b]fluoranthene	34230	205-99-2	1.9	µg/L	lrl
Benzo[k]fluoranthene	34242	207-08-9	1.7	µg/L	lrl
Benz[a]anthracene	34526	56-55-3	2.4	µg/L	lrl

Table 3. Laboratory analytical constituents and reporting limits for water samples collected during August and September 2002 from observation wells in the upper aquifer near Richmond, Indiana.—Continued

[USGS, U.S. Geological Survey; mg/L, milligram per liter; lrl, laboratory reporting limit; mrl, method reporting limit; N, nitrogen; P, phosphorus; µg/L, microgram per liter]

Constituent name	USGS parameter code	Chemical Abstracts Service identification number	Reporting-limit magnitude	Reporting-limit unit	Reporting-limit type
Semivolatile organic compounds—Unfiltered samples—Continued					
Benzo[ghi]perylene	34521	191-24-2	2.8	µg/L	lrl
Bis(2-Chloroethoxy)methane	34278	111-91-1	2.6	µg/L	lrl
Bis(2-Chloroethyl)ether	34273	111-44-4	2.2	µg/L	lrl
Bis(2-chloroisopropyl) ether	34283	108-60-1	2.2	µg/L	lrl
Bis(2-ethylhexyl) phthalate	39100	117-81-7	6	µg/L	lrl
Chrysene	34320	218-01-9	2.7	µg/L	lrl
Hexachlorocyclopentadiene	34386	77-47-4	4	µg/L	lrl
Diethyl phthalate	34336	84-66-2	2.4	µg/L	lrl
Dimethyl phthalate	34341	131-11-3	2.4	µg/L	lrl
Di-n-butyl phthalate	39110	84-74-2	1.7	µg/L	lrl
Di-n-octyl phthalate	34596	117-84-0	5	µg/L	lrl
Fluoranthene	34376	206-44-0	2.4	µg/L	lrl
Fluorene	34381	86-73-7	2	µg/L	lrl
Hexachlorobenzene	39700	118-74-1	2.2	µg/L	lrl
Indeno[1,2,3-cd]pyrene	34403	193-39-5	3	µg/L	lrl
Isophorone	34408	78-59-1	2.2	µg/L	lrl
Butylbenzyl phthalate	34292	85-68-7	4.2	µg/L	lrl
N-Nitrosodimethylamine	34438	62-75-9	2.8	µg/L	lrl
N-Nitrosodi-n-propylamine	34428	621-64-7	2.4	µg/L	lrl
N-Nitrosodiphenylamine	34433	86-30-6	2.1	µg/L	lrl
4-Chloro-3-methylphenol (Para-chloro-meta-cresol)	34452	59-50-7	3	µg/L	lrl
Pentachlorophenol	39032	87-86-5	3.8	µg/L	lrl
Phenanthrene	34461	85-01-8	2	µg/L	lrl
Phenol	34694	108-95-2	3.4	µg/L	lrl
Pyrene	34469	129-00-0	2.2	µg/L	lrl

Table 3. Laboratory analytical constituents and reporting limits for water samples collected during August and September 2002 from observation wells in the upper aquifer near Richmond, Indiana.—Continued

[USGS, U.S. Geological Survey; mg/L, milligram per liter; lrl, laboratory reporting limit; mrl, method reporting limit; N, nitrogen; P, phosphorus; µg/L, microgram per liter]

Constituent name	USGS parameter code	Chemical Abstracts Service identification number	Reporting-limit magnitude	Reporting-limit unit	Reporting-limit type
Wastewater-related organic compounds—Filtered samples					
1-Methylnaphthalene	62054	90-12-0	0.5	µg/L	mrl
2,6-Dimethylnaphthalene	62055	581-42-0	.5	µg/L	mrl
2-Methylnaphthalene	62056	91-57-6	.5	µg/L	mrl
3-Beta-coprostanol	62057	360-68-9	2	µg/L	mrl
3-Methyl-1(H)-indole (Skatole)	62058	83-34-1	1.0	µg/L	mrl
3-tert-Butyl-4-hydroxy anisole (BHA)	62059	25013-16-5	5.0	µg/L	mrl
4-Cumylphenol	62060	599-64-4	1.0	µg/L	mrl
4-n-Octylphenol	62061	1806-26-4	1.0	µg/L	mrl
4-tert-Octylphenol	62062	140-66-9	1.0	µg/L	mrl
5-Methyl-1H-benzotriazole	62063	136-85-6	2.0	µg/L	mrl
Acetophenone	62064	98-86-2	.5	µg/L	mrl
Acetyl hexamethyl tetrahydro naphthalene (AHTN)	62065	21145-77-7	.5	µg/L	mrl
Anthracene	34221	120-12-7	.5	µg/L	mrl
Benzo[a]pyrene	34248	50-32-8	.5	µg/L	mrl
Benzophenone	62067	119-61-9	.5	µg/L	mrl
beta-Sitosterol	62068	83-46-5	2.0	µg/L	mrl
Bisphenol A	62069	80-05-7	1.0	µg/L	mrl
Camphor	62070	76-22-2	.5	µg/L	mrl
Carbazole	62071	86-74-8	.5	µg/L	mrl
Cholesterol	62072	57-88-5	2.0	µg/L	mrl
Cotinine	62005	486-56-6	1.0	µg/L	mrl
d-Limonene	62073	5989-27-5	.5	µg/L	mrl
Fluoranthene	34377	206-44-0	.5	µg/L	mrl
Hexahydrohexamethylcyclopentabenzopyran (HHCB)	62075	1222-05-5	.5	µg/L	mrl
Indole	62076	120-72-9	.5	µg/L	mrl
Isoborneol	62077	124-76-5	.5	µg/L	mrl

Table 3. Laboratory analytical constituents and reporting limits for water samples collected during August and September 2002 from observation wells in the upper aquifer near Richmond, Indiana.—Continued

[USGS, U.S. Geological Survey; mg/L, milligram per liter; lrl, laboratory reporting limit; mrl, method reporting limit; N, nitrogen; P, phosphorus; µg/L, microgram per liter]

Constituent name	USGS parameter code	Chemical Abstracts Service identification number	Reporting-limit magnitude	Reporting-limit unit	Reporting-limit type
Wastewater-related organic compounds—Filtered samples—Continued					
Isophorone	34409	78-59-1	0.5	µg/L	mrl
Isopropylbenzene	62078	98-82-8	.5	µg/L	mrl
Isoquinoline	62079	119-65-3	.5	µg/L	mrl
Menthol	62068	89-78-1	.5	µg/L	mrl
Methyl salicylate	62081	119-36-8	.5	µg/L	mrl
N,N-diethyl-meta-toluamide (DEET)	62082	134-62-3	.5	µg/L	mrl
Naphthalene	34443	91-20-3	.5	µg/L	mrl
Nonylphenol, diethoxy-	62083	26027-38-2	5.0	µg/L	mrl
Octylphenol, diethoxy-	61705	26636-32-8	1.0	µg/L	mrl
Octylphenol, monoethoxy-	61706	26636-32-8	1.0	µg/L	mrl
p-Cresol	62084	106-44-5	1.0	µg/L	mrl
para-Nonylphenol	62085	84852-15-3	5.0	µg/L	mrl
Pentachlorophenol	34459	87-86-5	2	µg/L	mrl
Phenanthrene	34462	85-01-8	.5	µg/L	mrl
Phenol	34466	108-95-2	.5	µg/L	mrl
Pyrene	34470	129-00-0	.5	µg/L	mrl
beta-Stigmastanol	62086	19466-47-8	2.0	µg/L	mrl
Tetrachloroethylene	34476	127-18-4	.5	µg/L	mrl
Tri(2-chloroethyl)phosphate (Fyrol CEF)	62087	115-96-8	.5	µg/L	mrl
Tributyl phosphate	62089	126-73-8	.5	µg/L	mrl
Triclosan	62090	3380-34-5	1.0	µg/L	mrl
Triethyl citrate (ethyl citrate)	62091	77-93-0	.5	µg/L	mrl
Triphenyl phosphate	62092	115-86-6	.5	µg/L	mrl
Tri(2-butoxyethyl)phosphate	62093	78-51-3	.5	µg/L	mrl
Tri(2-chloroethyl)phosphate	62087	115-96-8	.5	µg/L	mrl
Tris(dichlorisopropyl)phosphate	62088	13674-87-8	.5	µg/L	mrl
Dichlorvos	38775	62-73-7	1.0	µg/L	mrl

Table 4. Water levels in wells in the upper aquifer and at surface-water-stage measurement sites near Richmond, Indiana, 2002–03.

[USGS, U.S. Geological Survey; mm/dd/yy, month/day/year; vertical datum is National Geodetic Vertical datum of 1929; < , less than; DRY, no water in well at time of measurement; - , negative depths to water indicate water levels above land surface; -- , no land-surface-altitude value available]

Well or station name	USGS station-identification number	Date of measurement (mm/dd/yy)	Water-level elevation (feet above vertical datum)	Depth to water below land surface (feet)
		Observation wells		
Well 1-16	394924084492501	06/25/02	1,043.04	9.97
		08/28/02	1,040.25	12.76
		12/24/02	1,039.69	13.32
		04/10/03	1,041.98	11.03
Well 1-23	394924084492502	06/25/02	1,043.02	9.86
		08/28/02	1,040.27	12.61
		12/24/02	1,039.70	13.18
		04/10/03	1,041.99	10.89
Well 2-15	394852084492501	06/19/02	1,052.48	5.94
		08/05/02	1,050.93	7.49
		08/20/02	1,050.64	7.78
		08/27/02	1,050.60	7.82
		12/24/02	1,050.71	7.71
		04/10/03	1,051.77	6.65
Well 2-26	394852084492502	06/19/02	1,052.49	5.89
		08/05/02	1,050.93	7.45
		08/20/02	1,050.68	7.70
		08/27/02	1,050.62	7.76
		12/24/02	1,050.81	7.57
		04/10/03	1,051.83	6.55
Well 3-13	394851084500001	08/21/02	1,037.59	5.57
		08/29/02	1,037.58	5.58
		12/24/02	1,037.55	5.61
		04/10/03	1,038.39	4.77

Table 4. Water levels in wells in the upper aquifer and at surface-water-stage measurement sites near Richmond, Indiana, 2002–03.—Continued

[USGS, U.S. Geological Survey; mm/dd/yy, month/day/year; vertical datum is National Geodetic Vertical datum of 1929; < , less than; DRY, no water in well at time of measurement; - , negative depths to water indicate water levels above land surface; -- , no land-surface-altitude value available]

Well or station name	USGS station-identification number	Date of measurement (mm/dd/yy)	Water-level elevation (feet above vertical datum)	Depth to water below land surface (feet)
		Observation wells—Continued		
Well 3-38	394851084500002	06/20/02	1,038.82	4.74
		08/21/02	1,037.60	5.96
		08/29/02	1,037.47	6.09
		12/24/02	1,037.57	5.99
		04/10/03	1,038.42	5.14
Well 4-14	394852084503301	06/21/02	1,040.37	6.39
		08/05/02	1,038.96	7.80
		09/05/02	1,038.46	8.30
		12/24/02	1,038.95	7.81
		04/10/03	1,040.13	6.63
		Hand-driven wells		
Well HD-1	394916084492501	12/24/02	<1,041.34	DRY
		04/10/03	1,044.41	9.37
Well HD-2	394852084492601	12/24/02	1,049.81	-.70
		04/10/03	1,050.00	-.89
Well HD-3	394851084494701	12/24/02	1,038.68	.96
		04/10/03	1,040.03	-.39
Well HD-4	394840084500701	12/24/02	1,035.20	-.44
		04/10/03	1,035.39	-.63
Well HD-5	394910084500001	12/24/02	1,039.15	2.98
		04/10/03	1,041.31	.82
Well HD-6	394838084503301	12/24/02	1,032.36	-1.02
		04/10/03	1,032.37	-1.03

Table 4. Water levels in wells in the upper aquifer and at surface-water-stage measurement sites near Richmond, Indiana, 2002–03.—Continued

[USGS, U.S. Geological Survey; mm/dd/yy, month/day/year; vertical datum is National Geodetic Vertical datum of 1929; < , less than; DRY, no water in well at time of measurement; - , negative depths to water indicate water levels above land surface; -- , no land-surface-altitude value available]

Well or station name	USGS station-identification number	Date of measurement (mm/dd/yy)	Water-level elevation (feet above vertical datum)	Depth to water below land surface (feet)
Surface-water-stage measurements at hand-driven wells				
Stage measurement site HD-1 in unnamed tributary to Short Creek near Industrial Parkway	--	12/24/02 04/10/03	DRY 1,054.45	DRY -.67
Stage measurement site HD-2 in Short Creek at Industrial Parkway and Hodgin Road	--	12/24/02 04/10/03	1,049.29 1,049.52	-.18 -.41
Stage measurement site HD-3 in Short Creek at Hodgin Road	--	12/24/02 04/10/03	DRY 1,040.30	DRY -.66
Stage measurement site HD-4 in Short Creek	--	12/24/02 04/10/03	1,034.83 1,035.18	-.07 -.42
Stage measurement site HD-5 in unnamed tributary to Short Creek north of HodginRoad	--	12/24/02 04/10/03	DRY DRY	DRY DRY
Stage measurement site HD-6 in Short Creek at Garwood Road	--	12/24/02 04/10/03	1,032.21 1,032.25	-.87 -.91

Table 5. Vertical water-level gradients between paired observation wells in the upper aquifer and between water levels in hand-driven wells in the upper aquifer and at adjacent surface-water-stage measurement sites near Richmond, Indiana, 2002–03.

[mm/dd/yy, month/day/year; NA, no water-level gradient could be computed because one or both sites were dry; - , negative water-level-gradient values indicate downward gradients; positive water-level-gradient values indicate upward gradients]

Name of shallow well or surface-water-stage measurement site	Name of deep well	Date of water-level-measurements (mm/dd/yy)	Vertical hydraulic gradient (feet/foot)[1, 2]	Direction of vertical gradient
		Paired observation wells		
Well 1-16	Well 1-23	08/28/02	0.0032	Upward.
		12/24/02	.0017	Upward.
		04/10/03	.0014	Upward.
Well 2-15	Well 2-26	08/05/02	.0	No gradient.
		08/20/02	.0035	Upward.
		08/27/02	.0018	Upward.
		12/24/02	.0087	Upward.
		04/10/03	.0050	Upward.
Well 3-13	Well 3-38	08/20/02	.0	No gradient.
		08/29/02	.0	No gradient.
		12/24/02	.00076	Upward.
		04/10/03	.0011	Upward.
		Paired surface-water-stage measurement site and hand-driven well		
Stage measurement site HD-1 in unnamed tributary to Short Creek near Industrial Parkway	Well HD-1	12/24/02	NA; stage site and well were dry	Downward.
		04/10/03	-.86	Downward.
Stage measurement site HD-2 in Short Creek at Industrial Parkway and Hodgin Road	Well HD-2	12/24/02	.17	Upward.
		04/10/03	.15	Upward.
Stage measurement site HD-3 in Short Creek at Hodgin Road	Well HD-3	12/24/02	NA; stage site was dry	Downward.
		04/10/03	-.087	Downward.
Stage measurement site HD-4 in Short Creek	Well HD-4	12/24/02	.15	Upward.
		04/10/03	.073	Upward.

Table 5. Vertical water-level gradients between paired observation wells in the upper aquifer and between water levels in hand-driven wells in the upper aquifer and at adjacent surface-water-stage measurement sites near Richmond, Indiana, 2002–03.—Continued

[mm/dd/yy, month/day/year; NA, no water-level gradient could be computed because one or both sites were dry; - , negative water-level-gradient values indicate downward gradients; positive water-level-gradient values indicate upward gradients]

Name of shallow well or surface-water-stage measurement site	Name of deep well	Date of water-level-measurements (mm/dd/yy)	Vertical hydraulic gradient (feet/foot)[1, 2]	Direction of vertical gradient
Paired surface-water-stage measurement site and hand-driven well—Continued				
Stage measurement site HD-5 in unnamed tributary to Short Creek north of Hodgin Road	Well HD-5	12/24/02	NA; stage site was dry	Downward.
		04/10/03	NA; stage site was dry	Downward.
Stage measurement site HD-6 in Short Creek at Garwood Road	Well HD-6	12/24/02	.040	Upward.
		04/10/03	.032	Upward.

[1] Vertical gradients were computed between water levels in wells (table 4), using the formula

$$\text{vertical gradient} = (WLs - WLd)/(ALTs - ALTd)$$

where

WLs is the water-level altitude in the shallow well or the surface-water stage;
WLd is the water-level altitude in the deep well;
$ALTs$ is one of the following values. When the water table was in the screened interval in the shallow well, $ALTs$ was the altitude of the midpoint between the water-table altitude and the altitude of the base of the shallow well screen. When the water table was above the screened interval of the shallow well, $ALTs$ was the altitude of the midpoint between the top and base of the shallow well screen; and
$ALTd$ is the midpoint of the altitude between the top of the deep well screen and the base of the deep well screen.

[2] Vertical gradients were computed between surface-water levels at a stage-measurement site and ground-water levels inside a well (table 4), using the formula

$$\text{vertical gradient} = (SWL - WLd)/(SWL - ALTd)$$

where

SWL is the altitude of the surface-water level;
WLd is the water-level altitude in the well; and
$ALTd$ is one of the following values. When the water table was in the screened interval in the well, $ALTd$ was the altitude of the midpoint between the water-table altitude and the altitude of the base of the well screen. When the water table was above the screened interval of the well, $ALTd$ was the altitude of the midpoint between the top of the well screen and the base of the well screen is the midpoint of the altitude between the top and base of the well screen.

Table 8. Concentrations of sulfur hexafluoride in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.

[mm/dd/yyyy, month/day/year; hhmm, hours and minutes; mg/L, miligram per liter; °C, degrees Celsius; ft-VD, altitude in feet above vertical datum (National Geodetic Vertical Datum of 1929); pptv, part per trillion by volume; E, estimated value]

Well name	Date sampled (mm/dd/yyyy)	Time sampled (hhmm)	Excess nitrogen concentration, (mg/L)[1]	Estimated recharge temperature[1] (°C)	Estimated recharge altitude (ft-VD)	Sulfur hexafluoride concentration, excess air corrected (pptv)
			Water samples			
Well 1-16	8/28/2002	0900	1.3	13.3	1,040	7.3
Well 1-23	8/28/2002	1345	.8	11.1	1,060	7.7
Well 2-15	8/27/2002	0915	E1.0	E9	1,050	7.0
Well 2-26	8/27/2002	1500	1.5	6.3	1,060	7.9
Well 3-13	8/29/2002	0900	2.0	9.6	1,038	10.0
Well 3-38	8/29/2002	1330	4.5	7.4	1,060	5.6
Well 4-14	8/30/2002	930	1.5	5.6	1,040	6.3
			Quality-assurance samples (Sequential duplicates)			
Well 1-16	8/28/2002	0910	1.3	13.3	1,040	6.8
Well 1-23	8/28/2002	1355	.8	11.1	1,060	8.6
Well 2-15	8/27/2002	0925	E1.0	E9	1,050	6.6
Well 2-26	8/27/2002	1510	1.5	6.3	1,060	7.6
Well 3-13	8/29/2002	0910	2.0	9.6	1,038	9.9
Well 3-38	8/29/2002	1340	4.5	7.4	1,060	6.2
Well 4-14	8/30/2002	940	1.5	5.6	1,040	7.2

[1] Excess air concentrations and recharge temperatures were evaluated, using a plot of dissolved nitrogen gas concentration with argon gas concentration in dissolved-gas analyses (table 6). It is assumed that the sample contains argon from air/water equilibrium and dissolution of excess air. The source of dissolved nitrogen gas is assumed to be that of argon plus excess nitrogen gas from another source such as denitrification.

Table 12. Concentrations of pesticides and pesticide transformation products in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.

[mm/dd/yy, month/day/year; hhmm, hours and minutes; µg/L, microgram per liter; < , less than; **bold** values indicate compound detected in sample; E, estimated value below reporting limit; M, presence verified but not quantified; --, not measured or determined; all concentrations are reported as unfiltered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	2,4-D (µg/L)	2,4-D methyl ester (µg/L)	2,4-DB (µg/L)	2,6-Diethyl-aniline (µg/L)	3-Hydroxy-carbofuran (µg/L)	3-Keto-carbofuran (µg/L)	Acetochlor (µg/L)	Acifluofen (µg/L)
Water samples										
Well 1-16	08/28/02	0900	<0.02	<0.009	<0.02	<0.006	<0.006	<2	<0.006	<0.007
Well 1-23	08/28/02	1345	<.02	<.009	<.02	<.006	<.006	<2	<.006	<.007
Well 2-15	08/27/02	0915	<.02	<.009	<.02	<.006	<.006	<2	<.006	<.007
Well 2-26	08/27/02	1400	<.02	<.009	<.02	<.006	<.006	<2	<.006	<.007
Well 3-13	08/29/02	0900	<.02	<.009	<.02	<.006	<.006	<2	<.006	<.007
Well 3-38	09/05/02	1030	<.02	<.009	<.02	<.006	<.006	<2	<.006	<.007
Well 4-14	08/30/02	0930	<.02	<.009	<.02	<.006	<.006	<2	<.006	<.007
Quality-assurance samples										
Well 3-13 (Sequential duplicate)	08/29/02	0930	<.02	<.009	<.02	<.006	<.006	<2	<.006	<.007
Well 2-15 (Equipment blank)	08/26/02	1800	<.02	<.009	<.02	<.006	<.006	<2	<.006	<.007

Table 12. Concentrations of pesticides and pesticide transformation products in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; µg/L, microgram per liter; < , less than; **bold** values indicate compound detected in sample; E, estimated value below reporting limit; M, presence verified but not quantified; -- , not measured or determined; all concentrations are reported as unfiltered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Alachlor (µg/L)	Aldicarb (µg/L)	Aldicarb sulfone (µg/L)	Aldicarb sulfoxide (µg/L)	Alpha-HCH (µg/L)	Atrazine (µg/L)	Azinphos-methyl (µg/L)	Bendiocarb (µg/L)
Water samples										
Well 1-16	08/28/02	0900	<0.005	<0.04	<0.02	<0.008	<0.005	**0.011**	<0.050	<0.03
Well 1-23	08/28/02	1345	<.005	<.04	<.02	<.008	<.005	**E.003**	<.050	<.03
Well 2-15	08/27/02	0915	<.005	<.04	<.02	<.008	<.005	**E.006**	<.050	<.03
Well 2-26	08/27/02	1400	<.005	<.04	<.02	<.008	<.005	<.007	<.050	<.03
Well 3-13	08/29/02	0900	<.005	<.04	<.02	<.008	<.005	**E.006**	<.050	<.03
Well 3-38	09/05/02	1030	<.005	<.04	<.02	<.008	<.005	<.007	<.050	<.03
Well 4-14	08/30/02	0930	<.005	<.04	<.02	<.008	<.005	**.036**	<.050	<.03
Quality-assurance samples										
Well 3-13 (Sequential duplicate)	08/29/02	0930	<.005	<.04	<.02	<.008	<.005	**E.006**	<.050	<.03
Well 2-15 (Equipment blank)	08/26/02	1800	<.005	<.04	<.02	<.008	<.005	<.007	<.050	<.03

Table 12. Concentrations of pesticides and pesticide transformation products in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; µg/L, microgram per liter; < , less than; **bold** values indicate compound detected in sample; E, estimated value below reporting limit; M, presence verified but not quantified; --, not measured or determined; all concentrations are reported as unfiltered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Benfluralin (µg/L)	Benomyl (µg/L)	Bensulfuron-methyl (µg/L)	Bentazon (µg/L)	Bromacil (µg/L)	Bromoxynil (µg/L)	Butylate (µg/L)	Caffeine (µg/L)
					Water samples					
Well 1-16	08/28/02	0900	<0.010	<0.004	<0.02	<0.01	<0.03	<0.02	<0.002	<0.5
Well 1-23	08/28/02	1345	<.010	<.004	<.02	<.01	<.03	<.02	<.002	<.010
Well 2-15	08/27/02	0915	<.010	<.004	<.02	<.01	<.03	<.02	<.002	<.5
Well 2-26	08/27/02	1400	<.010	<.004	<.02	<.01	<.03	<.02	<.002	<.5
Well 3-13	08/29/02	0900	<.010	<.004	<.02	<.01	<.03	<.02	<.002	<.010
Well 3-38	09/05/02	1030	<.010	<.004	<.02	<.01	<.03	<.02	<.002	<.5
Well 4-14	08/30/02	0930	<.010	<.004	<.02	<.01	<.03	<.02	<.002	<.5
					Quality-assurance samples					
Well 3-13 (Sequential duplicate)	08/29/02	0930	<.010	<.004	<.02	<.01	<.03	<.02	<.002	<.010
Well 2-15 (Equipment blank)	08/26/02	1800	<.010	<.004	<.02	<.01	<.03	<.02	<.002	<.5

Table 12. Concentrations of pesticides and pesticide transformation products in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; µg/L, microgram per liter; < , less than; **bold** values indicate compound detected in sample; E, estimated value below reporting limit; M, presence verified but not quantified; --, not measured or determined; all concentrations are reported as unfiltered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Carbaryl (µg/L)	Carbofuran (µg/L)	Chloramben, methyl ester (µg/L)	Chlorimuron-ethyl (µg/L)	Chlorothalonil (µg/L)	Chlorpyrifos (µg/L)
Water samples								
Well 1-16	08/28/02	0900	<0.041	<0.020	<0.02	<0.010	<0.04	<0.005
Well 1-23	08/28/02	1345	<.041	<.020	<.02	<.010	<.04	<.005
Well 2-15	08/27/02	0915	<.041	<.020	<.02	<.010	<.04	<.005
Well 2-26	08/27/02	1400	<.041	<.020	<.02	<.010	<.04	<.005
Well 3-13	08/29/02	0900	<.041	<.020	<.02	<.010	<.04	<.005
Well 3-38	09/05/02	1030	<.041	<.020	<.02	<.010	<.04	<.005
Well 4-14	08/30/02	0930	<.041	<.020	<.02	<.010	<.04	<.005
Quality-assurance samples								
Well 3-13 (Sequential duplicate)	08/29/02	0930	<.041	<.020	<.02	<.010	<.04	<.005
Well 2-15 (Equipment blank)	08/26/02	1800	<.041	<.020	<.02	<.010	<.04	<.005

Table 12. Concentrations of pesticides and pesticide transformation products in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; µg/L, microgram per liter; <, less than; **bold** values indicate compound detected in sample; E, estimated value below reporting limit; M, presence verified but not quantified; --, not measured or determined; all concentrations are reported as unfiltered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Clopyralid (µg/L)	Cyanazine (µg/L)	Cycloate (µg/L)	Dacthal monoacid (µg/L)	Dacthal (DCPA) (µg/L)	Deethyl-atrazine (µg/L)	Deiso-propyl-deethyl-atrazine (µg/L)	Deiso-propyl-atrazine (µg/L)
Water samples										
Well 1-16	08/28/02	0900	<0.01	<0.018	<0.01	<0.01	<0.003	**E0.017**	**E0.003**	<0.04
Well 1-23	08/28/02	1345	<.01	<.018	<.01	<.01	<.003	**E.005**	<.01	<.04
Well 2-15	08/27/02	0915	<.01	<.018	<.01	<.01	<.003	**E.007**	<.01	<.04
Well 2-26	08/27/02	1400	<.01	<.018	<.01	<.01	<.003	<.006	<.01	<.04
Well 3-13	08/29/02	0900	<.01	<.018	<.01	<.01	<.003	**E.015**	<.01	<.04
Well 3-38	09/05/02	1030	<.01	<.018	<.01	<.01	<.003	<.006	<.01	<.04
Well 4-14	08/30/02	0930	<.01	<.018	<.01	<.01	<.003	**E.096**	**E.01**	**E.01**
Quality-assurance samples										
Well 3-13 (Sequential duplicate)	08/29/02	0930	<.01	<.018	<.01	<.01	<.003	**E.012**	<.01	<.04
Well 2-15 (Equipment blank)	08/26/02	1800	<.01	<.018	<.01	<.01	<.003	<.006	<.01	<.04

Table 12. Concentrations of pesticides and pesticide transformation products in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; µg/L, microgram per liter; < , less than; **bold** values indicate compound detected in sample; E, estimated value below reporting limit; M, presence verified but not quantified; --, not measured or determined; all concentrations are reported as unfiltered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Diazinon (µg/L)	Dicamba (µg/L)	Dichlorprop (µg/L)	Dieldrin (µg/L)	Dinoseb (µg/L)	Diphenamid (µg/L)	Disulfoton (µg/L)	Diuron (µg/L)
Water samples										
Well 1-16	08/28/02	0900	<0.005	<0.01	<0.01	<0.005	<0.01	<0.03	<0.02	<0.01
Well 1-23	08/28/02	1345	<.005	<.01	<.01	<.005	<.01	<.03	<.02	<.01
Well 2-15	08/27/02	0915	<.005	<.01	<.01	<.005	<.01	<.03	<.02	<.01
Well 2-26	08/27/02	1400	<.005	<.01	<.01	<.005	<.01	<.03	<.02	<.01
Well 3-13	08/29/02	0900	<.005	<.01	<.01	<.005	<.01	<.03	<.02	<.01
Well 3-38	09/05/02	1030	<.005	<.01	<.01	<.005	<.01	<.03	<.02	<.01
Well 4-14	08/30/02	0930	<.005	<.01	<.01	<.005	<.01	<.03	<.02	<.01
Quality-assurance samples										
Well 3-13 (Sequential duplicate)	08/29/02	0930	<.005	<.01	<.01	<.005	<.01	<.03	<.02	<.01
Well 2-15 (Equipment blank)	08/26/02	1800	<.005	<.01	<.01	<.005	<.01	<.03	<.02	<.01

Table 12. Concentrations of pesticides and pesticide transformation products in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; µg/L, microgram per liter; < , less than; **bold** values indicate compound detected in sample; E, estimated value below reporting limit; M, presence verified but not quantified; --, not measured or determined; all concentrations are reported as unfiltered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	EPTC (µg/L)	Ethal-fluralin (µg/L)	Etho-prophos (µg/L)	Fenuron (µg/L)	Flumetsulam (µg/L)	Fluo-meturon (µg/L)	Fonofos (µg/L)	2-Hydroxy-atrazine (µg/L)
Water samples										
Well 1-16	08/28/02	0900	<0.002	<0.009	<0.005	<0.03	<0.01	<0.03	<0.003	**E0.016**
Well 1-23	08/28/02	1345	<.002	<.009	<.005	<.03	<.01	<.03	<.003	**E.004**
Well 2-15	08/27/02	0915	<.002	<.009	<.005	<.03	<.01	<.03	<.003	**E.010**
Well 2-26	08/27/02	1400	<.002	<.009	<.005	<.03	<.01	<.03	<.003	<.008
Well 3-13	08/29/02	0900	<.002	<.009	<.005	<.03	**E.02**	<.03	<.003	<.008
Well 3-38	09/05/02	1030	<.002	<.009	<.005	<.03	<.01	<.03	<.003	<.008
Well 4-14	08/30/02	0930	<.002	<.009	<.005	<.03	<.01	<.03	<.003	**E.020**
Quality-assurance samples										
Well 3-13 (Sequential duplicate)	08/29/02	0930	<.002	<.009	<.005	<.03	**E.02**	<.03	<.003	<.008
Well 2-15 (Equipment blank)	08/26/02	1800	<.002	<.009	<.005	<.03	<.01	<.03	<.003	<.008

Table 12. Concentrations of pesticides and pesticide transformation products in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; µg/L, microgram per liter; < , less than; **bold** values indicate compound detected in sample; E, estimated value below reporting limit; M, presence verified but not quantified; --, not measured or determined; all concentrations are reported as unfiltered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Imazaquin (µg/L)	Imazethapyr (µg/L)	Imid-acloprid (µg/L)	Lindane (µg/L)	Linuron (µg/L)	Malathion (µg/L)	MCPA (µg/L)	MCPB (µg/L)
Water samples										
Well 1-16	08/28/02	0900	<0.02	<0.02	<0.007	<0.004	<0.035	<0.027	<0.02	<0.01
Well 1-23	08/28/02	1345	<.02	<.02	<.007	<.004	<.035	<.027	<.02	<.01
Well 2-15	08/27/02	0915	<.02	<.02	<.007	<.004	<.035	<.027	<.02	<.01
Well 2-26	08/27/02	1400	<.02	--	<.007	<.004	<.035	<.027	<.02	<.01
Well 3-13	08/29/02	0900	<.02	<.02	<.007	<.004	<.035	<.027	<.02	<.01
Well 3-38	09/05/02	1030	<.02	<.02	<.007	<.004	<.035	<.027	<.02	<.01
Well 4-14	08/30/02	0930	<.02	<.02	<.007	<.004	<.035	<.027	<.02	<.01
Quality-assurance samples										
Well 3-13 (Sequential duplicate)	08/29/02	0930	<.02	<.02	<.007	<.004	<.035	<.027	<.02	<.01
Well 2-15 (Equipment blank)	08/26/02	1800	<.02	<.02	<.007	<.004	<.035	<.027	<.02	<.01

Table 12. Concentrations of pesticides and pesticide transformation products in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; µg/L, microgram per liter; < , less than; **bold** values indicate compound detected in sample; E, estimated value below reporting limit; M, presence verified but not quantified; --, not measured or determined; all concentrations are reported as unfiltered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Metalaxyl (µg/L)	Methiocarb (µg/L)	Methomyl (µg/L)	Methyl parathion (µg/L)	Metolachlor (µg/L)	Metribuzin (µg/L)	Met-sulfuron methyl (µg/L)	Molinate (µg/L)
Water samples										
Well 1-16	08/28/02	0900	<0.02	<0.008	<0.004	<0.006	<0.013	<0.006	<0.03	<0.002
Well 1-23	08/28/02	1345	<.02	<.008	<.004	<.006	<.013	<.006	<.03	<.002
Well 2-15	08/27/02	0915	<.02	<.008	<.004	<.006	<.013	<.006	<.03	<.002
Well 2-26	08/27/02	1400	<.02	<.008	<.004	<.006	<.013	<.006	<.03	<.002
Well 3-13	08/29/02	0900	<.02	<.008	<.004	<.006	<.013	<.006	<.03	<.002
Well 3-38	09/05/02	1030	<.02	<.008	<.004	<.006	<.013	<.006	<.03	<.002
Well 4-14	08/30/02	0930	<.02	<.008	<.004	<.006	<.013	<.006	<.03	<.002
Quality-assurance samples										
Well 3-13 (Sequential duplicate)	08/29/02	0930	<.02	<.008	<.004	<.006	<.013	<.006	<.03	<.002
Well 2-15 (Equipment blank)	08/26/02	1800	<.02	<.008	<.004	<.006	<.013	<.006	<.03	<.002

Table 12. Concentrations of pesticides and pesticide transformation products in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; µg/L, microgram per liter; < , less than; **bold** values indicate compound detected in sample; E, estimated value below reporting limit; M, presence verified but not quantified; --, not measured or determined; all concentrations are reported as unfiltered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Napropamide (µg/L)	Neburon (µg/L)	Nicosulfuron (µg/L)	Norflurazon (µg/L)	Oryzalin (µg/L)	Oxamyl (µg/L)	p,p′-DDE (µg/L)	Parathion (µg/L)
					Water samples					
Well 1-16	08/28/02	0900	<0.007	<0.01	<0.01	<0.02	<0.02	<0.01	<0.003	<0.010
Well 1-23	08/28/02	1345	<.007	<.01	<.01	<.02	<.02	<.01	<.003	<.010
Well 2-15	08/27/02	0915	<.007	<.01	<.01	<.02	<.02	<.01	<.003	<.010
Well 2-26	08/27/02	1400	<.007	<.01	<.01	<.02	<.02	<.01	<.003	<.010
Well 3-13	08/29/02	0900	<.007	<.01	<.01	<.02	<.02	<.01	<.003	<.010
Well 3-38	09/05/02	1030	<.007	<.01	<.01	<.02	<.02	<.01	<.003	<.010
Well 4-14	08/30/02	0930	<.007	<.01	<.01	<.02	<.02	<.01	<.003	<.010
					Quality-assurance samples					
Well 3-13 (Sequential duplicate)	08/29/02	0930	<.007	<.01	<.01	<.02	<.02	<.01	<.003	<.010
Well 2-15 (Equipment blank)	08/26/02	1800	<.007	<.01	<.01	<.02	<.02	<.01	<.003	<.010

Table 12. Concentrations of pesticides and pesticide transformation products in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; µg/L, microgram per liter; <, less than; **bold** values indicate compound detected in sample; E, estimated value below reporting limit; M, presence verified but not quantified; --, not measured or determined; all concentrations are reported as unfiltered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Pebulate (µg/L)	Pendi-methalin (µg/L)	cis-Permethrin (µg/L)	Phorate (µg/L)	Picloram (µg/L)	Prometon (µg/L)	Pronamide (µg/L)	Propachlor (µg/L)
Water samples										
Well 1-16	08/28/02	0900	<0.004	<0.022	<0.006	<0.011	<0.02	**0.04**	<0.004	<0.010
Well 1-23	08/28/02	1345	<.004	<.022	<.006	<.011	<.02	**E.01**	<.004	<.010
Well 2-15	08/27/02	0915	<.004	<.022	<.006	<.011	<.02	<.01	<.004	<.010
Well 2-26	08/27/02	1400	<.004	<.022	<.006	<.011	<.02	<.01	<.004	<.010
Well 3-13	08/29/02	0900	<.004	<.022	<.006	<.011	<.02	<.01	<.004	<.010
Well 3-38	09/05/02	1030	<.004	<.022	<.006	<.011	<.02	<.01	<.004	<.010
Well 4-14	08/30/02	0930	<.004	<.022	<.006	<.011	<.02	**M**	<.004	<.010
Quality-assurance samples										
Well 3-13 (Sequential duplicate)	08/29/02	0930	<.004	<.022	<.006	<.011	<.02	<.01	<.004	<.010
Well 2-15 (Equipment blank)	08/26/02	1800	<.004	<.022	<.006	<.011	<.02	<.01	<.004	<.010

Table 12. Concentrations of pesticides and pesticide transformation products in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; µg/L, microgram per liter; < , less than; **bold** values indicate compound detected in sample; E, estimated value below reporting limit; M, presence verified but not quantified; --, not measured or determined; all concentrations are reported as unfiltered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Propanil (µg/L)	Propargite (µg/L)	Propham (µg/L)	Propiconazole (µg/L)	Propoxur (µg/L)	Siduron (µg/L)	Simazine (µg/L)	Sulfometuron-methyl (µg/L)
					Water samples					
Well 1-16	08/28/02	0900	<0.011	<0.02	<0.010	<0.02	<0.008	<0.02	<0.005	<0.009
Well 1-23	08/28/02	1345	<.011	<.02	<.010	<.02	<.008	<.02	<.005	<.009
Well 2-15	08/27/02	0915	<.011	<.02	<.010	<.02	<.008	<.02	<.005	<.009
Well 2-26	08/27/02	1400	<.011	<.02	<.010	<.02	<.008	<.02	<.005	<.009
Well 3-13	08/29/02	0900	<.011	<.02	<.010	<.02	<.008	<.02	<.005	<.009
Well 3-38	09/05/02	1030	<.011	<.02	<.010	<.02	<.008	<.02	<.005	<.009
Well 4-14	08/30/02	0930	<.011	<.02	<.010	<.02	<.008	<.02	**E.003**	<.009
					Quality-assurance samples					
Well 3-13 (Sequential duplicate)	08/29/02	0930	<.011	<.02	<.010	<.02	<.008	<.02	<.005	<.009
Well 2-15 (Equipment blank)	08/26/02	1800	<.011	<.02	<.010	<.02	<.008	<.02	<.005	<.009

Table 12. Concentrations of pesticides and pesticide transformation products in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; µg/L, microgram per liter; < , less than; **bold** values indicate compound detected in sample; E, estimated value below reporting limit; M, presence verified but not quantified; --, not measured or determined; all concentrations are reported as unfiltered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Tebuthiuron (µg/L)	Terbacil (µg/L)	Terbufos (µg/L)	Thiobencarb (µg/L)	Triallate (µg/L)	Triclopyr (µg/L)	Trifluralin (µg/L)	3(4-Chloro-phenyl)-1-methyl urea (µg/L)
Water samples										
Well 1-16	08/28/02	0900	<0.02	<0.010	<0.034	<0.02	<0.005	<0.002	<0.009	<0.02
Well 1-23	08/28/02	1345	<.02	<.010	<.034	<.02	<.005	<.002	<.009	<.02
Well 2-15	08/27/02	0915	<.02	<.010	<.034	<.02	<.005	<.002	<.009	<.02
Well 2-26	08/27/02	1400	<.02	<.010	<.034	<.02	<.005	<.002	<.009	<.02
Well 3-13	08/29/02	0900	E.01	<.010	<.034	<.02	<.005	<.002	<.009	<.02
Well 3-38	09/05/02	1030	<.02	<.010	<.034	<.02	<.005	<.002	<.009	<.02
Well 4-14	08/30/02	0930	<.02	<.010	<.034	<.02	<.005	<.002	<.009	<.02
Quality-assurance samples										
Well 3-13 (Sequential duplicate)	08/29/02	0930	E.01	<.010	<.034	<.02	<.005	<.002	<.009	<.02
Well 2-15 (Equipment blank)	08/26/02	1800	<.02	<.010	<.034	<.02	<.005	<.002	<.009	<.02

Table 13. Concentrations of volatile organic compounds in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.

[mm/dd/yy, month/day/year; hhmm, hours and minutes; µg/L, microgram per liter; < , less than; E, estimated value below reporting limit; **bold** values indicate compound detected in sample; Q, concentration estimated because relative percent difference between environmental and sequential duplicate samples was greater than 25 percent; all concentrations are reported as unfiltered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	1,1,1-Trichloro-ethane (µg/L)	1,1,2-Trichloro-ethane (µg/L)	1,1-Dichloro-ethane (µg/L)	1,1-Dichloro-ethene (µg/L)	1,1-Dichloro-propene (µg/L)	1,2,3-Trichloro-propane (µg/L)	1,2-Dibromo-ethane (µg/L)
				Water samples					
Well 1-16	08/28/02	0900	<0.03	<0.06	<0.04	<0.04	<0.05	<0.16	<0.04
Well 1-23	08/28/02	1345	<.03	<.06	<.04	<.04	<.05	<.16	<.04
Well 2-15	08/27/02	0915	<.03	<.06	<.04	<.04	<.05	<.16	<.04
Well 2-26	08/27/02	1400	<.03	<.06	<.04	<.04	<.05	<.16	<.04
Well 3-13	08/29/02	0900	<.03	<.06	<.04	<.04	<.05	<.16	<.04
Well 3-38	09/05/02	1030	<.03	<.06	<.04	<.04	<.05	<.16	<.04
Well 4-14	08/30/02	0930	<.03	<.06	<.04	<.04	<.05	<.16	<.04
				Quality-assurance samples					
Well 1-23 (Sequential duplicate)	08/28/02	1415	<.03	<.06	<.04	<.04	<.05	<.16	<.04
Well 4-14 (Equipment blank)	08/30/02	1000	<.03	<.06	<.04	<.04	<.05	<.16	<.04
Well 2-15 (Equipment blank)	08/26/02	1800	<.03	<.06	<.04	<.04	<.05	<.16	<.04

Table 13. Concentrations of volatile organic compounds in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; µg/L, microgram per liter; < , less than; E, estimated value below reporting limit; **bold** values indicate compound detected in sample; Q, concentration estimated because relative percent difference between environmental and sequential duplicate samples was greater than 25 percent; all concentrations are reported as unfiltered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	1,2-Dichloro-ethane (µg/L)	1,2-Dichloro-propane (µg/L)	trans-1,2-Di-chloro-ethylene (µg/L)	2,2-Dichloro-propane (µg/L)	trans-1,4-Di-chloro-2-butene (µg/L)	2-Hexanone (µg/L)	Acetone (µg/L)
Water samples									
Well 1-16	08/28/02	0900	<0.1	<0.03	<0.03	<0.05	<0.7	<0.7	<7
Well 1-23	08/28/02	1345	<.1	<.03	<.03	<.05	<.7	<.7	<7
Well 2-15	08/27/02	0915	<.1	<.03	<.03	<.05	<.7	<.7	<7
Well 2-26	08/27/02	1400	<.1	<.03	<.03	<.05	<.7	<.7	<7
Well 3-13	08/29/02	0900	<.1	<.03	<.03	<.05	<.7	<.7	<7
Well 3-38	09/05/02	1030	<.1	<.03	<.03	<.05	<.7	<.7	<7
Well 4-14	08/30/02	0930	<.1	<.03	<.03	<.05	<.7	<.7	<7
Quality-assurance samples									
Well 1-23 (Sequential duplicate)	08/28/02	1415	<.1	<.03	<.03	<.05	<.7	<.7	<7
Well 4-14 (Equipment blank)	08/30/02	1000	<.1	<.03	<.03	<.05	<.7	<.7	<7
Well 2-15 (Equipment blank)	08/26/02	1800	<.1	<.03	<.03	<.05	<.7	<.7	<7

Table 13. Concentrations of volatile organic compounds in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; µg/L, microgram per liter; < , less than; E, estimated value below reporting limit; **bold** values indicate compound detected in sample; Q, concentration estimated because relative percent difference between environmental and sequential duplicate samples was greater than 25 percent; all concentrations are reported as unfiltered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Acrylonitrile (µg/L)	1,2,3-Trichloro-benzene (µg/L)	1,2,3-Trimethyl-benzene (µg/L)	1,2,4-Trichloro-benzene (µg/L)	1,2,4-Trimethyl-benzene (µg/L)	1,3,5-Trimethyl-benzene (µg/L)	1,2-Dichloro-benzene (µg/L)	1,3-Dichloro-benzene (µg/L)
Water samples										
Well 1-16	08/28/02	0900	<1	<0.3	<0.1	<0.1	<0.06	<0.04	<0.03	<0.03
Well 1-23	08/28/02	1345	<1	<.3	<.1	<.1	<.06	<.04	<.03	<.03
Well 2-15	08/27/02	0915	<1	<.3	<.1	<.1	<.06	<.04	<.03	<.03
Well 2-26	08/27/02	1400	<1	<.3	<.1	<.1	<.06	<.04	<.03	<.03
Well 3-13	08/29/02	0900	<1	<.3	<.1	<.1	<.06	<.04	<.03	<.03
Well 3-38	09/05/02	1030	<1	<.3	<.1	<.1	<.06	<.04	<.03	<.03
Well 4-14	08/30/02	0930	<1	<.3	<.1	<.1	<.06	<.04	<.03	<.03
Quality-assurance samples										
Well 1-23 (Sequential duplicate)	08/28/02	1415	<1	<.3	<.1	<.1	<.06	<.04	<.03	<.03
Well 4-14 (Equipment blank)	08/30/02	1000	<1	<.3	<.1	<.1	<.06	<.04	<.03	<.03
Well 2-15 (Equipment blank)	08/26/02	1800	<1	<.3	<.1	<.1	<.06	<.04	<.03	<.03

Table 13. Concentrations of volatile organic compounds in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; µg/L, microgram per liter; < , less than; E, estimated value below reporting limit; **bold** values indicate compound detected in sample; Q, concentration estimated because relative percent difference between environmental and sequential duplicate samples was greater than 25 percent; all concentrations are reported as unfiltered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	1,4-Dichloro-benzene (µg/L)	Isopropyl-benzene (µg/L)	n-Butyl-benzene (µg/L)	n-Propyl-benzene (µg/L)	sec-Butyl-benzene (µg/L)	tert-Butyl-benzene (µg/L)	Benzene (µg/L)	Bromo-benzene (µg/L)
Water samples										
Well 1-16	08/28/02	0900	<0.05	<0.06	<0.2	<0.04	<0.03	<0.05	<0.04	<0.04
Well 1-23	08/28/02	1345	<.05	<.06	<.2	<.04	<.03	<.05	<.04	<.04
Well 2-15	08/27/02	0915	<.05	<.06	<.2	<.04	<.03	<.05	<.04	<.04
Well 2-26	08/27/02	1400	<.05	<.06	<.2	<.04	<.03	<.05	<.04	<.04
Well 3-13	08/29/02	0900	<.05	<.06	<.2	<.04	<.03	<.05	<.04	<.04
Well 3-38	09/05/02	1030	<.05	<.06	<.2	<.04	<.03	<.05	<.04	<.04
Well 4-14	08/30/02	0930	<.05	<.06	<.2	<.04	<.03	<.05	<.04	<.04
Quality-assurance samples										
Well 1-23 (Sequential duplicate)	08/28/02	1415	<.05	<.06	<.2	<.04	<.03	<.05	<.04	<.04
Well 4-14 (Equipment blank)	08/30/02	1000	<.05	<.06	<.2	<.04	<.03	<.05	<.04	<.04
Well 2-15 (Equipment blank)	08/26/02	1800	<.05	<.06	<.2	<.04	<.03	<.05	<.04	<.04

Table 13. Concentrations of volatile organic compounds in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; µg/L, microgram per liter; < , less than; E, estimated value below reporting limit; **bold** values indicate compound detected in sample; Q, concentration estimated because relative percent difference between environmental and sequential duplicate samples was greater than 25 percent; all concentrations are reported as unfiltered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Bromoethene (µg/L)	Bromoform (µg/L)	Carbon disulfide (µg/L)	Carbon tetrachloride (µg/L)	Chloro-benzene (µg/L)	Dibromo-chloro-methane (µg/L)	Chloroethane (µg/L)	Chloroform (µg/L)
					Water samples					
Well 1-16	08/28/02	0900	<0.1	<0.06	<0.07	<0.06	<0.03	<0.2	<0.1	[1]**E0.01**
Well 1-23	08/28/02	1345	<.1	<.06	<.07	<.06	<.03	<.2	<.1	<.02
Well 2-15	08/27/02	0915	<.1	<.06	<.07	<.06	<.03	<.2	<.1	<.02
Well 2-26	08/27/02	1400	<.1	<.06	**E.02**	<.06	<.03	<.2	<.1	<.02
Well 3-13	08/29/02	0900	<.1	<.06	<.07	<.06	<.03	<.2	<.1	<.02
Well 3-38	09/05/02	1030	<.1	<.06	<.07	<.06	<.03	<.2	<.1	<.02
Well 4-14	08/30/02	0930	<.1	<.06	<.07	<.06	<.03	<.2	<.1	[1]**E.04**
					Quality-assurance samples					
Well 3-13 (Sequential duplicate)	08/28/02	1415	<.1	<.06	<.07	<.06	<.03	<.2	<.1	<.02
Well 4-14 (Equipment blank)	08/30/02	1000	<.1	<.06	<.07	<.06	<.03	<.2	<.1	<.02
Well 2-15 (Equipment blank)	08/26/02	1800	<.1	<.06	<.07	<.06	<.03	<.2	<.1	**E.02**

Table 13. Concentrations of volatile organic compounds in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; µg/L, microgram per liter; < , less than; E, estimated value below reporting limit; **bold** values indicate compound detected in sample; Q, concentration estimated because relative percent difference between environmental and sequential duplicate samples was greater than 25 percent; all concentrations are reported as unfiltered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	cis-1,2-Dichloro-ethene (µg/L)	cis-1,3-Dichloro-propene (µg/L)	1,2-Dibromo-3-chloro-propane (µg/L)	Dibromo-methane (µg/L)	Bromo-dichloro-methane (µg/L)	Dichloro-difluoro-methane (µg/L)	Diisopropyl ether (µg/L)	1,1,1,2 Tetra-chloroethane (µg/L)
					Water samples					
Well 1-16	08/28/02	0900	<0.04	<0.09	<0.5	<0.05	<0.05	<0.18	<0.10	<0.03
Well 1-23	08/28/02	1345	<.04	<.09	<.5	<.05	<.05	<.18	<.10	<.03
Well 2-15	08/27/02	0915	<.04	<.09	<.5	<.05	<.05	<.18	<.10	<.03
Well 2-26	08/27/02	1400	<.04	<.09	<.5	<.05	<.05	<.18	<.10	<.03
Well 3-13	08/29/02	0900	<.04	<.09	<.5	<.05	<.05	<.18	<.10	<.03
Well 3-38	09/05/02	1030	<.04	<.09	<.5	<.05	<.05	<.18	<.10	<.03
Well 4-14	08/30/02	0930	<.04	<.09	<.5	<.05	<.05	<.18	<.10	<.03
					Quality-assurance samples					
Well 1-23 (Sequential duplicate)	08/28/02	1415	<.04	<.09	<.5	<.05	<.05	<.18	<.10	<.03
Well 4-14 (Equipment blank)	08/30/02	1000	<.04	<.09	<.5	<.05	<.05	<.18	<.10	<.03
Well 2-15 (Equipment blank)	08/26/02	1800	<.04	<.09	<.5	<.05	<.05	<.18	<.10	<.03

Table 13. Concentrations of volatile organic compounds in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; µg/L, microgram per liter; < , less than; E, estimated value below reporting limit; **bold** values indicate compound detected in sample; Q, concentration estimated because relative percent difference between environmental and sequential duplicate samples was greater than 25 percent; all concentrations are reported as unfiltered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	1,1,2,2-Tetra-chloro-ethane (µg/L)	Hexachloro-ethane (µg/L)	Ethyl-benzene (µg/L)	Diethyl ether (µg/L)	Ethyl tert-butyl ether (µg/L)	tert-Pentyl methyl ether (µg/L)	Freon-113 (µg/L)	Tetra-hydrofuran (µg/L)
Water samples										
Well 1-16	08/28/02	0900	<0.09	<0.2	<0.03	<0.2	<0.05	<0.08	<0.06	<2
Well 1-23	08/28/02	1345	<.09	<.2	<.03	<.2	<.05	<.08	<.06	<2
Well 2-15	08/27/02	0915	<.09	<.2	<.03	<.2	<.05	<.08	<.06	<2
Well 2-26	08/27/02	1400	<.09	<.2	<.03	<.2	<.05	<.08	<.06	<2
Well 3-13	08/29/02	0900	<.09	<.2	<.03	<.2	<.05	<.08	<.06	<2
Well 3-38	09/05/02	1030	<.09	<.2	<.03	<.2	<.05	<.08	<.06	<2
Well 4-14	08/30/02	0930	<.09	<.2	<.03	<.2	<.05	<.08	<.06	<2
Quality-assurance samples										
Well 1-23 (Sequential duplicate)	08/28/02	1415	<.09	<.2	<.03	<.2	<.05	<.08	<.06	<2
Well 4-14 (Equipment blank)	08/30/02	1000	<.09	<.2	<.03	<.2	<.05	<.08	<.06	<2
Well 2-15 (Equipment blank)	08/26/02	1800	<.09	<.2	<.03	<.2	<.05	<.08	<.06	<2

Table 13. Concentrations of volatile organic compounds in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; µg/L, microgram per liter; < , less than; E, estimated value below reporting limit; **bold** values indicate compound detected in sample; Q, concentration estimated because relative percent difference between environmental and sequential duplicate samples was greater than 25 percent; all concentrations are reported as unfiltered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Hexachloro-butadiene (µg/L)	1,2,3,5-Tetra-methyl-benzene (Isodurene) (µg/L)	Ethyl methacrylate (µg/L)	Methyl meth-acrylate (µg/L)	Methyl acrylo-nitrile (µg/L)	Bromo-chloro-methane (µg/L)	Methyl acrylate (µg/L)	Methyl iodide (µg/L)
					Water samples					
Well 1-16	08/28/02	0900	<0.1	<0.2	<0.2	<0.3	<0.6	<0.07	<2.0	<0.25
Well 1-23	08/28/02	1345	<.1	<.2	<.2	<.3	<.6	<.07	<2.0	<.25
Well 2-15	08/27/02	0915	<.1	<.2	<.2	<.3	<.6	<.07	<2.0	<.25
Well 2-26	08/27/02	1400	<.1	<.2	<.2	<.3	<.6	<.07	<2.0	<.25
Well 3-13	08/29/02	0900	<.1	<.2	<.2	<.3	<.6	<.07	<2.0	<.25
Well 3-38	09/05/02	1030	<.1	<.2	<.2	<.3	<.6	<.07	<2.0	<.25
Well 4-14	08/30/02	0930	<.1	<.2	<.2	<.3	<.6	<.07	<2.0	<.25
					Quality-assurance samples					
Well 1-23 (Sequential duplicate)	08/28/02	1415	<.1	<.2	<.2	<.3	<.6	<.07	<2.0	<.25
Well 4-14 (Equipment blank)	08/30/02	1000	<.1	<.2	<.2	<.3	<.6	<.07	<2.0	<.25
Well 2-15 (Equipment blank)	08/26/02	1800	<.1	<.2	<.2	<.3	<.6	<.07	<2.0	<.25

Table 13. Concentrations of volatile organic compounds in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; µg/L, microgram per liter; < , less than; E, estimated value below reporting limit; **bold** values indicate compound detected in sample; Q, concentration estimated because relative percent difference between environmental and sequential duplicate samples was greater than 25 percent; all concentrations are reported as unfiltered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Methyl tert-Butyl ether (µg/L)	Bromo-methane (µg/L)	Chloro-methane (µg/L)	Methylene chloride (µg/L)	Methyl ethyl ketone (µg/L)	Methyl isobutyl ketone (µg/L)	m- and p-Xylene (µg/L)	Napthalene (µg/L)
					Water samples					
Well 1-16	08/28/02	0900	<0.2	<0.3	<0.2	<0.2	<5.0	<0.4	<0.06	<0.5
Well 1-23	08/28/02	1345	<.2	<.3	<.2	<.2	<5.0	<.4	<.06	<.5
Well 2-15	08/27/02	0915	<.2	<.3	<.2	<.2	<5.0	<.4	<.06	<.5
Well 2-26	08/27/02	1400	<.2	<.3	<.2	<.2	<5.0	<.4	<.06	<.5
Well 3-13	08/29/02	0900	<.2	<.3	<.2	<.2	<5.0	<.4	<.06	<.5
Well 3-38	09/05/02	1030	<.2	<.3	<.2	<.2	<5.0	<.4	<.06	<.5
Well 4-14	08/30/02	0930	<.2	<.3	<.2	<.2	<5.0	<.4	<.06	<.5
					Quality-assurance samples					
Well 1-23 (Sequential duplicate)	08/28/02	1415	<.2	<.3	<.2	<.2	<5.0	<.4	<.06	<.5
Well 4-14 (Equipment blank)	08/30/02	1000	<.2	<.3	<.2	<.2	<5.0	<.4	<.06	<.5
Well 2-15 (Equipment blank)	08/26/02	1800	<.2	<.3	<.2	<.2	**E4.2**	<.4	<.06	<.5

Table 13. Concentrations of volatile organic compounds in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; µg/L, microgram per liter; < , less than; E, estimated value below reporting limit; **bold** values indicate compound detected in sample; Q, concentration estimated because relative percent difference between environmental and sequential duplicate samples was greater than 25 percent; all concentrations are reported as unfiltered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	2-Chloro-toluene (µg/L)	o-Xylene (µg/L)	p-Isopropyl toluene (µg/L)	1,2,3,4-Tetramethyl-benzene (µg/L)	1,3-Dichloro-propane (µg/L)	3-Chloro-propene (µg/L)	Styrene (µg/L)	Tetra-chloroethene (µg/L)
Water samples										
Well 1-16	08/28/02	0900	<0.03	<0.07	<0.07	<0.2	<0.1	<0.07	<0.04	<0.03
Well 1-23	08/28/02	1345	<.03	<.07	<.07	<.2	<.1	<.07	<.04	<.03
Well 2-15	08/27/02	0915	<.03	<.07	<.07	<.2	<.1	<.07	<.04	<.03
Well 2-26	08/27/02	1400	<.03	<.07	<.07	<.2	<.1	<.07	<.04	<.03
Well 3-13	08/29/02	0900	<.03	<.07	<.07	<.2	<.1	<.07	<.04	<.03
Well 3-38	09/05/02	1030	<.03	<.07	<.07	<.2	<.1	<.07	<.04	<.03
Well 4-14	08/30/02	0930	<.03	<.07	<.07	<.2	<.1	<.07	<.04	<.03
Quality-assurance samples										
Well 1-23 (Sequential duplicate)	08/28/02	1415	<.03	<.07	<.07	<.2	<.1	<.07	<.04	<.03
Well 4-14 (Equipment blank)	08/30/02	1000	<.03	<.07	<.07	<.2	<.1	<.07	**E.02**	<.03
Well 2-15 (Equipment blank)	08/26/02	1800	<.03	<.07	<.07	<.2	<.1	<.07	**E.05**	<.03

Table 13. Concentrations of volatile organic compounds in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; µg/L, microgram per liter; < , less than; E, estimated value below reporting limit; **bold** values indicate compound detected in sample; Q, concentration estimated because relative percent difference between environmental and sequential duplicate samples was greater than 25 percent; all concentrations are reported as unfiltered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	o-Ethyl toluene (µg/L)	p-Chloro toluene (µg/L)	Toluene (µg/L)	trans-1,3-Dichloro-propene (µg/L)	Trichloro-ethene (µg/L)	Trichloro-fluoromethane (µg/L)	Vinyl chloride (µg/L)
					Water samples				
Well 1-16	08/28/02	0900	<0.06	<0.05	<0.05	<0.09	<0.04	<0.09	<0.1
Well 1-23	08/28/02	1345	<.06	<.05	**[1]Q,E.05**	<.09	<.04	<.09	<.1
Well 2-15	08/27/02	0915	<.06	<.05	<.05	<.09	<.04	<.09	<.1
Well 2-26	08/27/02	1400	<.06	<.05	<.05	<.09	<.04	<.09	<.1
Well 3-13	08/29/02	0900	<.06	<.05	<.05	<.09	<.04	<.09	<.1
Well 3-38	09/05/02	1030	<.06	<.05	<.05	<.09	<.04	<.09	<.1
Well 4-14	08/30/02	0930	<.06	<.05	<.05	<.09	<.04	<.09	<.1
					Quality-assurance samples				
Well 1-23 (Sequential duplicate)	08/28/02	1415	<.06	<.05	**.17**	<.09	<.04	<.09	<.1
Well 4-14 (Equipment blank)	08/30/02	1000	<.06	<.05	**E.01**	<.09	<.04	<.09	<.1
Well 2-15 (Equipment blank)	08/26/02	1800	<.06	<.05	<.05	<.09	<.04	<.09	<.1

[1] Compound detected in equipment blank sample.

Table 14. Concentrations of semivolatile organic compounds in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.

[mm/dd/yy, month/day/year; hhmm, hours and minutes; mg/L, milligram per liter; µg/L, microgram per liter; < , less than; E, estimated value below reporting limit; **bold** values indicate compound detected in sample; all concentrations are reported as unfiltered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Dibenz[a,h] anthracene (mg/L)	1,2-Diphenyl-hydrazine (µg/L)	2,4,6-Trichloro-phenol (µg/L)	2,4-Dimethyl-phenol (µg/L)	2,4-Dichloro-phenol (µg/L)	2,4-Dinitro-phenol (µg/L)	2,4-Dinitro-toluene (µg/L)	2,6-Dinitro-toluene (µg/L)
Water samples										
Well 1-16	08/28/02	0900	<3	<2	<3	<0.7	<3	<3	<3	<2
Well 1-23	08/28/02	1345	<3	<2	<3	<.7	<3	<3	<3	<2
Well 2-15	08/27/02	0915	<3	<2	<3	<.7	<3	<3	<3	<2
Well 2-26	08/27/02	1400	<3	<2	<3	<.7	<3	<3	<3	<2
Well 3-13	08/29/02	0900	<3	<2	<3	<.7	<3	<3	<3	<2
Well 3-38	09/05/02	1030	<3	<2	<3	<.7	<3	<3	<3	<2
Well 4-14	08/30/02	0930	<3	<2	<3	<.7	<3	<3	<3	<2
Quality-assurance samples										
Well 1-23 (Sequential duplicate)	08/28/02	1415	<3	<2	<3	<.7	<3	<3	<3	<2
Well 2-15 (Equipment blank)	08/26/02	1800	<3	<2	<3	<.7	<3	<3	<3	<2

Table 14. Concentrations of semivolatile organic compounds in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; mg/L, milligram per liter; µg/L, microgram per liter; < , less than; E, estimated value below reporting limit; **bold** values indicate compound detected in sample; all concentrations are reported as unfiltered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	2-Chloro-napthalene (µg/L)	2-Chloro-phenol (µg/L)	2-Nitro-phenol (µg/L)	3-3′-Dichloro-benzidine (µg/L)	4,6-Dinitro-o-cresol (µg/L)	4-Bromo-phenyl phenyl ether (µg/L)	4-Chloro-phenyl phenyl ether (µg/L)	4-Nitro-phenol (µg/L)	Ace-napthene (µg/L)
Water samples											
Well 1-16	08/28/02	0900	<2	<2	<1	<5	<3	<2	<2	<3	<2
Well 1-23	08/28/02	1345	<2	<2	<1	<5	<3	<2	<2	<3	<2
Well 2-15	08/27/02	0915	<2	<2	<1	<5	<3	<2	<2	<3	<2
Well 2-26	08/27/02	1400	<2	<2	<1	<5	<3	<2	<2	<3	<2
Well 3-13	08/29/02	0900	<2	<2	<1	<5	<3	<2	<2	<3	<2
Well 3-38	09/05/02	1030	<2	<2	<1	<5	<3	<2	<2	<3	<2
Well 4-14	08/30/02	0930	<2	<2	<1	<5	<3	<2	<2	<3	<2
Quality-assurance samples											
Well 1-23 (Sequential duplicate)	08/28/02	1415	<2	<2	<1	<5	<3	<2	<2	<3	<2
Well 2-15 (Equipment blank)	08/26/02	1800	<2	<2	<1	<5	<3	<2	<2	<3	<2

Table 14. Concentrations of semivolatile organic compounds in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; mg/L, milligram per liter; µg/L, microgram per liter; < , less than; E, estimated value below reporting limit; **bold** values indicate compound detected in sample; all concentrations are reported as unfiltered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Ace-napthylene (µg/L)	Anthracene (µg/L)	Nitrobenzene (µg/L)	Benzidine (µg/L)	Benzo[a] pyrene (µg/L)	Benzo[b] fluoranthene (µg/L)
				Water samples				
Well 1-16	08/28/02	0900	<2	<2	<2	<40	<1	<2
Well 1-23	08/28/02	1345	<2	<2	<2	<40	<1	<2
Well 2-15	08/27/02	0915	<2	<2	<2	<40	<1	<2
Well 2-26	08/27/02	1400	<2	<2	<2	<40	<1	<2
Well 3-13	08/29/02	0900	<2	<2	<2	<40	<1	<2
Well 3-38	09/05/02	1030	<2	<2	<2	<40	<1	<2
Well 4-14	08/30/02	0930	<2	<2	<2	<40	<1	<2
				Quality-assurance samples				
Well 1-23 (Sequential duplicate)	08/28/02	1415	<2	<2	<2	<40	<1	<2
Well 2-15 (Equipment blank)	08/26/02	1800	<2	<2	<2	<40	<1	<2

Table 14. Concentrations of semivolatile organic compounds in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; mg/L, milligram per liter; µg/L, microgram per liter; < , less than; E, estimated value below reporting limit; **bold** values indicate compound detected in sample; all concentrations are reported as unfiltered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Benzo[k] fluoranthene (µg/L)	Benz[a] anthracene (µg/L)	Benzo [ghi] perylene (µg/L)	Bis (2-Chloro-ethoxy) methane (µg/L)	Bis (2-Chloro-ethyl) ether (µg/L)	Bis (2-chloro-isopropyl) ether (µg/L)	Bis (2-ethylhexyl) phthalate (µg/L)	Chrysene (µg/L)
					Water samples					
Well 1-16	08/28/02	0900	<2	<2	<3	<3	<2	<2	<6	<3
Well 1-23	08/28/02	1345	<2	<2	<3	<3	<2	<2	<6	<3
Well 2-15	08/27/02	0915	<2	<2	<3	<3	<2	<2	<6	<3
Well 2-26	08/27/02	1400	<2	<2	<3	<3	<2	<2	**E4**	<3
Well 3-13	08/29/02	0900	<2	<2	<3	<3	<2	<2	<6	<3
Well 3-38	09/05/02	1030	<2	<2	<3	<3	<2	<2	<6	<3
Well 4-14	08/30/02	0930	<2	<2	<3	<3	<2	<2	<6	<3
					Quality-assurance samples					
Well 1-23 (Sequential duplicate)	08/28/02	1415	<2	<2	<3	<3	<2	<2	<6	<3
Well 2-15 (Equipment blank)	08/26/02	1800	<2	<2	<3	<3	<2	<2	<6	<3

Table 14. Concentrations of semivolatile organic compounds in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; mg/L, milligram per liter; µg/L, microgram per liter; < , less than; E, estimated value below reporting limit; **bold** values indicate compound detected in sample; all concentrations are reported as unfiltered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Hexachloro-cyclo-pentadiene (µg/L)	Diethyl phthalate (µg/L)	Dimethyl phthalate (µg/L)	Di-n-butyl phthalate (µg/L)	Di-n-octyl phthalate (µg/L)	Fluoranthene (µg/L)	Fluorene (µg/L)	Hexa-chloro-benzene (µg/L)
Water samples										
Well 1-16	08/28/02	0900	<4	<2	<2	<2	<5	<2	<2	<2
Well 1-23	08/28/02	1345	<4	<2	<2	<2	<5	<2	<2	<2
Well 2-15	08/27/02	0915	<4	<2	<2	<2	<5	<2	<2	<2
Well 2-26	08/27/02	1400	<4	<2	<2	<2	<5	<2	<2	<2
Well 3-13	08/29/02	0900	<4	<2	<2	<2	<5	<2	<2	<2
Well 3-38	09/05/02	1030	<4	<2	<2	<2	<5	<2	<2	<2
Well 4-14	08/30/02	0930	<4	<2	<2	<2	<5	<2	<2	<2
Quality-assurance samples										
Well 3-13 (Sequential duplicate)	08/28/02	1415	<4	<2	<2	<2	<5	<2	<2	<2
Well 2-15 (Equipment blank)	08/26/02	1800	<4	<2	<2	<2	<5	<2	<2	<2

Table 14. Concentrations of semivolatile organic compounds in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; mg/L, milligram per liter; µg/L, microgram per liter; < , less than; E, estimated value below reporting limit; **bold** values indicate compound detected in sample; all concentrations are reported as unfiltered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Indeno [1,2,3-cd] pyrene (µg/L)	Isophorone (µg/L)	Butyl-benzyl phthalate (µg/L)	N-nitroso-dimethyl-amine (µg/L)	N-nitrosodi-n-propyl-amine (µg/L)	N-nitroso-diphenyl-amine (µg/L)	4-Chloro-3-methyl-phenol (mg/L)	Penta-chloro-phenol (µg/L)
Water samples										
Well 1-16	08/28/02	0900	<3	<2	<4	<3	<2	<2	<3	<4
Well 1-23	08/28/02	1345	<3	<2	<4	<3	<2	<2	<3	<4
Well 2-15	08/27/02	0915	<3	<2	<4	<3	<2	<2	<3	<4
Well 2-26	08/27/02	1400	<3	<2	<4	<3	<2	<2	<3	<4
Well 3-13	08/29/02	0900	<3	<2	<4	<3	<2	<2	<3	<4
Well 3-38	09/05/02	1030	<3	<2	<4	<3	<2	<2	<3	<4
Well 4-14	08/30/02	0930	<3	<2	<4	<3	<2	<2	<3	<4
Quality-assurance samples										
Well 1-23 (Sequential duplicate)	08/28/02	1415	<3	<2	<4	<3	<2	<2	<3	<4
Well 2-15 (Equipment blank)	08/26/02	1800	<3	<2	<4	<3	<2	<2	<3	<4

Table 14. Concentrations of semivolatile organic compounds in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; mg/L, milligram per liter; µg/L, microgram per liter; < , less than; E, estimated value below reporting limit; **bold** values indicate compound detected in sample; all concentrations are reported as unfiltered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Phenanthrene (µg/L)	Phenol (µg/L)	Pyrene (µg/L)
			Water samples		
Well 1-16	08/28/02	0900	<2	<3	<2
Well 1-23	08/28/02	1345	<2	<3	<2
Well 2-15	08/27/02	0915	<2	<3	<2
Well 2-26	08/27/02	1400	<2	<3	<2
Well 3-13	08/29/02	0900	<2	<3	<2
Well 3-38	09/05/02	1030	<2	<3	<2
Well 4-14	08/30/02	0930	<2	<3	<2
			Quality-assurance samples		
Well 1-23 (Sequential duplicate)	08/28/02	1415	<2	<3	<2
Well 2-15 (Equipment blank)	08/26/02	1800	<2	<3	<2

Table 15. Concentrations of wastewater-related organic compounds in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.

[mm/dd/yy, month/day/year; hhmm, hours and minutes; µg/L, microgram per liter; < , less than; E, estimated value below reporting limit; **bold** values indicate compound detected in sample; Q, concentration estimated because relative percent difference between environmental and sequential duplicate samples was greater than 25 percent; all concentrations are reported as filtered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	1-Methyl-napthalene (µg/L)	2,6-Dimethyl-napthalene (µg/L)	2-Methyl-napthalene (µg/L)	3-Beta-coprostanol (µg/L)	3-Methyl-1(H)-indole (µg/L)	3-tert-Butyl-4-hydroxy anisole (µg/L)
Water samples								
Well 1-16	08/28/02	0900	<0.5	<0.5	<0.5	<2	<1	<5
Well 1-23	08/28/02	1345	<.5	<.5	<.5	<2	<1	<5
Well 2-15	08/27/02	0915	<.5	<.5	<.5	<2	<1	<5
Well 2-26	08/27/02	1400	<.5	<.5	<.5	<2	<1	<5
Well 3-13	08/29/02	0900	<.5	<.5	<.5	<2	<1	<5
Well 3-38	09/05/02	1030	<.5	<.5	<.5	<2	<1	<5
Well 4-14	08/30/02	0930	<.5	<.5	<.5	<2	<1	<5
Quality-assurance samples								
Well 1-23 (Sequential duplicate)	08/28/02	1415	<.5	<.5	<.5	<2	<1	<5
Well 2-15 (Equipment blank)	08/26/02	1800	<.5	<.5	<.5	<2	<1	<5

Table 15. Concentrations of wastewater-related organic compounds in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; µg/L, microgram per liter; < , less than; E, estimated value below reporting limit; **bold** values indicate compound detected in sample; Q, concentration estimated because relative percent difference between environmental and sequential duplicate samples was greater than 25 percent; all concentrations are reported as filtered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	4-Cumyl-phenol (µg/L)	4-n-Octyl-phenol (µg/L)	4-tert-Octyl-phenol (µg/L)	5-Methyl-1H-benzo-triazole (µg/L)	Aceto-phenone (µg/L)	Acetyl hexa-methyl tetrahydro naphthalene (AHTN) (mg/L)	Anthracene, filtered (µg/L)	Anthraquinone (µg/L)
Water samples										
Well 1-16	08/28/02	0900	<1	<1	<1	<2	<0.5	<0.5	<0.5	<0.5
Well 1-23	08/28/02	1345	<1	<1	<1	<2	<.5	<.5	<.5	<.5
Well 2-15	08/27/02	0915	<1	<1	<1	<2	<.5	<.5	<.5	<.5
Well 2-26	08/27/02	1400	<1	<1	<1	<2	<.5	<.5	<.5	<.5
Well 3-13	08/29/02	0900	<1	<1	<1	<2	<.5	<.5	<.5	<.5
Well 3-38	09/05/02	1030	<1	<1	<1	<2	<.5	<.5	<.5	<.5
Well 4-14	08/30/02	0930	<1	<1	<1	<2	<.5	<.5	<.5	<.5
Quality-assurance samples										
Well 1-23 (Sequential duplicate)	08/28/02	1415	<1	<1	<1	<2	<.5	<.5	<.5	<.5
Well 2-15 (Equipment blank)	08/26/02	1800	<1	<1	<1	<2	<.5	<.5	<.5	<.5

Table 15. Concentrations of wastewater-related organic compounds in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; µg/L, microgram per liter; < , less than; E, estimated value below reporting limit; **bold** values indicate compound detected in sample; Q, concentration estimated because relative percent difference between environmental and sequential duplicate samples was greater than 25 percent; all concentrations are reported as filtered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Benzo[a]-pyrene (µg/L)	Benzo-phenone (µg/L)	beta-Sitosterol (µg/L)	Bisphenol A (µg/L)	Camphor (µg/L)	Carbazole (µg/L)	Cholesterol (µg/L)
Water samples									
Well 1-16	08/28/02	0900	<0.5	<0.5	<2	<1	<0.5	<0.5	<2
Well 1-23	08/28/02	1345	<.5	<.5	<2	<1	<.5	<.5	<2
Well 2-15	08/27/02	0915	<.5	<.5	<2	<1	<.5	<.5	<2
Well 2-26	08/27/02	1400	<.5	<.5	<2	<1	<.5	<.5	<2
Well 3-13	08/29/02	0900	<.5	<.5	<2	<1	<.5	<.5	<2
Well 3-38	09/05/02	1030	<.5	<.5	<2	<1	<.5	<.5	<2
Well 4-14	08/30/02	0930	<.5	<.5	<2	<1	<.5	<.5	<2
Quality-assurance samples									
Well 1-23 (Sequential duplicate)	08/28/02	1415	<.5	<.5	<2	<1	<.5	<.5	<2
Well 2-15 (Equipment blank)	08/26/02	1800	<.5	<.5	<2	<1	<.5	<.5	<2

Table 15. Concentrations of wastewater-related organic compounds in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; µg/L, microgram per liter; < , less than; E, estimated value below reporting limit; **bold** values indicate compound detected in sample; Q, concentration estimated because relative percent difference between environmental and sequential duplicate samples was greater than 25 percent; all concentrations are reported as filtered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Cotinine (µg/L)	d-Limonene (µg/L)	Fluoranthene (µg/L)	Hexahydro-hexamethyl-cyclopenta-benzopyran (µg/L)	Indole (µg/L)	Isoborneol (µg/L)	Isophorone (µg/L)	Isopropyl-benzene (µg/L)
Water samples										
Well 1-16	08/28/02	0900	<1	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Well 1-23	08/28/02	1345	<1	<.5	<.5	<.5	<.5	<.5	<.5	<.5
Well 2-15	08/27/02	0915	<1	<.5	<.5	<.5	<.5	<.5	<.5	<.5
Well 2-26	08/27/02	1400	<1	<.5	<.5	<.5	<.5	<.5	<.5	<.5
Well 3-13	08/29/02	0900	<1	<.5	<.5	<.5	<.5	<.5	<.5	<.5
Well 3-38	09/05/02	1030	<1	<.5	<.5	<.5	<.5	<.5	[1]**E.2**	<.5
Well 4-14	08/30/02	0930	<1	<.5	<.5	<.5	<.5	<.5	<.5	<.5
Quality-assurance samples										
Well 1-23 (Sequential duplicate)	08/28/02	1415	<1	<.5	<.5	<.5	<.5	<.5	<.5	<.5
Well 2-15 (Equipment blank)	08/26/02	1800	<1	<.5	<.5	<.5	<.5	<.5	**E.2**	<.5

Table 15. Concentrations of wastewater-related organic compounds in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; µg/L, microgram per liter; < , less than; E, estimated value below reporting limit; **bold** values indicate compound detected in sample; Q, concentration estimated because relative percent difference between environmental and sequential duplicate samples was greater than 25 percent; all concentrations are reported as filtered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Isoquinoline (µg/L)	Menthol (µg/L)	Methyl salicylate (µg/L)	N,N-diethyl-meta-toluamide (µg/L)	Napthalene (µg/L)	Diethoxy-nonyl-phenol (µg/L)	Diethoxy-octyl-phenol (µg/L)	Mono-ethoxy-octyl-phenol (µg/L)
					Water samples					
Well 1-16	08/28/02	0900	<0.5	<0.5	<0.5	[1]**E0.07**	<0.5	<5	<1	<1
Well 1-23	08/28/02	1345	<.5	<.5	<.5	[1]**E.18**	<.5	<5	<1	<1
Well 2-15	08/27/02	0915	<.5	<.5	<.5	[1]**E.19**	<.5	<5	<1	<1
Well 2-26	08/27/02	1400	<.5	<.5	<.5	[1]**E.25**	<.5	<5	<1	<1
Well 3-13	08/29/02	0900	<.5	<.5	<.5	[1]**Q,E.07**	<.5	<5	<1	<1
Well 3-38	09/05/02	1030	<.5	<.5	<.5	[1]**E.1**	<.5	<5	<1	<1
Well 4-14	08/30/02	0930	<.5	<.5	<.5	[1]**E.05**	<.5	<5	<1	<1
					Quality-assurance samples					
Well 3-13 (Sequential duplicate)	08/28/02	1415	<.5	<.5	<.5	[1]**E.03**	<.5	<5	<1	<1
Well 2-15 (Equipment blank)	08/26/02	1800	<.5	<.5	<.5	[1]**E.38**	<.5	<5	<1	<1

Table 15. Concentrations of wastewater-related organic compounds in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; µg/L, microgram per liter; < , less than; E, estimated value below reporting limit; **bold** values indicate compound detected in sample; Q, concentration estimated because relative percent difference between environmental and sequential duplicate samples was greater than 25 percent; all concentrations are reported as filtered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	p-Cresol (µg/L)	p-Nonyl-phenol (µg/L)	Penta-chloro-phenol (µg/L)	Phenan-threne (µg/L)	Phenol (µg/L)	Pyrene (µg/L)	Stigma-stanol (µg/L)	Tetra-chloro-ethene (µg/L)	Tri (2-chloro-ethyl) phosphate (µg/L)
Water samples											
Well 1-16	08/28/02	0900	<1	<5	<2	<0.5	<0.5	<0.5	<2	<0.5	<0.5
Well 1-23	08/28/02	1345	<1	<5	<2	<.5	<.5	<.5	<2	<.5	<.5
Well 2-15	08/27/02	0915	<1	<5	<2	<.5	<.5	<.5	<2	<.5	<.5
Well 2-26	08/27/02	1400	<1	<5	<2	<.5	<.5	<.5	<2	<.5	<.5
Well 3-13	08/29/02	0900	<1	<5	<2	<.5	<.5	<.5	<2	<.5	<.5
Well 3-38	09/05/02	1030	<1	<5	<2	<.5	.5	<.5	<2	**E.1**	<.5
Well 4-14	08/30/02	0930	<1	<5	<2	<.5	<.5	<.5	<2	<.5	<.5
Quality-assurance samples											
Well 1-23 (Sequential duplicate)	08/28/02	1415	<1	<5	<2	<.5	<.5	<.5	<2	<.5	<.5
Well 2-15 (Equipment blank)	08/26/02	1800	<1	<5	<2	<.5	<.5	<.5	<2	<.5	<.5

Table 15. Concentrations of wastewater-related organic compounds in water samples from the upper aquifer near Richmond, Indiana, and in quality-assurance samples, 2002.—Continued

[mm/dd/yy, month/day/year; hhmm, hours and minutes; µg/L, microgram per liter; < , less than; E, estimated value below reporting limit; **bold** values indicate compound detected in sample; Q, concentration estimated because relative percent difference between environmental and sequential duplicate samples was greater than 25 percent; all concentrations are reported as filtered constituents]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Tributyl phosphate (µg/L)	Triclosan (µg/L)	Triethyl citrate (µg/L)	Triphenyl phosphate (µg/L)	Tri (2-butoxy-ethyl) phosphate (mg/L)	Tri (2-chloro-ethyl) phosphatel (mg/L)	Tris (dichloro-isopropyl) phosphate (mg/L)	Dichlorvos (µg/L)
Water samples										
Well 1-16	08/28/02	0900	<0.5	<1	<0.5	<0.5	<0.5	<0.5	<0.5	<1
Well 1-23	08/28/02	1345	<.5	<1	<.5	<.5	<.5	<.5	<.5	<1
Well 2-15	08/27/02	0915	<.5	<1	<.5	<.5	<.5	<.5	<.5	<1
Well 2-26	08/27/02	1400	<.5	<1	<.5	<.5	<.5	<.5	<.5	<1
Well 3-13	08/29/02	0900	<.5	<1	<.5	<.5	<.5	<.5	<.5	<1
Well 3-38	09/05/02	1030	<.5	<1	<.5	<.5	<.5	<.5	<.5	<1
Well 4-14	08/30/02	0930	<.5	<1	<.5	<.5	<.5	<.5	<.5	<1
Quality-assurance samples										
Well 3-13 (Sequential duplicate)	08/28/02	1415	<.5	<1	<.5	<.5	<.5	<.5	<.5	<1
Well 2-15 (Equipment blank)	08/26/02	1800	<.5	<1	<.5	**E.004**	<.5	<.5	**E.02**	<1

[1] Reported concentrations in this analysis represent a potential sampling-related interference.

Buszka, Watson, Greeman—**Hydrogeology, Ground-Water-Age Dating, Water Quality, and Vulnerability of Ground Water to Contamination near Richmond, Indiana, 2002–03**—Scientific Investigations Report 2006–5281