GROUND-WATER QUALITY IN THE WESTERN PART OF THE CAMBRIAN-ORDOVICIAN AQUIFER IN THE WESTERN LAKE MICHIGAN DRAINAGES, WISCONSIN AND MICHIGAN

By David A. Saad

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NATIONAL WATER-QUALITY ASSESSMENT PROGRAM

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FOREWORD

The mission of the U.S. Geological Survey (USGS) is to assess the quantity and quality of the earth resources of the Nation and to provide information that will assist resource managers and policymakers at Federal, State, and local levels in making sound decisions. Assessment of water-quality conditions and trends is an important part of this overall mission.

One of the greatest challenges faced by water-resources scientists is acquiring reliable information that will guide the use and protection of the Nation's water resources. That challenge is being addressed by Federal, State, interstate, and local water-resource agencies and by many academic institutions. These organizations are collecting water-quality data for a host of purposes that include: compliance with permits and water-supply standards; development of remediation plans for specific contamination problems; operational decisions on industrial, wastewater, or water-supply facilities; and research on factors that affect water quality. An additional need for water-quality information is to provide a basis on which regional- and national-level policy decisions can be based. Wise decisions must be based on sound information. As a society we need to know whether certain types of water-quality problems are isolated or ubiquitous, whether there are significant differences in conditions among regions, whether the conditions are changing over time, and why these conditions change from place to place and over time. The information can be used to help determine the efficacy of existing water-quality policies and to help analysts determine the need for and likely consequences of new policies.

To address these needs, the U.S. Congress appropriated funds in 1986 for the USGS to begin a pilot program in seven project areas to develop and refine the National Water-Quality Assessment (NAWQA) Program. In 1991, the USGS began full implementation of the program. The NAWQA Program builds upon an existing base of water-quality studies of the USGS, as well as those of other Federal, State, and local agencies. The objectives of the NAWQA Program are to:

- Describe current water-quality conditions for a large part of the Nation's freshwater streams, rivers, and aquifers.
- Describe how water quality is changing over time.
- Improve understanding of the primary natural and human factors that affect water-quality conditions.

This information will help support the development and evaluation of management, regulatory, and monitoring decisions by other Federal, State, and local agencies to protect, use, and enhance water resources.

The goals of the NAWQA Program are being achieved through ongoing and proposed investigations of 60 of the Nation's most important river basins and aquifer systems, which are referred to as study units. These study units are distributed throughout the Nation and cover a diversity of hydrogeologic settings. More than two-thirds of the Nation's freshwater use occurs within the 60 study units and more than two-thirds of the people served by public water-supply systems live within their boundaries.

National synthesis of data analysis, based on aggregation of comparable information obtained from the study units, is a major component of the program. This effort focuses on selected water-quality topics using nationally consistent information. Comparative studies will explain differences and similarities in observed water-quality conditions among study areas and will identify changes and trends and their causes. The first topics addressed by the national synthesis are pesticides, nutrients, volatile organic compounds, and aquatic biology. Discussions on these and other water-quality topics will be published in periodic summaries of the quality of the Nation's ground and surface water as the information becomes available.

This report is an element of the comprehensive body of information developed as part of the NAWQA Program. The program depends heavily on the advice, cooperation, and information from many Federal, State, interstate, Tribal, and local agencies and the public. The assistance and suggestions of all are greatly appreciated.

Robert M. Hirsch

Robert M. Hirsch
Chief Hydrologist

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

Multiply	By	To Obtain
feet (ft)	0.3048	meter (m)
square mile (mi^2)	2.59	square kilometer (km^2)
pound (lb)	453,600	milligram (mg)
gallon (gal)	3.785	liter (L)

Temperature, in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) by use of the following equation:

$$°F = [1.8(°C)] + 32.$$

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

Abbreviated water-quality units: Chemical concentrations and water temperature are given in metric units. Chemical concentration is given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to one milligram per liter. For concentrations less than 7,000 mg/L, the numerical value is the same as for concentrations in parts per million.

Radioactivity is expressed in picocuries per liter (pCi/L). A picocurie is the amount of radioactivity that yields 2.22 radioactive disintegrations per minute.

MISCELLANEOUS ABBREVIATIONS

DOC	Dissolved organic carbon
ES	Enforcement Standard
GIS	Geographic information system
NWQL	National Water Quality Laboratory
MDL	Laboratory Method Detection Limit
MCL	Maximum Contaminant Level
NAWQA	National Water-Quality Assessment
as HCO_3^-	as quantified as measured bicarbonate
as N	as quantified as measured nitrogen
as P	as quantified as measured phosphorus
PAL	Preventive Action Limit
PMCL	Proposed Maximum Contaminant Level
SMCL	Secondary Maximum Contaminant Level
USEPA	United States Environmental Protection Agency
USGS	U.S. Geological Survey
VOCs	Volatile organic compounds

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Ground-Water Quality in the Western Part of the Cambrian-Ordovician Aquifer in the Western Lake Michigan Drainages, Wisconsin and Michigan

By David A. Saad

Abstract

Ground-water samples were collected during the summer of 1995 from 29 wells in the western part of the Cambrian-Ordovician aquifer in the Western Lake Michigan Drainages study unit of the National-Water Quality Assessment Program. Analyses of ground-water samples from these wells were used to provide an indication of water-quality conditions in this heavily used part of the aquifer.

Ground-water samples from domestic, institutional, and public-supply wells were analyzed for major ions, nutrients, dissolved organic carbon (DOC), pesticides, volatile organic compounds (VOCs), radon-222, and tritium, as well as field measurements of temperature, pH, specific conductance, dissolved oxygen, and bicarbonate. The results of water-quality analyses indicate that the presence of the Maquoketa-Sinnipee confining unit has an important effect on the ground-water quality in the study area. Where the study area is overlain by the confining unit (that is, where it is regionally confined) sampled water was older (based on tritium analyses) and often contained relatively high concentrations of dissolved solids, up to 2,800 mg/L. Additionally, contaminants such as nitrate and pesticides were typically detected at lower concentrations and detected less frequently in samples from the regionally confined part of the study area.

The dominant ions in samples from the study area were calcium, magnesium, and bicarbonate which resulted from the dissolution of carbonate minerals such as dolomite and calcite. Sulfate was also a dominant ion in water from some of the deeper wells in the regionally confined part of the study area.

Radon-222 was detected in all samples and 66 percent (19 of 29) had concentrations that exceed the U.S Environmental Protection Agency (USEPA) proposed maximum concentration level of 300 pCi/L. Concentrations greater than 300 pCi/L were detected in samples from wells throughout most of the study area except the southwest. The higher concentrations were found in samples from a variety of geohydrologic conditions and do not appear to correlate to a particular formation or location.

Dissolved nitrate and ammonium were the most commonly detected nutrients. Dissolved nitrate concentrations were significantly higher in ground-water samples from the regionally unconfined part of the study area. The highest concentrations were detected in samples from the agricultural southwestern part of the study area from relatively shallow wells that produced modern water. Dissolved ammonium concentrations were significantly higher in samples from the regionally confined part of the study area and probably resulted from nitrate reduction.

Seven pesticides or metabolites were detected in ground-water samples, and at least one pesticide was detected in samples from 24 percent (7 of 29) of wells. Most of the pesticides were detected at low concentrations and were from wells in the regionally unconfined, agricultural, southwest part of the study area. Atrazine was the most commonly detected pesticide and was typically detected in samples from wells that produced modern water.

INTRODUCTION

The Western Lake Michigan Drainages study unit of the National Water-Quality Assessment (NAWQA) Program encompasses an area of about

19,900 square miles in eastern Wisconsin and central Upper Michigan (fig. 1). Collection and analysis of ground-water data in the study unit began in 1993. The NAWQA design for examining ground-water quality includes flowpath studies, land-use studies, and study-unit surveys (Gilliom and others, 1995). Flowpath studies are generally small in scale and are designed to examine ground-water quality along inferred flowpaths and interactions of ground water and surface water. Land-use studies are designed to examine natural and human factors that affect shallow ground-water quality in an area characterized by a specific land use and typically cover an area ranging from several hundred to several thousand square miles. Study-unit surveys are designed to provide an indication of water-quality conditions in the major aquifers or defined hydrogeologic settings in a study unit and typically cover an area ranging from several thousand to tens of thousands of square miles.

The Western Lake Michigan Drainages study unit includes parts of three major aquifers: the Cambrian-Ordovician aquifer; the Silurian-Devonian aquifer; and the Quaternary aquifers. The Cambrian-Ordovician aquifer underlies the eastern two-thirds of the study unit (fig. 2) and, where it is sufficiently thick, can produce large yields of water; typically 500 to 1,000 gallons per minute to properly constructed wells (Olcott, 1968). For this reason, it is the most used aquifer in the study unit and accounts for about 40 percent of ground-water use. Because it is the most used aquifer, the Cambrian-Ordovician aquifer was chosen as the first aquifer to be examined as part of the study-unit survey in the Western Lake Michigan Drainages. The western part of the Cambrian-Ordovician aquifer was further targeted for study because few wells exist in the eastern part of the aquifer where it is overlain by the more readily accessible Silurian-Devonian and Quaternary aquifers.

Purpose and Scope

The purpose of this report is to provide an indication of the water-quality conditions in the western part of the Cambrian-Ordovician aquifer in the Western Lake Michigan Drainages NAWQA study unit. Well-water samples were collected and analyzed to determine the concentrations of major ions, nutrients, dissolved organic carbon (DOC), 85 pesticides or metabolites, 60 volatile organic compounds (VOCs), radon-222, and tritium; field measurements of temperature, pH, specific conductance, dissolved oxygen, and bicarbonate were also collected. The samples were collected between June, 1995 and September, 1995 from 29 existing wells in the western part of the Cambrian-Ordovician aquifer in eastern Wisconsin and central Upper Michigan.

Interpretations made in this report were based on wells that were randomly located throughout the western part of the Cambrian-Ordovician aquifer. Ground-water quality information from this study and future studies of the other major aquifers will be useful for three purposes: (1) comparing the water quality from similar aquifers in different parts of the country; (2) examining regional differences in the water quality of an aquifer and between the aquifers in the NAWQA study unit; and (3) providing a starting point for examining long-term trends in the water quality of the major aquifers.

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DESCRIPTION OF STUDY AREA

The study area includes the Cambrian-Ordovician aquifer in the Western Lake Michigan Drainages west of the western extent of the Silurian-Devonian aquifer and underlies an area of about 8,100 square miles (fig. 2). Land use/land cover overlying the study area [based on Anderson's land-use/land-cover categories (Anderson and others, 1976)] is mainly forest and forested wetland in the north and agricultural in the south (fig. 3). Forest and forested wetland accounts of the largest percentage of land use/land cover (45 per-

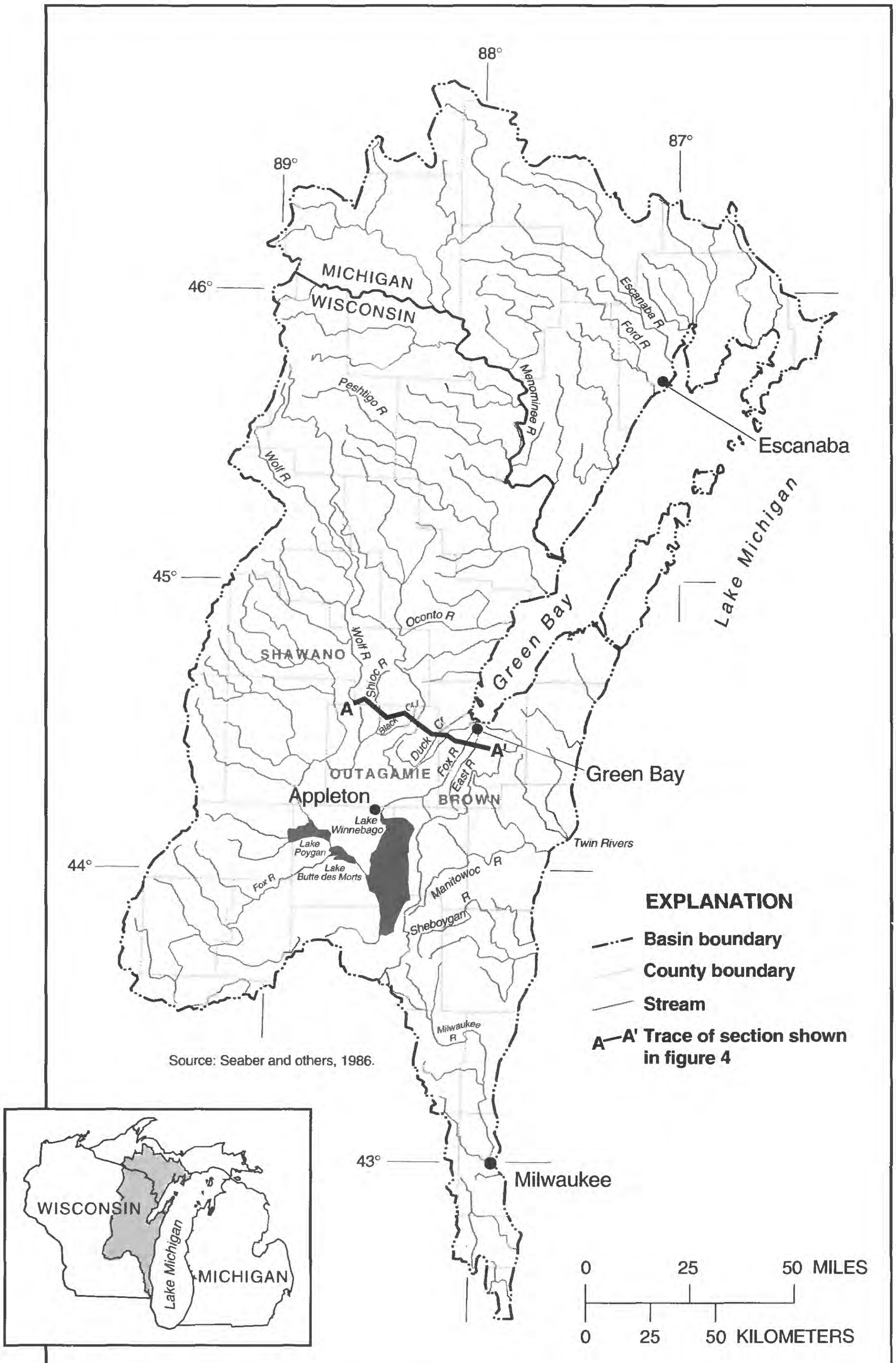


Figure 1. Western Lake Michigan Drainages study unit of the National Water-Quality Assessment program.

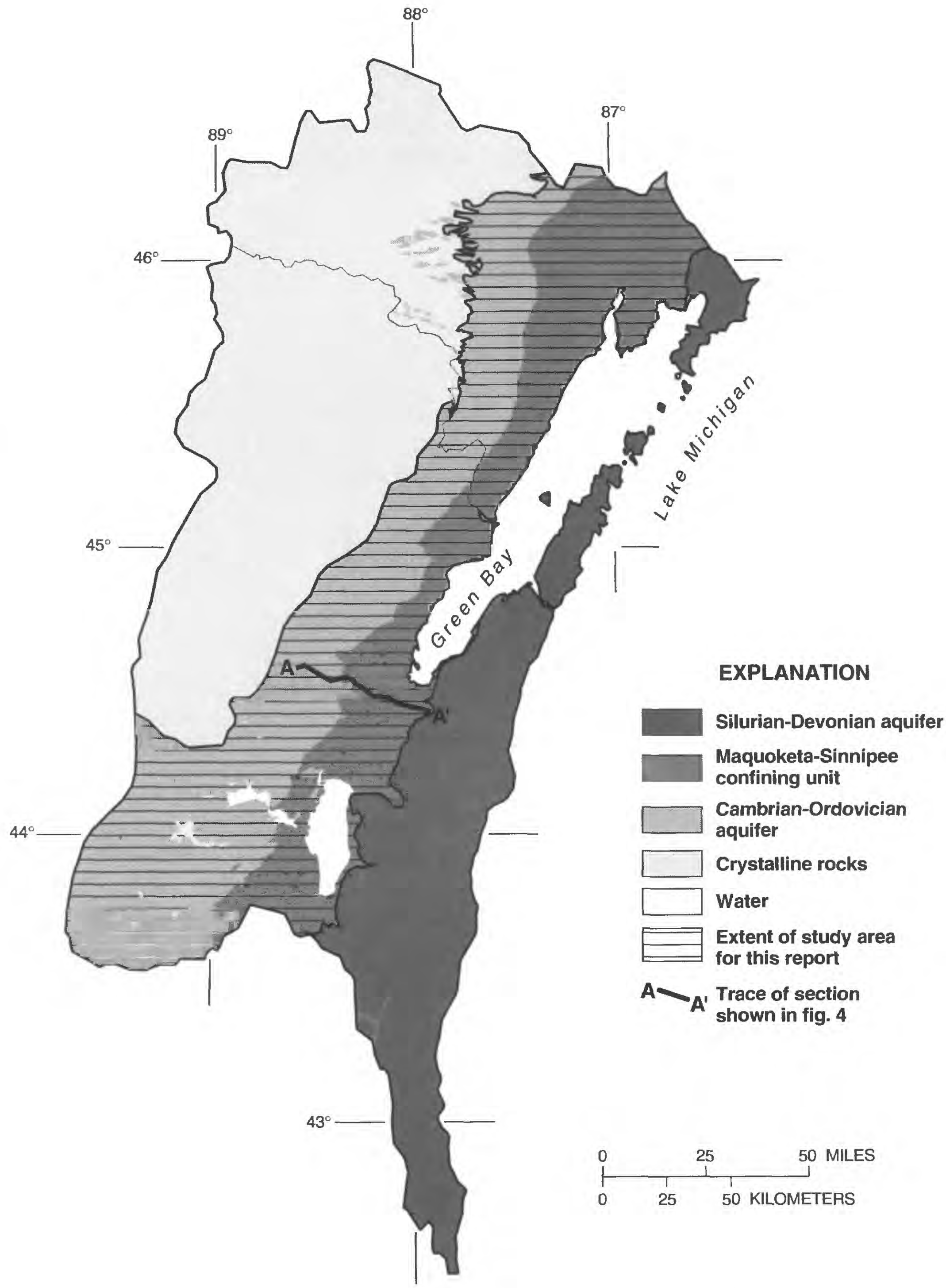
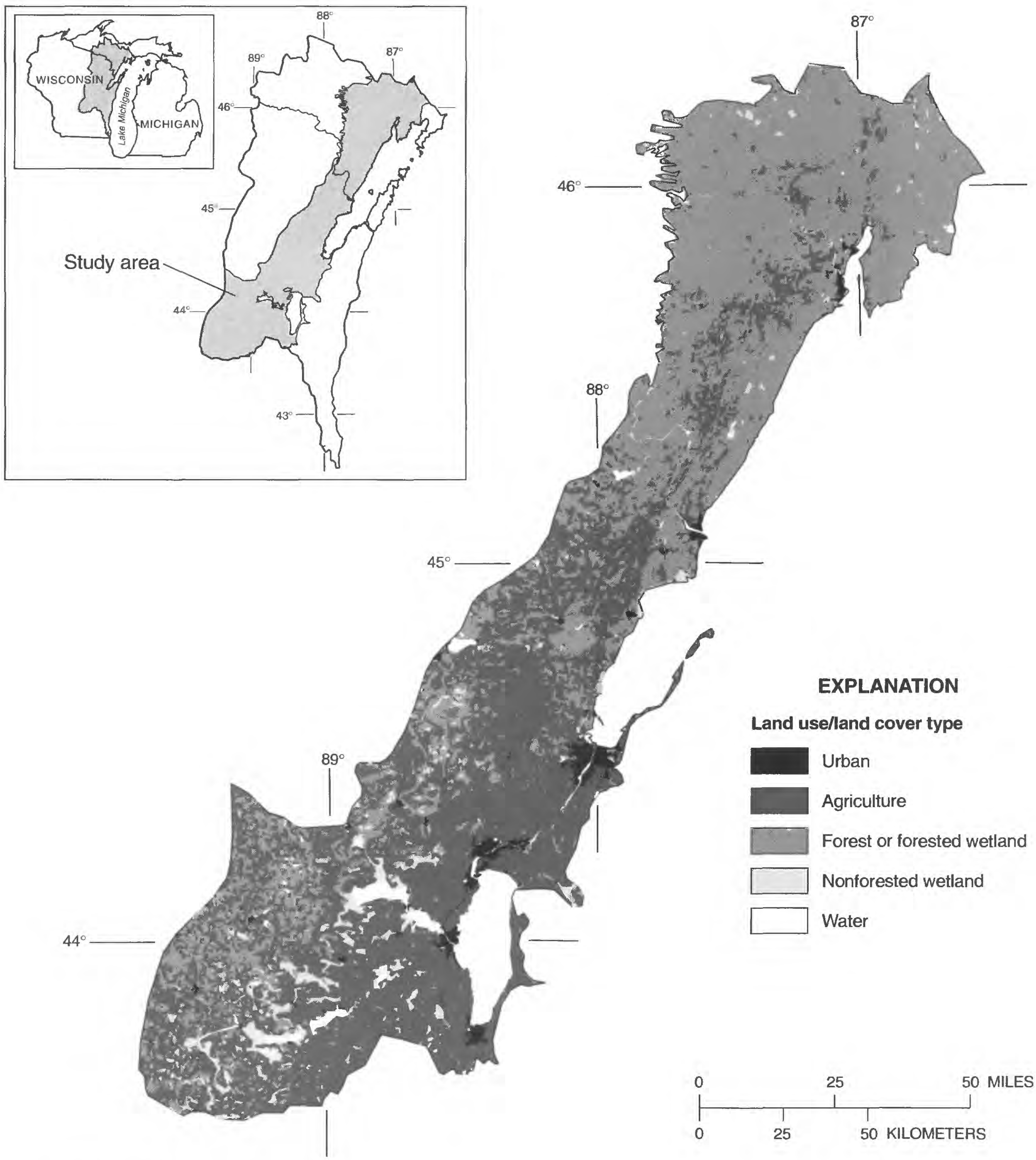


Figure 2. Location of study area and bedrock-surface extent of bedrock aquifers and confining units in the Western Lake Michigan Drainages.



Land use/land cover categories from Anderson and others (1976).

Figure 3. Distribution of land use/land cover in the study area.

Table 1. Hydrogeologic units in the vicinity of the study area
[Modified from Olcott, 1992; Batten and Bradbury, 1996]

<table>
<tr><th>Geologic age</th><th>Nomenclature used in this report</th><th>Hydrogeologic units in Wisconsin and Michigan</th><th>Principal lithology</th></tr>
<tr><td>Quaternary</td><td>Quaternary aquifers</td><td>Quaternary aquifers</td><td>Unconsolidated sediments of gravel, sand, silt, and clay</td></tr>
<tr><td>Silurian-Devonian</td><td>Silurian-Devonian aquifer</td><td>Silurian-Devonian aquifer</td><td>Dolomite, limestone, and shale</td></tr>
<tr><td rowspan="2">Ordovician</td><td>Maquoketa-Sinnipee confining unit</td><td>Maquoketa-Sinnipee confining unit</td><td>Shale and dolomite</td></tr>
<tr><td rowspan="3">Cambrian-Ordovician aquifer</td><td>St. Peter aquifer</td><td>Sandstone and dolomite</td></tr>
<tr><td rowspan="2">Cambrian</td><td>St. Lawrence-Tunnel City confining unit</td><td>Dolomite and fine-grained sandstone</td></tr>
<tr><td>Elk Mound aquifer</td><td>Sandstone</td></tr>
<tr><td>Precambrian</td><td>Crystalline rocks</td><td>Crystalline rocks</td><td>Crystalline rocks</td></tr>
</table>

cent) in the study area, followed by agriculture (44 percent), water (4 percent), nonforested wetland (3 percent), and urban (3 percent). Urban land use in the study area is located mainly along the shores of Lake Winnebago and in the lower Fox River valley from Appleton to Green Bay. Most of the larger urban areas in the study area obtain the majority of their water from surface-water sources, such as Lake Winnebago, but some supplement this source with ground water primarily from the Cambrian-Ordovician aquifer.

Geohydrologic Setting

The bedrock units in the vicinity of the study area dip southeast towards Lake Michigan; the oldest rocks subcrop in the northwest and the youngest subcrop in the southeast (fig. 4). The Cambrian-Ordovician aquifer in the vicinity of the study area consists principally of Cambrian- and Ordovician-age sandstone and dolomite (table 1). Although some researchers have defined several aquifers within the Cambrian-Ordovician aquifer (Krohelski, 1986; Emmons, 1987; Mandle and Kontis, 1992; and Olcott, 1992), it is defined as one aquifer for the purposes of this study. The Cambrian-Ordovician aquifer is underlain by Precambrian-age crystalline rocks which are assumed to be impermeable (fig. 4). In the eastern half of the study area, the Cambrian-Ordovician aquifer is overlain by the Maquoketa-Sinnipee confining unit (figs. 2 and 4) which consists of Ordovician-age shale and dolomite. In the western half of the study area, the Cambrian-Ordovician aquifer is overlain by Quaternary-age unconsolidated deposits that vary in texture from sand and gravel to clay. Where the unconsolidated deposits are sufficiently thick and permeable they comprise the Quaternary aquifers (fig. 4). The geology of the area is described in more detail by Krohelski (1986), Emmons (1987), Olcott (1992), Young (1992), and Batten and Bradbury (1996).

Where the Cambrian-Ordovician aquifer is overlain by the Maquoketa-Sinnipee confining unit, it is regionally confined. Elsewhere in the study area, the aquifer is unconfined, except locally where it is overlain by fine grained unconsolidated deposits.

Recharge and Flow

Recharge to the Cambrian-Ordovician aquifer is from precipitation and direct infiltration where it is unconfined (Young, 1992, p. 58). Some recharge to the aquifer can also occur by leakage through the Maquoketa-Sinnipee confining unit (Krohelski, 1986; Young, 1992). Prior to development as a water source, ground water in the Cambrian-Ordovician aquifer discharged to surface-water bodies. Some ground water also moved along deep, regional flow paths down the structural bedrock dip beneath Lake Michigan. Since, development, ground water also flows toward pumping centers where it is withdrawn. In the western part of the study area, wells that withdraw water from the Cam-

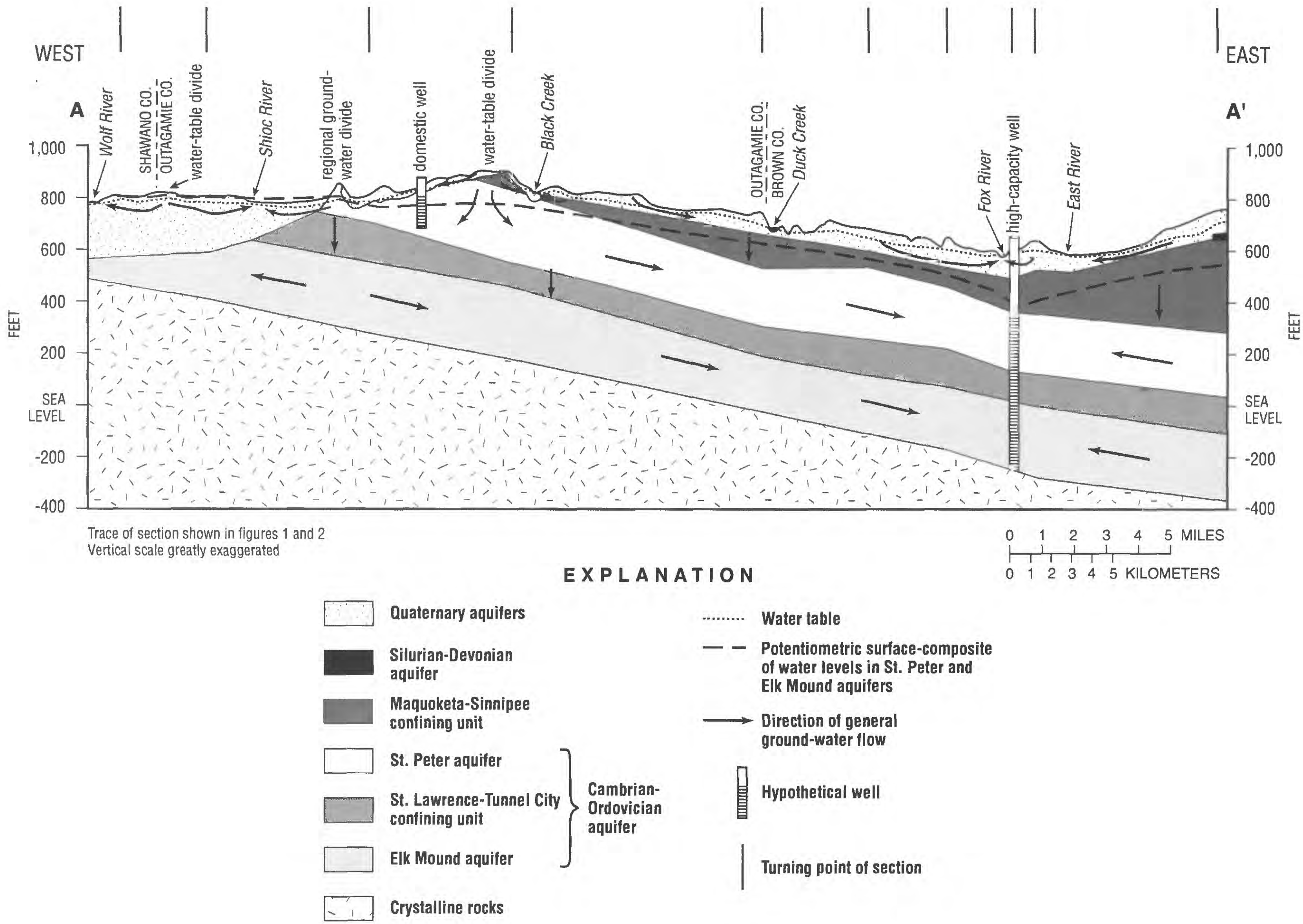


Figure 4. Hydrogeologic section through the study area.

brian-Ordovician aquifer are typically shallow and used for domestic purposes. In the eastern part of the study area, deeper, high-capacity wells are common and are concentrated in urban areas. Large cones of depression have developed at some of the major pumping centers such as in the lower Fox River Valley near Green Bay, Wisconsin (fig. 4).

STUDY DESIGN AND METHODS

This study was designed to provide an indication of the water-quality conditions in the western part of the Cambrian-Ordovician aquifer. Sampling locations consist of existing wells which were randomly selected throughout the study area.

Well Selection

Sampling locations were selected from existing wells identified from USGS and Wisconsin Department of Natural Resources (WDNR) digital databases, and Wisconsin Geological and Natural History Survey (WGNHS) and Michigan Department of Natural Resources (MDNR) paper files. All wells considered for sampling were identified as being open to the Cambrian-Ordovician aquifer and used for domestic, institutional, or public-supply purposes.

Potential sampling locations were initially chosen from an area that included all of the Cambrian-Ordovician aquifer in the Western Lake Michigan Drainages. An attempt was made to choose 30 wells from 1,251 existing wells in USGS and WDNR digital databases using a geographic information system (GIS)-based, stratified-random selection computer program (Scott, 1990). The computer program divided the entire area into 30 cells of equal area and then randomly chose a sampling location (as well as several alternative locations) from the existing USGS and WNDR sites that fell within a cell. All randomly selected wells were verified, based on driller's or geologic logs, to be open only to the Cambrian-Ordovician aquifer. Many of the cells in the eastern part of the area contained no wells from which to choose and the few cells that did contain potential sampling locations mostly included wells that were open to more than just the Cambrian-Ordovician aquifer. The study area was reduced to the western part of the Cambrian-Ordovician aquifer which was again divided into 30 cells of equal area. Wells randomly selected from the original area and verified to be open only to the Cambrian-Ordovician aquifer were used in the new area where possible and additional wells were randomly selected in other cells that required potential sampling locations. Cells that still did not contain a well from the USGS or WDNR databases were supplemented with wells identified from WGNHS and MDNR paper files. If a potential sampling location could still not be found for a cell then an additional site was chosen in the closest nearby cell.

Potential sampling locations in each cell were field located and permission to sample was requested. If permission was granted then the well was inspected to determine if it was suitable for sampling. Wells were suitable for sampling if they were flowing or withdrew water using a positive-displacement pump (such as submersible of turbine pumps), and if a sample could be obtained from the discharge line at a point prior to any treatments, pressure tanks, or holding tanks. If permission to sample was not granted or a well was not suitable for sampling then one of the alternative locations for a cell was pursued.

Thirty sampling locations were selected in this manner, however, one of those locations was determined to be outside of the study area and was not included in this report. The resulting distribution of wells covers much of the study area (fig. 5) and includes a variety of land uses and hydrogeologic characteristics.

Well Descriptions

The 29 sampled wells in the study area included 22 domestic, 5 public supply, and 2 institutional wells (table 2). Three of the public supply wells had turbine pumps, and two of the domestic wells were flowing. The remaining wells used submersible pumps to withdraw ground water. Nineteen of 29 wells were open to regionally unconfined parts of the aquifer, and 10 wells were open to regionally confined parts of the aquifer (fig. 5). A well was considered regionally confined if the open interval was overlain by the Maquoketa-Sinnipee confining unit. Twenty-five of 29 wells are considered locally confined. A well was considered locally confined if the open interval was overlain by any unconsolidated deposits described as clay or hardpan. The wells range in depth from 31 to 870 ft deep, and water levels ranged from 3 ft above land surface to 196 ft below land surface. All wells were constructed of steel, and most were cased at least to the top of the

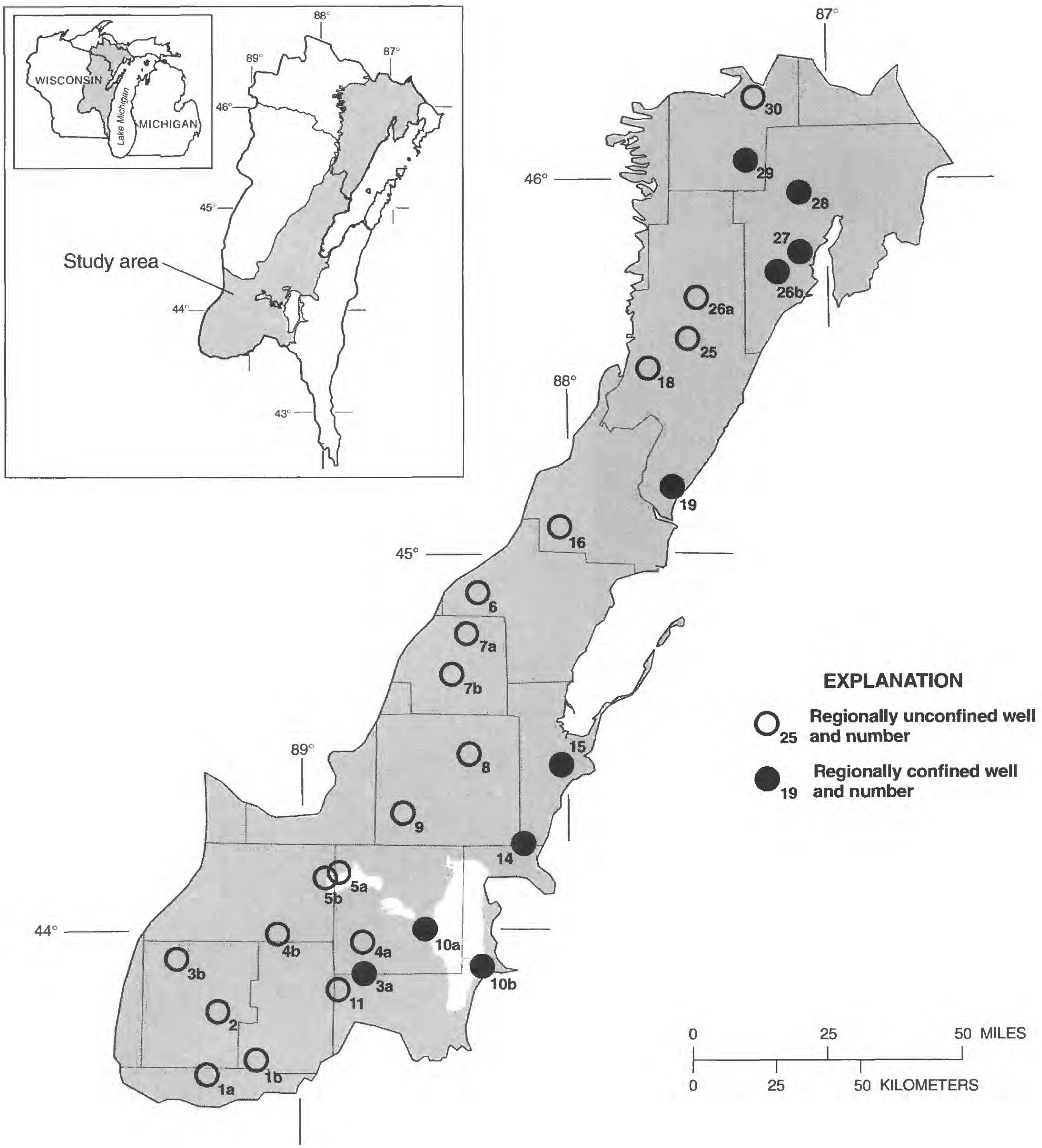


Figure 5. Location, well number, and regional aquifer condition of sampled wells.

Table 2. Location and characteristics of sampled wells in the western part of the Cambrian-Ordovician aquifer

[deg, degree; min, minute; sec, second; yyyy, year; mm, month; dd, day; --, no data]

Well number	Latitude longitude[1] (deg min sec)	Elevation, in feet above mean sea level	Well constr. date (yyyymmdd)	Water use[2]	Pump type[3]	Well depth, in feet below land surface	Water level, in feet below land surface[4]	Depth to top of open interval, in feet below land surface	Length of open interval, in feet	Depth to top of aquifer, in feet	Regionally confined[5]	Locally confined[6]	Land use[7]
Well 1a	43 37 34 89 21 04	822	19650520	H	sub	105	20.80	88	17	88	no	yes	a
Well 1b	43 40 04 89 10 07	855	19850404	H	sub	138	66.02	86	52	34	no	no	a
Well 2	43 47 45 89 18 48	845	19840712	T	sub	210	48.0*	179	31	154	no	yes	fu
Well 3a	43 53 54 88 46 09	895	--	H	sub	111	40.63	66	45	45	yes	yes	a
Well 3b	43 56 02 89 16 54	895	19871128	H	sub	179	40.00	125	54	93	no	no	a
Well 4a	43 59 07 88 46 25	835	--	H	sub	131	13.8*	78	53	70	no	yes	a
Well 4b	44 00 15 89 05 33	800	19880510	H	sub	95	15.30	63	32	55	no	yes	a
Well 5a	44 10 15 88 51 55	759	--	H	flow	95	-3.00	80	15	80	no	yes	a
Well 5b	44 09 20 88 54 55	757	19890911	H	flow	170	0.0*	146	24	83	no	yes	a
Well 6	44 55 04 88 09 41	905	19830620	H	sub	85	35.0*	73	12	60	no	yes	a
Well 7a	44 48 34 88 23 22	858	19890503	H	sub	140	33.10	117	23	60	no	yes	a
Well 7b	44 41 58 88 26 36	895	19881017	H	sub	125	51.50	97	28	42	no	yes	a
Well 8	44 29 12 88 22 41	785	--	H	sub	114	10.0*	114	0.0	96	no	yes	a
Well 9	44 19 48 88 22 33	790	19871009	H	sub	140	18.00	119	21	107	no	yes	f
Well 10a	44 01 17 88 32 30	766	--	P	sub	195	19.0*	103	92	115	yes	yes	u
Well 10b	43 55 15 88 19 31	756	1951--	H	sub	466	37.12	324	142	324	yes	yes	af

Table 2. Location and characteristics of sampled wells in the western part of the Cambrian-Ordovician aquifer—Continued

Well number	Latitude longitude[1] (deg min sec)	Elevation, in feet above mean sea level	Well constr. date (yyyymmdd)	Water use[2]	Pump type[3]	Well depth, in feet below land surface	Water level, in feet below land surface[4]	Depth to top of open interval, in feet below land surface	Length of open interval, in feet	Depth to top of aquifer, in feet	Regionally confined[5]	Locally confined[6]	Land use[7]
Well 11	43 51 23 88 38 06	840	197206--	P	turb	320	32.0*	135	185	105	no	yes	u
Well 14	44 15 00 88 07 42	760	19800924	P	sub	675	196.0*	457	218	450	yes	yes	au
Well 15	44 27 30 88 01 41	608	--	P	turb	870	150.0*	235	140	220	yes	yes	u
Well 16	45 05 33 88 02 05	690	19600830	P	turb	346	36.0*	120	226	35	no	no	u
Well 18	45 31 01 87 41 49	790	19870124	H	sub	123	8.0*	110	13	30	no	no	f
Well 19	45 11 54 87 36 15	640	19750506	H	sub	432	11.62	332	100	257	yes	yes	a
Well 25	45 35 42 87 32 44	865	19800707	P	sub	483	7.05*	212	271	77	no	yes	f
Well 26a	45 42 15 87 30 43	890	19900110	H	sub	353	35.0*	311	42	304	no	yes	a
Well 26b	45 46 22 87 11 48	728	19891113	H	sub	290	39.0*	252	38	223	yes	yes	a
Well 27	45 49 32 87 06 36	720	19880902	H	sub	300	48.0*	260	40	260	yes	yes	u
Well 28	45 59 02 87 06 47	830	19841107	T	sub	305	29.0*	203	102	201	yes	yes	u
Well 29	46 04 18 87 18 55	1005	19940513	H	sub	92	24.0*	51	42	45	yes	yes	af
Well 30	46 14 27 87 17 10	1135	1981--	H	sub	31	4.0*	28	3.0	28	no	yes	f

[1]Latitude, longitude, and a sequence number (01), correspond to the USGS well identification number for each site. For example, the identification number for Well 1a is 433734089210401.

[2]Water use: H, domestic; P, public supply; T, institutional.

[3]Pump type: sub, submersible; turb, turbine; flow, flowing well.

[4]Water levels that were obtained from drillers logs are marked with an asterisk (*). Water level values without an asterisk were measured on the date of sampling (see appendix 2). Negative water levels are above land surface.

[5]Regionally confined: "yes" means that the open interval of the well is overlain by the Maquoketa confining unit.

[6]Locally confined: "yes" means that the open interval of the well is overlain by unconsolidated deposits described as clay or hardpan.

[7]Land-use: a, agricultural; f, forest; u, urban. Land use describes the general land use within a 1/4-mile radius of the well. Two letters indicates a mixture of those land uses.

Table 3. Laboratory analysis methods for inorganic and organic constituents

Constituent or category	Analysis method	Reference
Inorganics[1]	Various methods	Fishman and Friedman (1989)
Radon-222	Liquid scintillation counting	ASTM (1992)
Tritium	Electrolytic enrichment with gas counting	Östlund and Dorsey (1977)
DOC	UV-promoted persulfate oxidation and infrared spectrometry	Brenton and Arnett (1993)
Pesticides (USGS NWQL schedule 2001 and 2010)	Solid-phase extraction (SPE) technology on a C-18 cartridge and gas chromatograph/mass spectrometry	Zaugg and others (1995)
Pesticides (USGS NWQL schedule 2050 and 2051)	SPE technology with a Carbopak-B cartridge and high performance liquid chromatography with UV detection	Werner and others (1996)
VOCs	Purge and trap capillary gas chromatography/mass spectrometry	Rose and Schroeder (1995)

[1]Not including radon-222 and tritium

Cambrian-Ordovician aquifer. One well (10a) is cased to just above the Cambrian-Ordovician aquifer, and is open to about 12 ft of the Maquoketa-Sinnipee confining unit, which was assumed to produce little or no water. Fifteen of 29 wells are located in agricultural areas, based on a description of land use within a 1/4-mile radius of the well. Six wells are in urban areas, four wells are in forested areas, and four wells are in areas of mixed land use.

Sample Collection

Wells were sampled according to USGS ground-water sampling protocols (Koterba and others, 1995). All wells were purged of at least three casing volumes and until the field measurements (temperature, pH, specific conductance, and dissolved oxygen) stabilized for three successive measurements at least five minutes apart. Ground water was sampled from the well using tubing constructed of Teflon[1] and stainless steel connected to a spigot located in the discharge line.

Water samples from flowing wells and from wells with submersible pumps were analyzed for major ions, nutrients, DOC, 85 pesticides or metabolites, 60 VOCs, radon-222, tritium, and field measurements including bicarbonate. For wells with turbine pumps, water samples were analyzed for all constituents, except VOCs. VOCs were not analyzed in water from these wells because VOCs are probably volatilized from a water sample as a result of turbulence and cavitation caused by the turbine pump. A complete list of constituents and contaminants for which water samples were collected, the number of constituents and contaminants detected, and the laboratory method detection limit (MDL) for each constituent and contaminant is in appendix 1.

[1]Use of trade names is for identification purposes only and does not constitute an endorsement by the USGS.

Water-Quality Analysis

Samples collected for this study were analyzed at the USGS National Water-Quality Laboratory (NWQL) for inorganic and organic constituents using methods described in table 3. Field measurements of temperature, pH, specific conductance, and dissolved oxygen, were collected using a Hydrolab H20 which was calibrated daily. Field measurements of bicarbonate were determined using the titration method described by Wood (1981).

Quality control included submitting field blanks, trip blanks, sample replicates, and field-spiked samples for analysis with ground-water samples. Additional quality control included analysis of laboratory surrogate recoveries for pesticides and VOCs in each ground-water sample. Quality-control samples included two field blanks for major ions, nutrients, DOC, pesticides, and VOCs; two VOC trip blanks; four sample replicates for radon; two sample replicates for major ions, nutrients, and DOC; one replicate for pesticides and VOCs; and two field-spiked samples (plus field-spike replicates) for pesticides and VOCs.

Field blanks showed that most constituents in ground-water samples were not contaminated from either the sampling equipment or the cleaning procedure done between sites. However, several nutrients, VOCs, and DOC were detected in field blanks at concentrations greater than one percent of the lowest ground-water sample concentration for that constituent. Dissolved nitrite plus nitrate and dissolved phosphorus were detected in one field blank at concentrations of 0.05 and 0.02 mg/L, respectively, which were at or just above the respective MDLs. Because of this, concentrations of dissolved nitrite plus nitrate and dissolved phosphorus near the detection limit may be questionable. Three VOCs, benzene, toluene, and xylene, were detected at concentrations near the MDL in one field blank. However, these VOCs were not detected in ground-water samples. Both field blanks had detectable concentrations of DOC that ranged from 0.2 to 4.6 mg/L. The concentration of 4.6 mg/L was higher than all but one of the ground-water sample concentrations for DOC. Even the DOC field blank concentration of 0.2 mg/L was a large percentage of some of the ground-water sample concentrations. The detection of DOC in field blanks may be artifacts of field (sample-collection, processing, and shipping) or laboratory (processing and analysis) methods. Consequently, concentrations of DOC in ground-water samples may be questionable. Trip blanks, for VOCs, showed that samples were not contaminated during transport. Ground-water sample concentrations were not adjusted for measured blank concentrations.

Replicate samples indicated that field and laboratory procedures were consistent. Concentrations from replicate samples were within 10 percent (calculated as the difference between the two measurements divided by the average of the two measurements) for all constituents except dissolved phosphorus and dissolved bromide. The actual difference in concentrations between the replicates for these two constituents was small, 0.01 mg/L for dissolved phosphorus, and 0.02 mg/L for dissolved bromide. However, the measured concentrations were also small which resulted in the large percent difference.

Field-spiked samples and laboratory surrogate recoveries were used to determine the recovery of pesticide and VOC analytes in different ground-water matrices. Acceptable recovery ranges for pesticides are typically from 80 to 120 percent and for VOCs the acceptable range is about 70 to 130 percent. Recoveries of pesticides for one field spike, containing many of the analytes from schedules 2001 and 2010, ranged from 38 to 113 percent, and averaged 89 percent. Two pesticide field spikes, containing many of the analytes from schedules 2050 and 2051, had recoveries that ranged from 15 to 262 percent, and averaged between 71 and 88 percent recovery. Recoveries from field spikes for pesticides that were detected in ground-water samples ranged from 38 to 101 percent. Deethyl atrazine was the only pesticide detected in ground-water samples with less than 80 percent recovery in a spiked sample. Laboratory surrogate recoveries for four pesticides ranged from 71 to 97 percent. Two VOC field spikes had recoveries that ranged from 37 to 76 percent, and averaged between 53 and 60 percent recovery. Only one VOC, methylene chloride, was detected in ground-water samples but was not included in the field-spike mixture. Laboratory surrogate recoveries for three VOCs ranged from 96 to 102 percent.

In general, schedule 2001 and 2010 pesticide spike recoveries were fairly good while recoveries for schedule 2050 and 2051 were often quite poor. VOC spike recoveries were often below the acceptable range. Measured concentrations of pesticides and VOCs in ground-water samples were not changed to reflect the recoveries of the field spikes.

Statistical Analysis

Parametric and nonparametric statistical methods were used to analyze the data collected for this study. A parametric test for comparisons of slope (Iman and Conover, 1983, p. 374) was used to determine if a significant difference existed between the regression slope for millimoles of calcium plus magnesium versus millimoles of bicarbonate, as measured in ground-water samples, and the theoretical slope for those same parameters that should result from the dissolution of dolomite and calcite in water. The parametric test was used because residuals from the regression analysis were determined to be normally distributed. Regression analysis and a test of normality were performed using the computer program SAS (SAS, 1989). In the test for slope, the null hypothesis that the slopes are equal was used.

Boxplots of data were constructed to demonstrate differences between groups of data, such as concentrations of dissolved nitrate from regionally confined and regionally unconfined wells. Boxplots in this report illustrate the 10th, 25th, 50th (median), 75th, and 90th percentiles of the data, as well as values outside of the 10th and 90th percentiles. In order to determine whether any apparent differences shown by the boxplots were statistically significant, the nonparametric Wilcoxon-Mann-Whitney rank sum test (Iman and Conover, 1983, p. 281) was performed using the computer program SAS. The null hypothesis that the mean rank of the data from the two groups are equal was used. Estimated values were treated as actual data and values below the detection limit (less than values) were set to a value lower than the lowest measured value above the detection limit (Helsel and Hirsch, 1992, p. 367) so that they could be included in nonparametric statistical analyses.

Contingency tables and a nonparametric test for independence (Iman and Conover, 1983, p. 296) were used to measure the statistical association between factors that could be grouped into categories. For example, a contingency table was used to measure the association between tritium-based recharge date (with the categories of "old" and "modern") and regional aquifer condition (with the categories "regionally confined" and "regionally unconfined"). Percentages of all possible combinations of categories were calculated and a nonparametric test for independence was performed using the computer program SAS to determine if the null hypothesis, that the two categories were independent of each other, were true.

The alpha value used for all statistical tests in this report is 0.05. The probability (or p-value) that observed differences occur by chance are described in the text and shown on each graph. If the p-value is smaller than or equal to the alpha value then the null hypothesis of the test is rejected.

Age-Dating Analysis

Tritium-based ground-water recharge dates were determined by matching the measured tritium concentrations in a sample to a tritium input curve for precipitation (decayed to the sample date using a half-life of 12.43 years). A tritium input curve was developed for precipitation near Madison, Wisconsin, by Bradbury (1991), and was assumed to be representative of that for the study area. Using this input curve ground-water samples were described as "modern" or "old." For this report, modern refers to water that entered the subsurface after about 1955 and old refers to water that entered the subsurface before about 1955. Using Bradbury's input curve, the cut off point between modern and old water corresponds to about 16 picocuries per liter (pCi/L) or 5 tritium units, where 1 tritium unit equals 3.193 pCi/L (appendix 2c).

GROUND-WATER QUALITY

Ground-water samples were analyzed for inorganic constituents, which include major ions, nutrients, radon-222, and tritium, as well as pH, dissolved oxygen, and bicarbonate, and organic constituents which include DOC, pesticides, and VOCs. Analytical results for constituents that were detected in at least one sample are shown in appendix 2. Some of the constituents collected as part of this study have standards set by the U.S. Environmental Protection Agency (USEPA) and the state of Wisconsin that define limits on the health aspects or aesthetic qualities of drinking water (U.S. Environmental Protection Agency, 1991a, 1991b, 1991c) and ground water (Wisconsin Department of Natural Resources, 1994). Some of the USEPA drinking water standards include maximum contaminant levels (MCL), which are health-based and legally enforceable, and secondary maximum contaminant levels (SMCL), which are generally for constituents that can affect the aesthetic qualities of drinking water and are not enforceable. The USEPA has proposed maximum contaminant levels (PMCL) for constituents that may have negative health affects in drinking water. The state of Wisconsin ground-water-quality standards include an enforcement standard (ES) and a preventive action limit (PAL).

The following discussion is limited to the dominant ions, inorganic constituents that exceeded a drinking-water or ground-water-quality standard, nutrients, radon-222, tritium, pH, and dissolved oxygen. Additionally, organic constituents that were detected in ground-water samples will be discussed in the following report section.

Occurrence of Inorganic and Organic Chemicals

The dominant ions in water from wells in the study area were calcium, magnesium, and bicarbonate (fig. 6). Sulfate was also a dominant ion in water samples from three wells. These dominant ions and their ranges in concentration are similar to those described by Kammerer (1981 and 1984) for ground-water samples from the Cambrian-Ordovician aquifer in Wisconsin. They are also similar to the hydrochemical facies described by Siegel (1989) for a previous study of Cambrian-Ordovician aquifer system in the Northern Midwest United States.

Drinking-water standards were exceeded for several inorganic constituents. The USEPA SMCL was exceeded for concentrations of dissolved iron (300

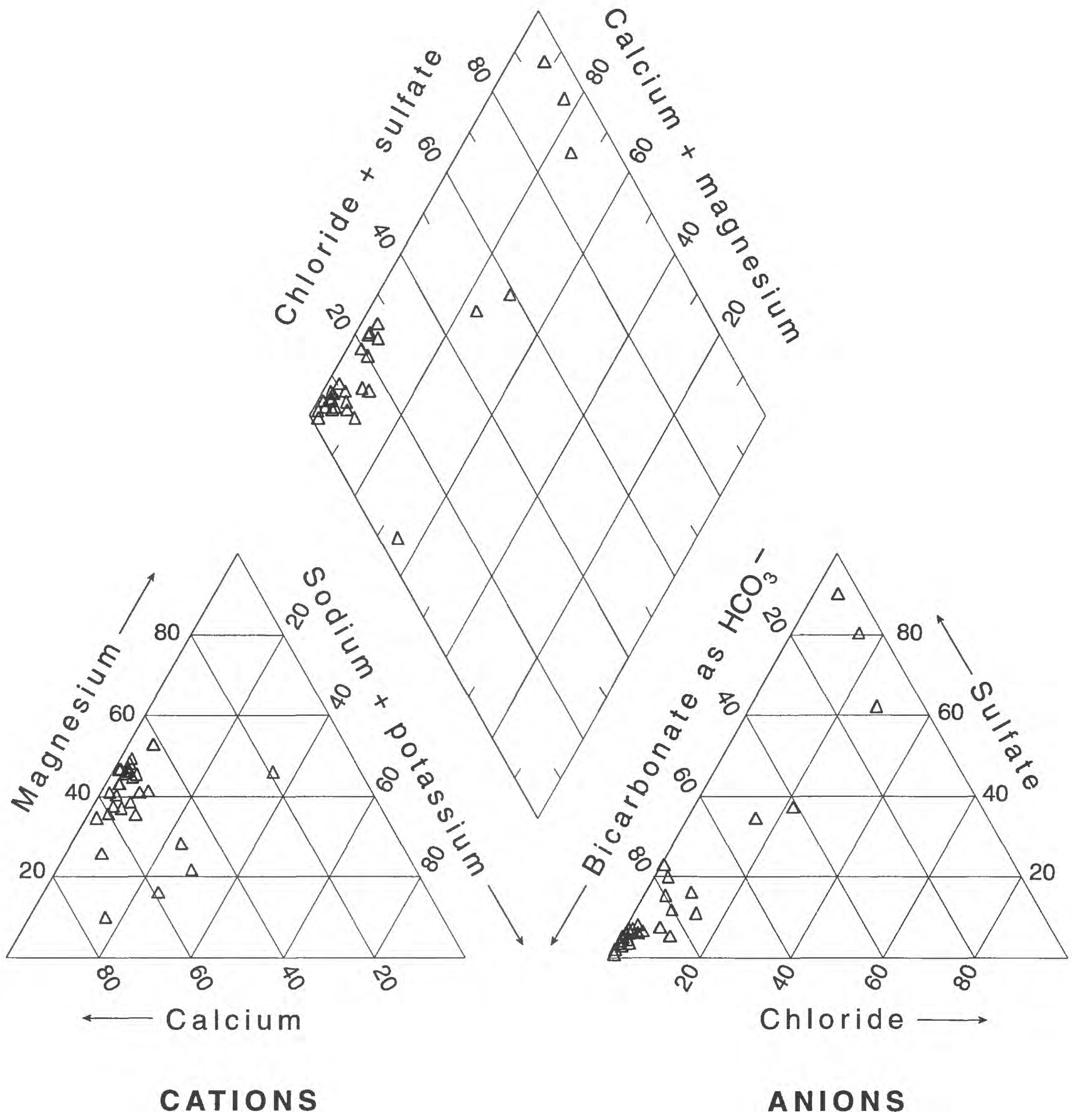


Figure 6. Trilinear diagram of percent equivalents of dominant cations and anions in water from sampled wells.

Table 4. Pesticides and metabolites detected in ground water from sampled wells
[µg/L, micrograms per liter; ES, Wisconsin ground-water-quality enforcement standard; PAL, Wisconsin ground-water-quality preventive action limit]

Pesticide or metabolite	Percent detection/ number of samples	Maximum concentration, in µg/L	Enforcement standard/ Preventive action limit, in µg/L	Use or origin
Alachlor	3.4 / 29	0.096	2.0 / 0.2	herbicide
Atrazine	20.7 / 29	2.6	3.0 / 0.3	herbicide
Deethyl atrazine	20.7 / 29	2.0	3.0 / 0.3	herbicide metabolite (atrazine)
Dichlobenil	3.4 / 29	.06	NONE	herbicide
Metolachlor	3.4 / 29	1.2	15 / 1.5	herbicide
Prometon	3.4 / 29	.14	NONE	herbicide
Simazine	3.4 / 29	.017	4.0 / 0.4	herbicide

µg/L) in 38 percent (11 of 29) samples and for total dissolved solids (500 mg/L) in 17 percent (5 of 29) samples (fig. 7). Concentrations in samples from several wells also exceed the USEPA SMCL for dissolved chloride (250 mg/L), dissolved fluoride (2.0 mg/L), dissolved manganese (50 µg/L), and dissolved sulfate (250 mg/L) (fig. 7).

Nutrients were analyzed in samples from all wells. Dissolved ammonium and dissolved nitrite plus nitrate were the two most commonly detected nutrients. Dissolved ammonium was detected in 72 percent (21 of 29) of samples and concentrations as nitrogen (N) ranged from <0.015 to 0.32 mg/L. Dissolved nitrite plus nitrate was detected in 41 percent (12 of 29) of samples and concentrations as N ranged from <0.05 to 23.0 mg/L. Kammerer (1981) reported that dissolved nitrate ranged from less than detection to 41.0 mg/L in water samples from the Cambrian-Ordovician aquifer in Wisconsin. Concentrations of dissolved nitrite as N were at or below the MDL (0.01 mg/L) in 97 percent (28 of 29) of samples. For this reason the constituent dissolved nitrite plus nitrate will be hereafter referred to as dissolved nitrate. Concentrations of dissolved ammonium plus organic nitrogen and dissolved phosphorus were at or below the MDL (0.20 mg/L as N and 0.01 mg/L as P, respectively) in 90 percent (26 of 29) of samples. Dissolved orthophosphate was at or below the MDL (0.01 mg/L as P) in 93 (27 of 29) of samples. Concentrations of dissolved nitrate as N exceeded the Wisconsin PAL of 2.0 mg/L in 17 percent (5 of 29) of samples and 10 percent (3 of 29) exceeded the Wisconsin ES and USEPA MCL of 10 mg/L (figs. 7 and 8).

Radon-222 was detected in water from all of the sampled wells in the study area, and concentrations ranged from 130 to 1,400 pCi/L which is within the range of previously reported values for ground water in Wisconsin (Warzecha and others, 1995, DeWild and Krohelski, 1994; and Weaver and Bahr, 1991). Concentrations exceeded the USEPA PMCL of 300 pCi/L, in more than 65 percent (19 of 29) of samples (figs.7 and 9), however, this is not uncommon.

Tritium was analyzed in samples from each well in order to have a rough estimate of the recharge date of the ground water. Tritium was detected in water samples from 27 of 29 sampled wells. Ten of 29 samples contained tritium concentrations above 16 pCi/L and were considered modern water (fig. 10).

Measurements of pH were done at all of the sampled wells. Values of pH ranged from 7.0 to 8.1 units but was usually between 7.1 and 7.6. Dissolved oxygen was measured at 28 of 29 wells in the study area, and ranged from 0.10 to 9.88 mg/L. Though detected at low concentrations, dissolved oxygen may not have been present in ground-water from wells 10b, 18, 26a, 26b, and 27, where the smell of hydrogen sulfide (HS^-) was noticeable during sampling. Hydrogen sulfide is produced under anaerobic conditions which is difficult to confirm with a dissolved oxygen probe.

DOC was analyzed in samples from 28 of 29 wells in the study area. However, as discussed earlier in this report, based on high concentrations of DOC in field blank samples, much of the DOC data may be questionable and will not be discussed further in this report.

Pesticides and some of their metabolites were analyzed in water samples from the 29 wells in the study area. Seven different pesticides or metabolites, including alachlor, atrazine, deethyl atrazine (a metabolite of atrazine), dichlobenil, metolachlor, prometon, and simazine, were detected (table 4), however, only atrazine and deethyl atrazine exceeded a Wisconsin drinking-water standard. Alachlor, atrazine, meto-

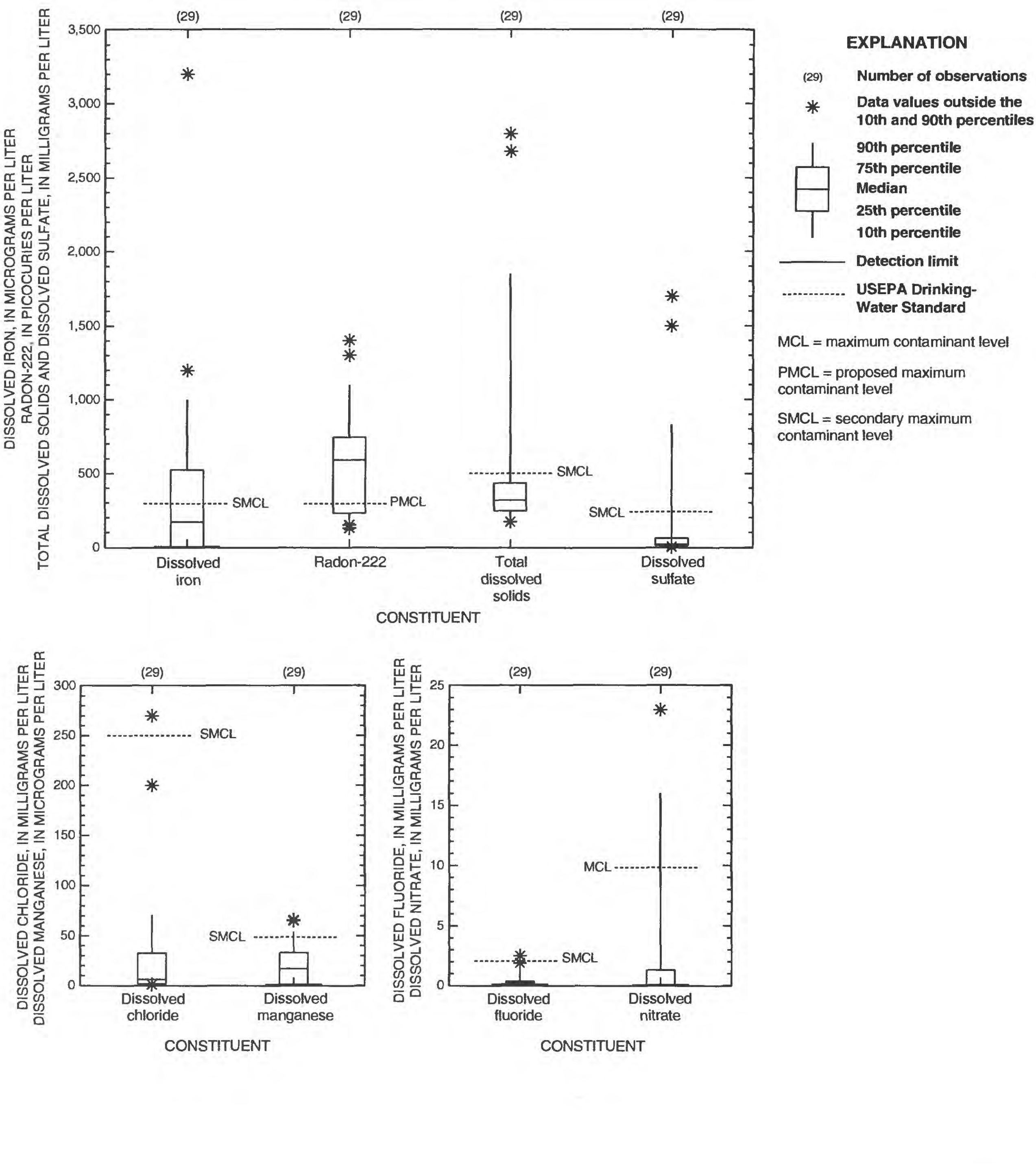


Figure 7. Boxplots of concentration of constituents, in water from sampled wells, that exceeded a U.S. Environmental Protection Agency drinking-water standard.

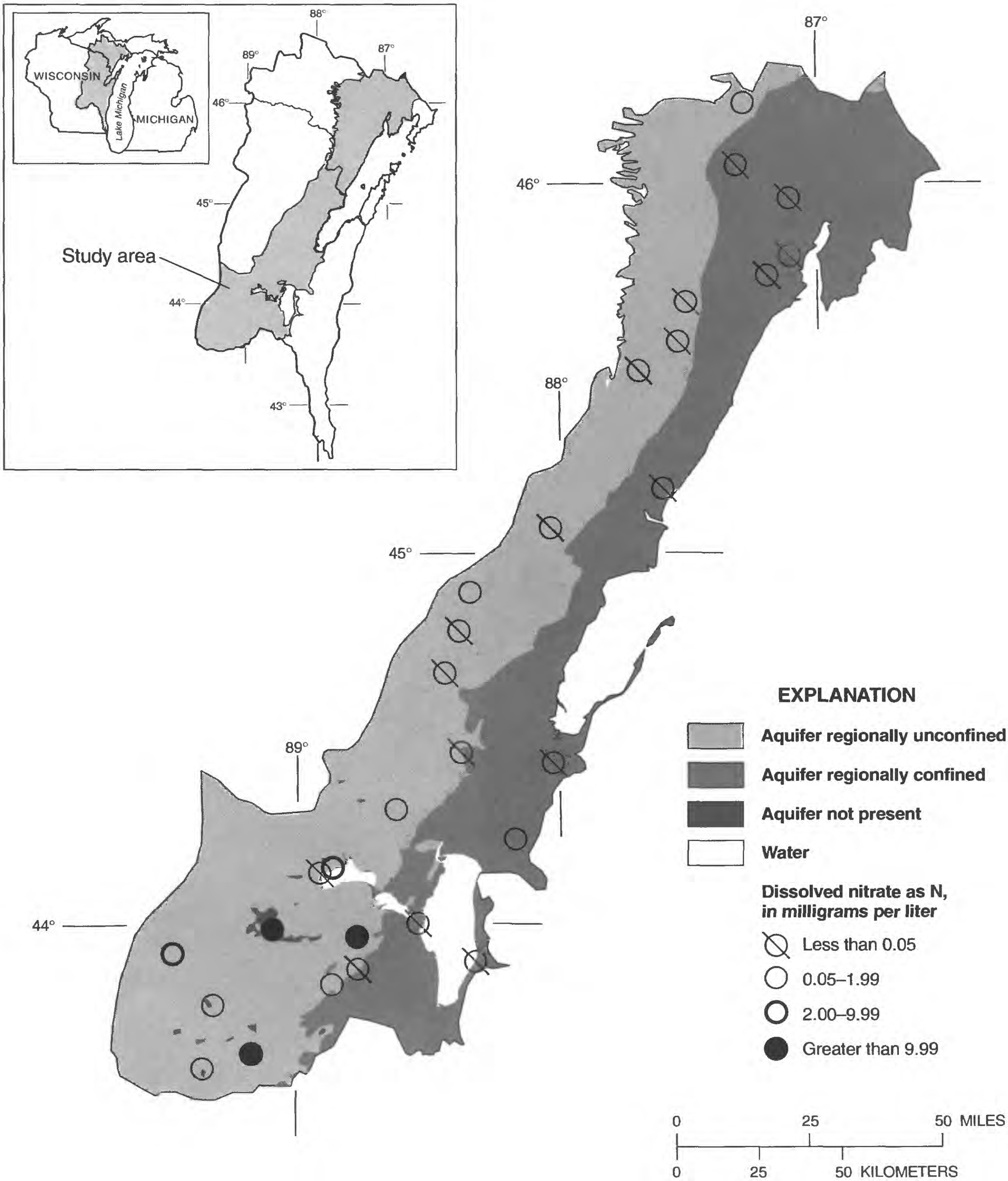


Figure 8. Spatial distribution of dissolved nitrate concentrations in ground water from sampled wells.

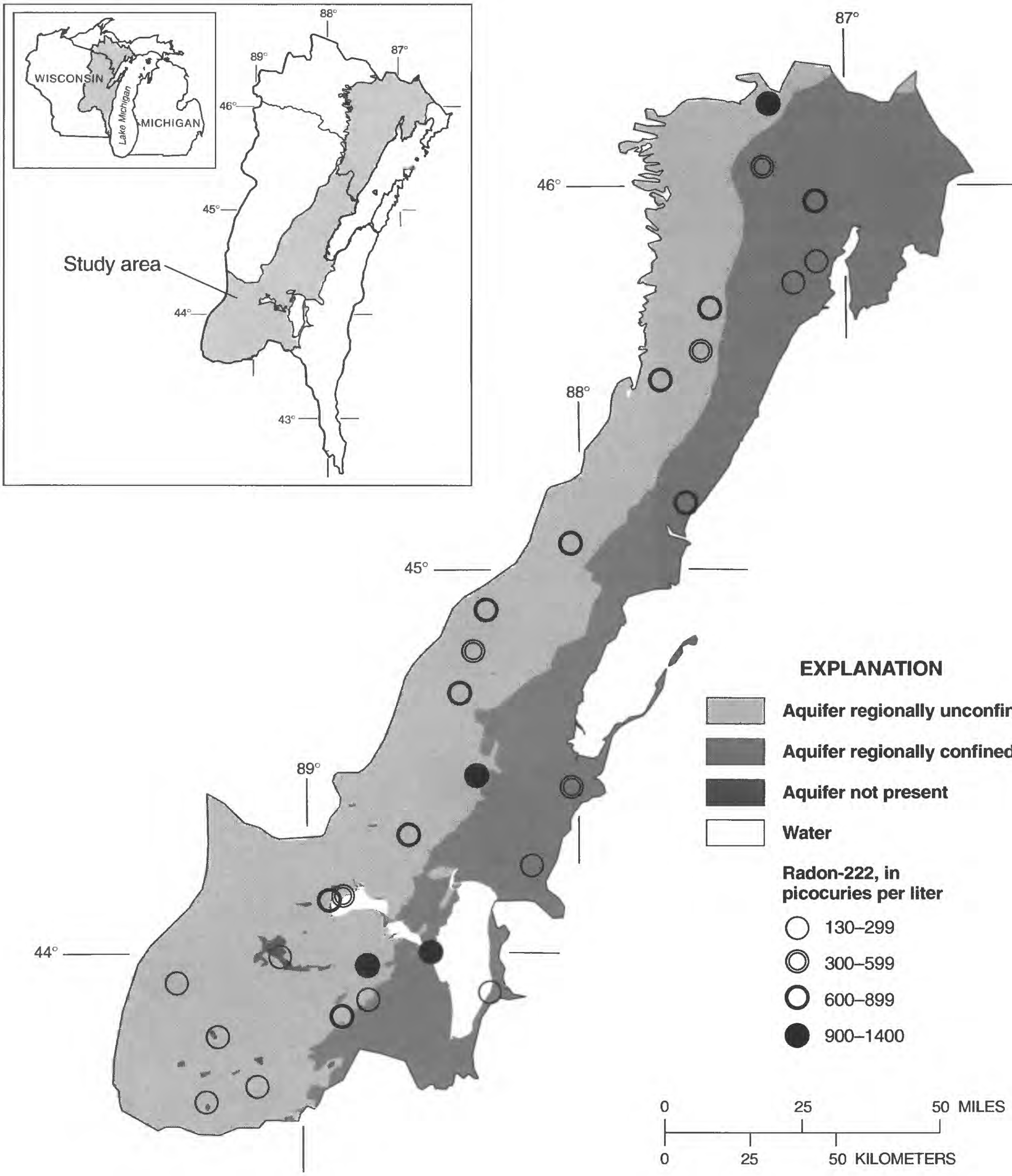


Figure 9. Spatial distribution of radon-222 concentrations in ground water from sampled wells.

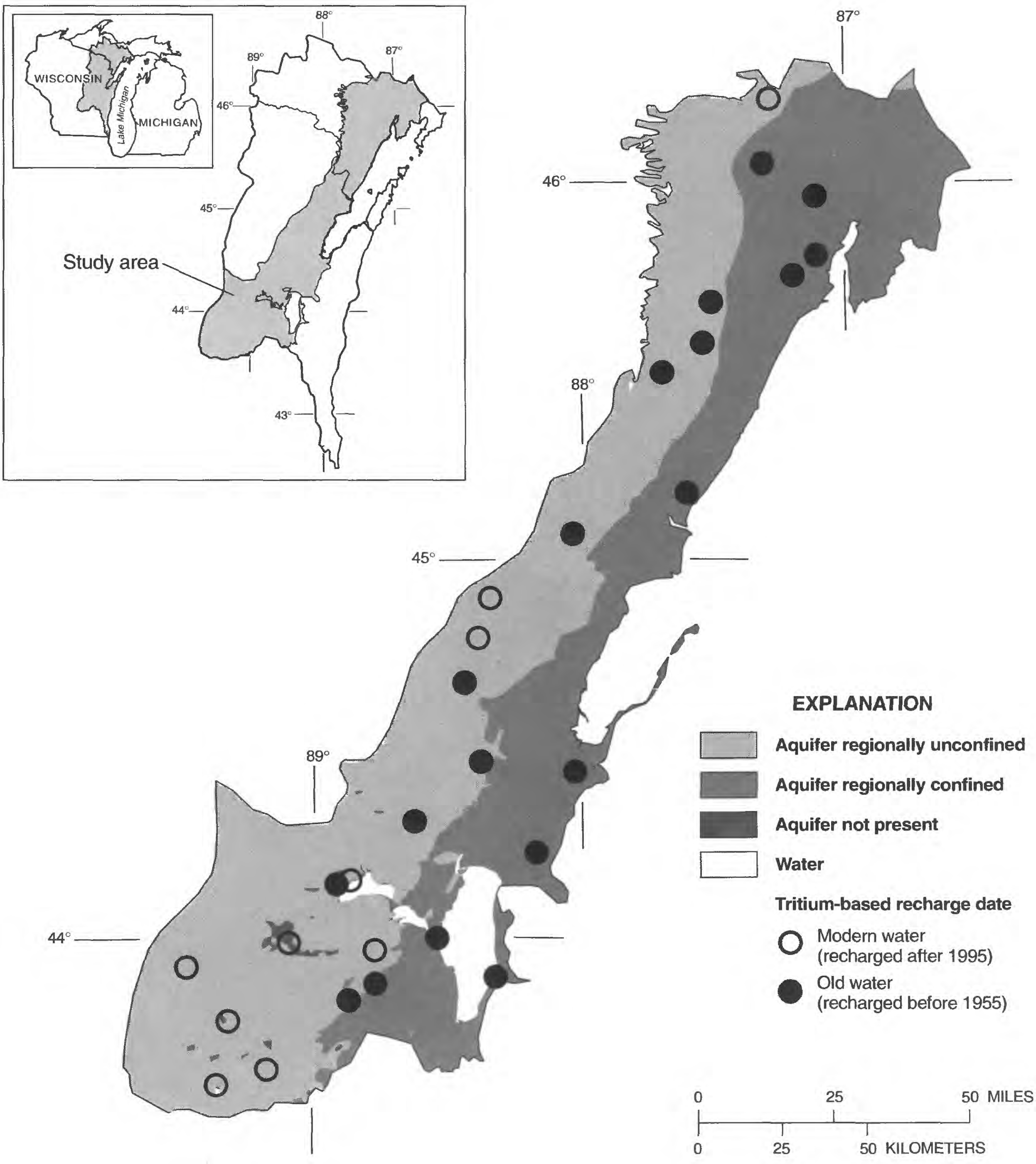


Figure 10. Spatial distribution of tritium-based recharge dates for ground water from sampled wells.

lachlor, and simazine are some of the most used herbicides in and around the study area and are typically used in agricultural areas where corn, soybeans, and other vegetables are grown. Dichlobenil is a herbicide typically used in cranberry bogs and around woody perennial crops such as christmas tree farms, fruit orchards, and vineyards. Prometon often is used for industrial purposes as a non-selective herbicide. At least one pesticide was detected in 24 percent (7 of 29) of samples (fig. 11); atrazine and deethyl atrazine, the most commonly detected pesticides, were both detected in 21 percent (6 of 29) of samples. Concentrations of atrazine plus deethyl atrazine exceeded the Wisconsin PAL of 0.30 µg/L in samples from two wells, and in one sample it exceeded the Wisconsin ES (3.0 µg/L). Five different pesticides or metabolites, including alachlor, atrazine, deethyl atrazine, metolachlor, and simazine, were detected in well 4a.

VOCs were analyzed in samples from 26 of 29 wells in the study area. The only VOC detected was methylene chloride, which was found in 2 of 26 samples. Methylene chloride is a commonly detected laboratory contaminant (Rose and Schroeder, 1995). The measured concentrations were at or just above the MDL (0.2 µg/L) and may be due to contamination of the sample in the laboratory.

Effects of Geohydrologic Factors and Land Use on Water Quality

Geohydrologic factors and land use can affect the quality of water in the Cambrian-Ordovician aquifer. Geohydrologic factors, such as permeability and rock type, affect ground-water quality by controlling water movement through geologic materials and by controlling what and how much of the geologic material dissolves. Land use can affect ground-water quality when land-use practices contribute to the water chemistry in the underlying aquifer.

The Maquoketa-Sinnipee confining unit is an important geohydrologic factor affecting the ground-water quality in the study area. Ground water removed from the regionally confined part of the study area is typically old water that has traveled a long distance from the recharge area. The long contact time between the water and geologic materials can result in relatively high concentrations of dissolved solids in ground water. The Maquoketa-Sinnipee confining unit can also affect ground-water quality by inhibiting the flow of water that may contain contaminants, such as nitrate and pesticides, from land surface to the Cambrian-Ordovician aquifer.

Based on tritium analyses, 100 percent (10 of 10) of the regionally confined wells sampled for this study produced old water and 53 percent (10 of 19) of the regionally unconfined wells produced modern water. A nonparametric test of independence using a contingency table showed that the age of water samples was dependent on whether the samples were from regionally confined or regionally unconfined wells (p-value= 0.005). The highest concentrations (greater than 1,000 mg/L) of dissolved solids were in ground-water samples from wells in the regionally confined part of the study area, overall however, concentrations were not significantly different (p-value = 0.333) than those from the regionally unconfined part of the study area (fig. 12).

The type of geologic material in the study area can affect which dissolved ions are dominant in ground water. The dominant ions found in most water samples included calcium, magnesium, and bicarbonate. These probably resulted from the dissolution of carbonate minerals such as dolomite and calcite in the aquifer material, and in some places, from dissolution of those minerals in the overlying glacial deposits. The combined dissolution of dolomite [$CaMg(CO_3)_2$] and calcite ($CaCO_3$) in near neutral pH conditions, such as those in the study area, should result in a molar ratio of calcium plus magnesium to bicarbonate of 1:2 (Siegel, 1989). Figure 13 shows that all but three of the samples collected from the Cambrian-Ordovician aquifer plot along a slope (slope = 0.53, $r^2 = 0.74$, calculated for all but the three outliers) that is not significantly different (p-value=0.33) from the theoretical slope of 1:2 (or 0.5).

The chemical composition of the three samples, which appear to have been less affected by dolomite and calcite dissolution, are from relatively deep, regionally confined wells where sulfate is the dominant anion. Water samples from these three wells had the highest concentrations of sulfate and calcium which may have resulted from the dissolution of a mineral like gypsum ($CaSO_4 \cdot 2H_2O$). The smell of hydrogen sulfide was noticeable in at least one of these samples, and though not measured, may also be a dominant anion. Sulfate from gypsum dissolution could have been reduced under anaerobic conditions to form hydrogen sulfide. Petrographic evidence of gypsum in the Cambrian-Ordovician aquifer, however is lacking

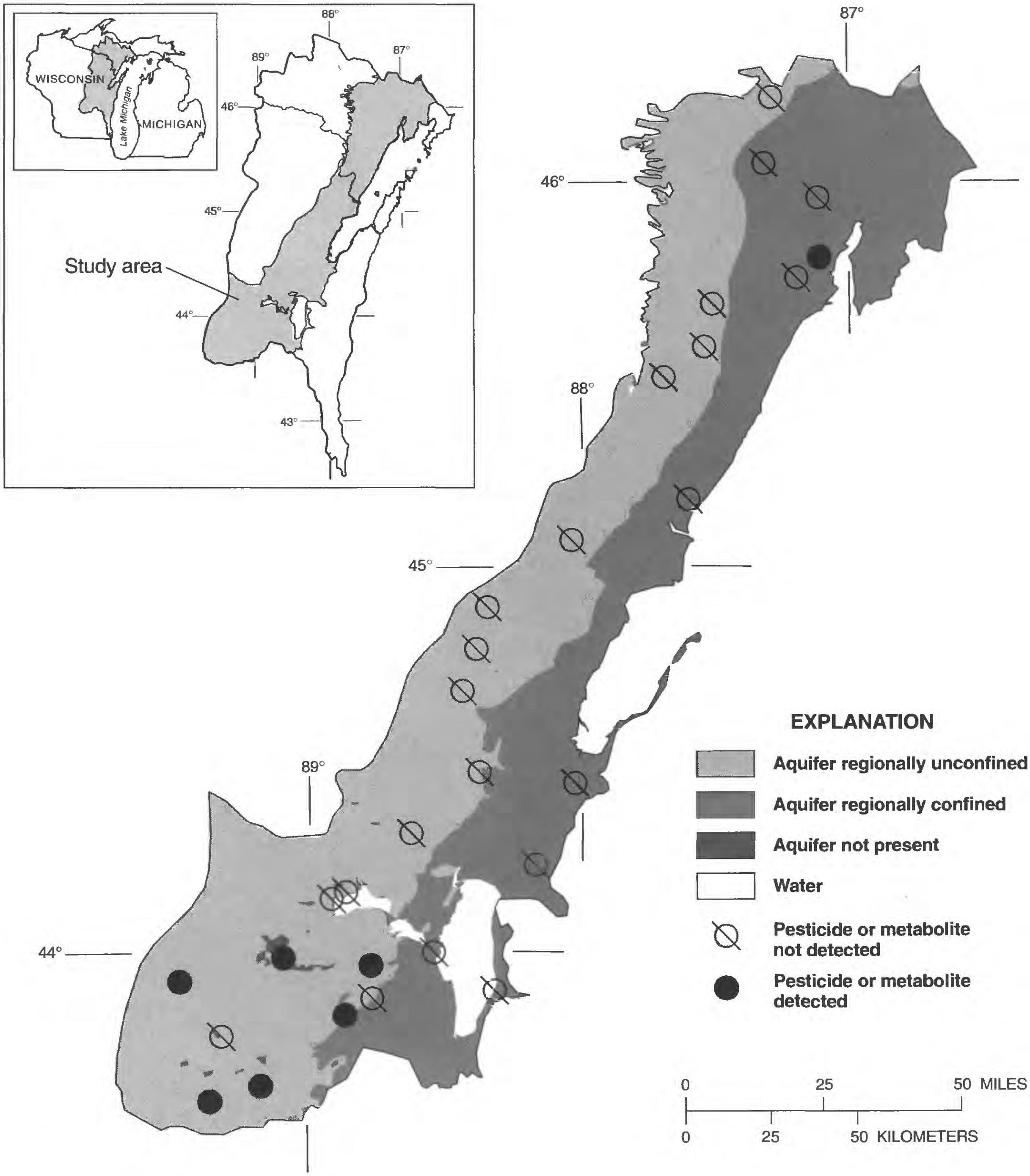


Figure 11. Spatial distribution of sampled wells in which the ground water contained at least one detectable pesticide or metabolite.

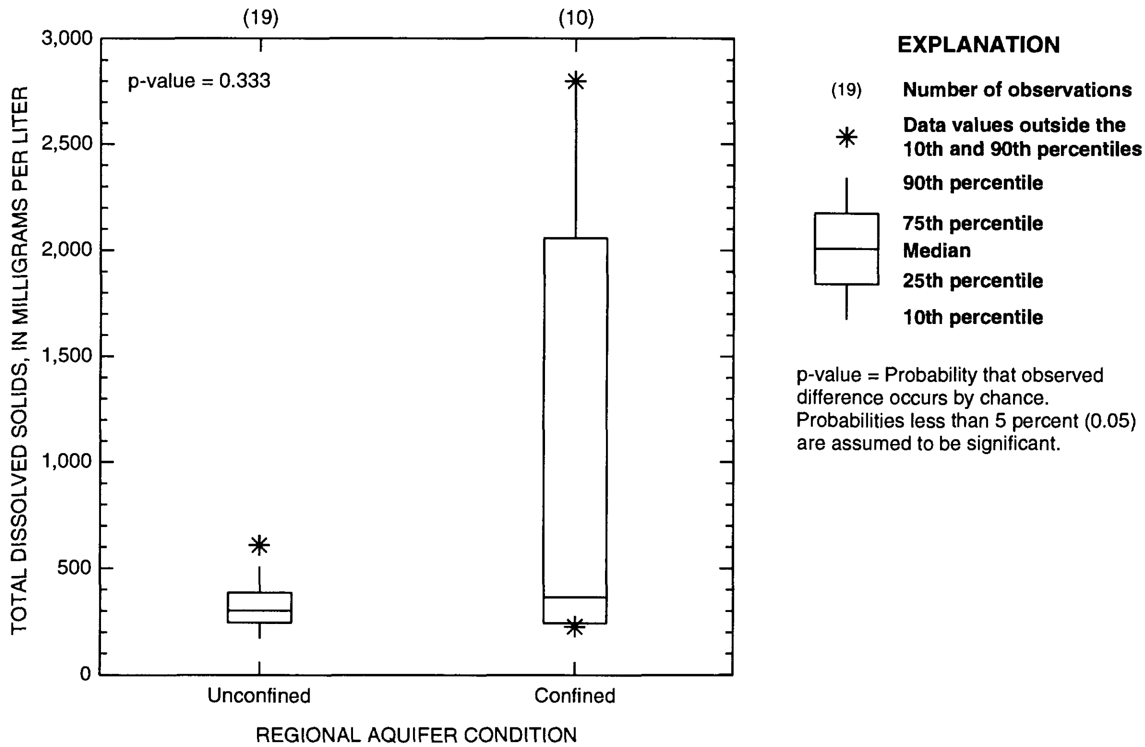


Figure 12. Boxplots of concentration of total dissolved solids, by regional aquifer condition, in water from sampled wells.

(Siegel, 1989). A more likely source of gypsum is the overlying Maquoketa Shale (Weaver and Bahr, 1991), which is part of the Maquoketa-Sinnipee confining unit. Other possible explanations for the high sulfate concentrations include oxidation of sulfides to sulfate in recharge areas and a regional ground-water flow reversal during Pleistocene glaciations (Weaver and Bahr, 1991). It has been hypothesized that glacial loadings caused sulfate-rich evaporite brines, in the Michigan Basin (to the east of the study area), to move westward into the Cambrian-Ordovician aquifer (Gilkeson and others, 1983).

Water samples from many wells in the Cambrian-Ordovician aquifer had relatively high concentrations of dissolved iron (up to 3,200 µg/L). Iron-bearing minerals and compounds are common in the Cambrian-Ordovician aquifer (Siegel, 1989), yet concentrations were significantly lower (p-value=0.007) in water samples from regionally unconfined wells than from regionally confined wells (fig. 14). Iron is not very soluble under aerobic conditions and the absence of dissolved iron in ground water is typically an indication that the aquifer contains dissolved oxygen (Stumm and Morgan, 1970, p. 545). Concentrations of dissolved oxygen were typically higher in water samples from regionally unconfined wells (fig. 15), however, this difference was not statistically significant (p=0.276).

Radon-222 is a naturally occurring radioactive gas that results from the decay of uranium and it was detected in samples from all wells. Radon-222 concentrations greater than the PMCL (300 pCi/L) in ground water were found in much of the study area except in the southwest (fig. 9). The distribution of concentrations above the PMCL is similar to that reported by Warzecha and others (1995) for northeastern Wisconsin. These concentrations do not appear to correlate to a particular formation or location, because they were found in much of the study area under a variety of geohydrologic conditions.

Nutrients in ground water can originate from several sources including atmospheric deposition, precipitation, fixation, and dissolution of geologic materials, but elevated concentrations usually are associated with releases from septic systems or agricultural land-use practices that apply fertilizer and manure to the land surface. Nitrate concentrations in the Cambrian-Ordovician aquifer were significantly higher (p-value=0.006) in samples from the regionally unconfined part of the study area than from where

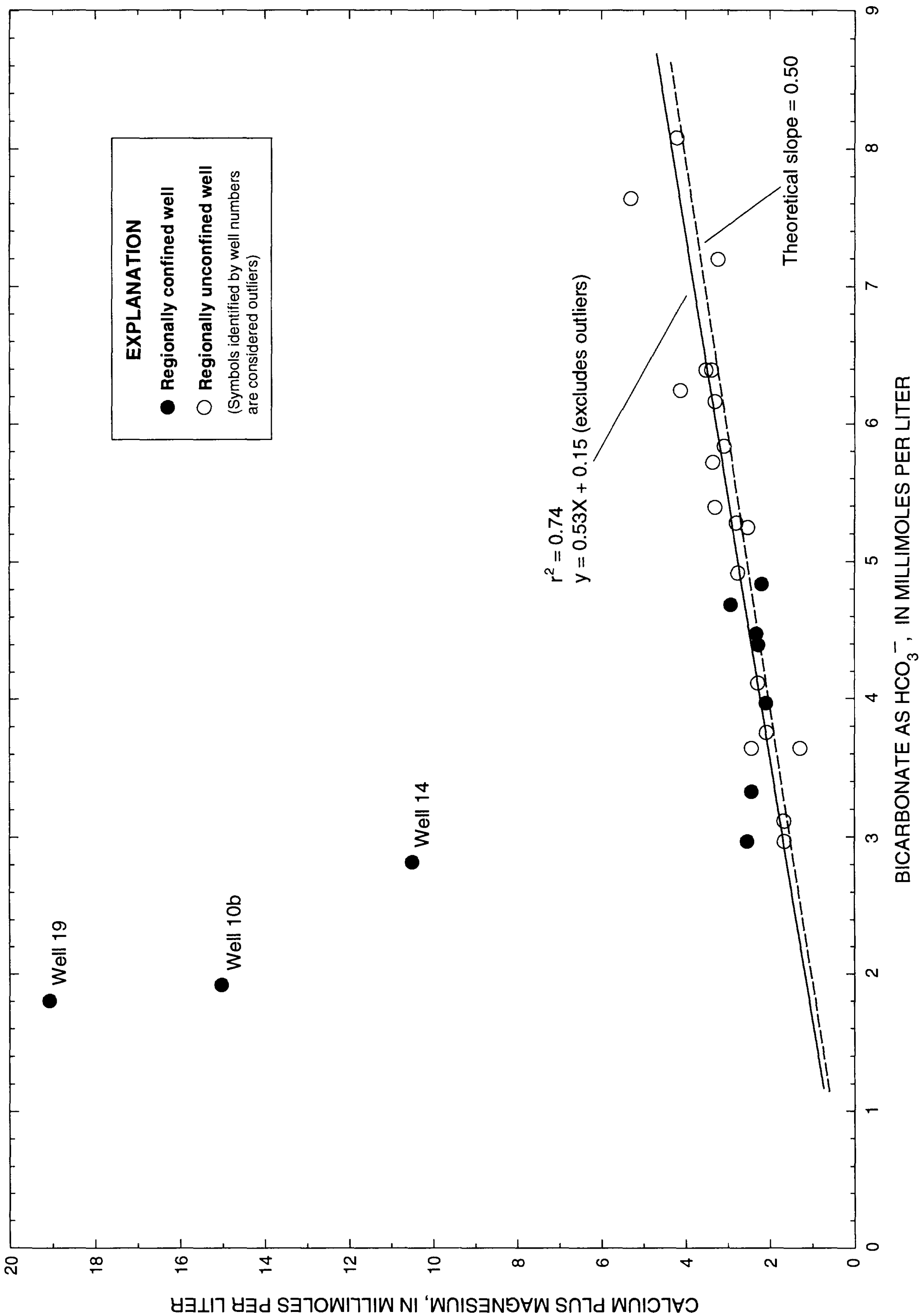


Figure 13. Correlation of calcium plus magnesium and bicarbonate in water from sampled wells.

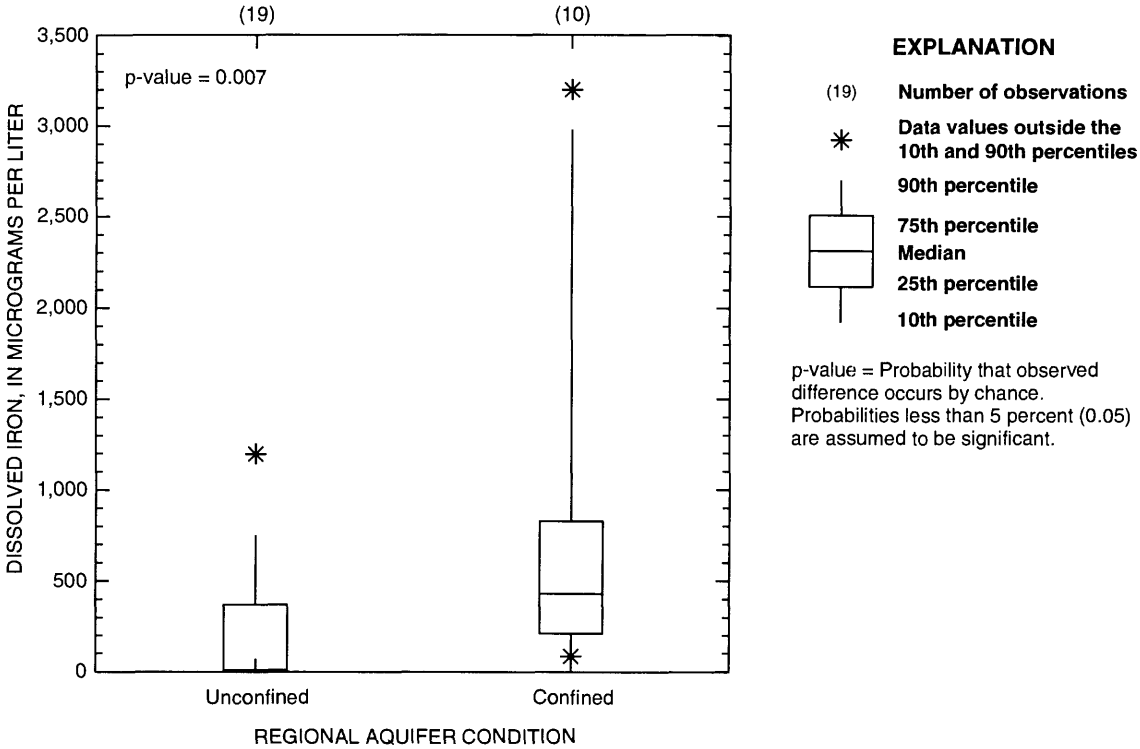


Figure 14. Boxplots of concentration of dissolved iron, by regional aquifer condition, in water from sampled wells.

it is regionally confined (fig. 16). Further, the highest nitrate concentrations (greater than the PAL of 2.0 mg/L) were detected in samples from the southwest part of the study area (fig. 8) where land use is primarily agricultural and surficial deposits are relatively permeable. A retrospective study of nutrient data in the Western Lake Michigan Drainages also indicated high nitrate concentrations in ground water in this area (Robertson and Saad, 1996). Most of the samples from the Cambrian-Ordovician aquifer study that had high nitrate concentrations were from relatively shallow wells that produced modern water. Nitrate was detected in only 1 of 10 wells in the regionally confined part of the study area even though six of the wells are in areas that include agricultural land use.

Concentrations of dissolved ammonium were significantly higher in water samples from regionally confined wells than from regionally unconfined wells (fig. 17). The reason for higher concentrations of dissolved ammonium and lower concentrations of dissolved nitrate in samples from the regionally confined part of the study area may be due to reduction of nitrate to ammonium and denitrification. Reduction of nitrate to ammonium and denitrification occur under anaerobic conditions (Korom, 1992). The median concentration of dissolved oxygen in samples from the regionally confined area was 0.30 mg/L, compared to 2.38 mg/L in the regionally unconfined area (fig. 15), however, as mentioned earlier, this difference was not statistically significant.

The pesticides or metabolites detected in water samples from this study do not naturally occur in ground water. These chemicals in ground water primarily result from leaching of pesticides applied or spilled at the land surface. Pesticides are used for different purposes, in all parts of the study area but most of those detected in ground-water samples in the study area are used for agricultural practices. Pesticides or metabolites were detected in water samples from seven wells (fig. 11), and as with high concentrations of nitrate, most of the wells are located in the regionally unconfined, southwestern part of the study area where the land use is primarily agricultural. Most of the samples containing detectable pesticides or metabolites were from wells that produced modern water. Atrazine, for example, was detected in 6 of 29 water samples and five of those samples were of modern water (water that was recharged after about 1955). This follows because atrazine was not registered until 1958 and was not widely used in the study area until the early 1960s

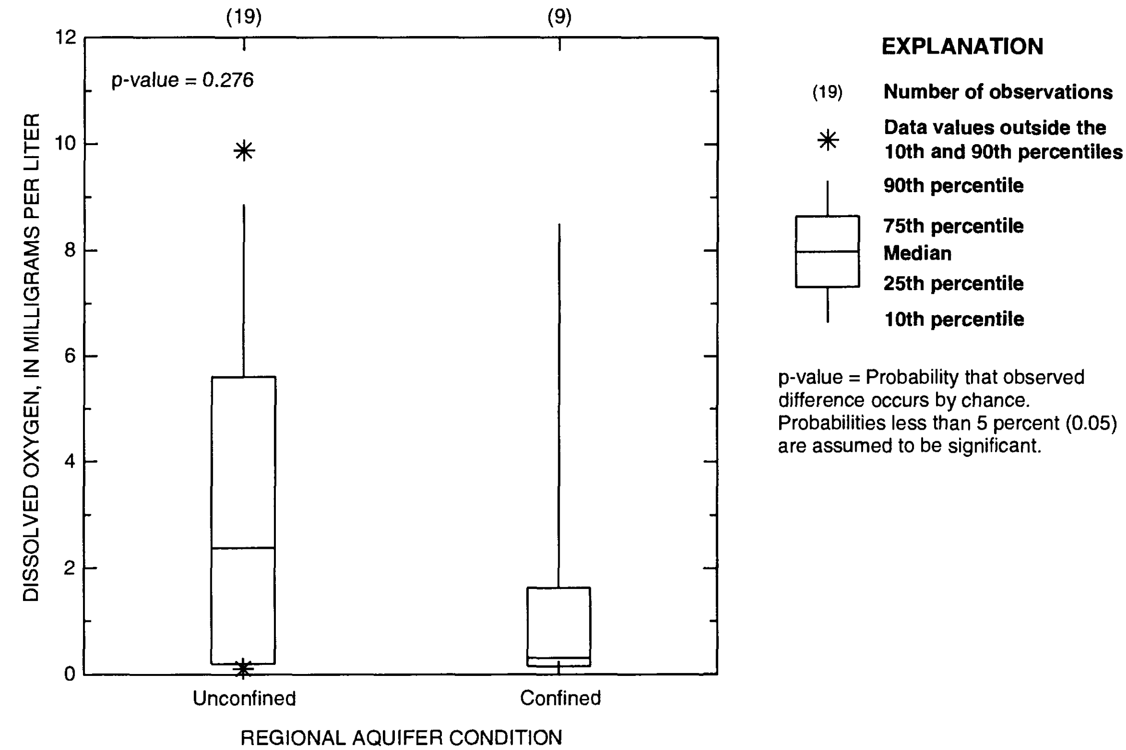


Figure 15. Boxplots of concentration of dissolved oxygen, by regional aquifer condition, in water from sampled wells.

(Wollenhaupt and others, 1990). The one old water sample that contained atrazine was probably due to mixing of waters of different ages. Any ground-water sample is a composite of water of different ages and it would require only a small amount of modern water, containing atrazine, to be mixed with old water to show detectable concentrations of atrazine without affected the tritium-based recharge date. The concentration of atrazine in the sample of old water was the lowest of any of the detections.

SUMMARY

Ground-water samples were collected during the summer of 1995 from 29 wells in the western part of the Cambrian-Ordovician aquifer in the Western Lake Michigan Drainages. These wells were used to provide an indication of water-quality conditions in this heavily used part of the aquifer.

The results of water-quality analyses indicate that the presence of the Maquoketa-Sinnipee confining unit has an important effect on the ground-water quality in the study area. Where the study area is overlain by the confining unit (that is, where it is regionally confined) sampled water was older (based on tritium analyses) and often contained high concentrations (greater than 1,000 mg/L) of dissolved solids. Additionally, contaminants such as nitrate and pesticides were typically detected at lower concentrations and detected less frequently in samples from the regionally confined part of the study area.

The dominant ions in samples from the study area were calcium, magnesium, and bicarbonate which resulted from the dissolution of carbonate minerals such as dolomite and calcite. Sulfate was also a dominant ion in water from some of the deeper wells in the regionally confined part of the study area.

Radon-222 was detected in all samples and 66 percent (19 of 29) had concentrations that exceed the U.S Environmental Protection Agency (USEPA) proposed maximum concentration level of 300 pCi/L. Concentrations greater than 300 pCi/L were detected in samples from wells throughout most of the study area except the southwest. The higher concentrations were found in samples from a variety of geohydrologic conditions and do not appear to correlate to a particular formation or location.

Dissolved nitrate and ammonium were the most commonly detected nutrients. Dissolved nitrate concentrations were significantly higher in ground-water sam-

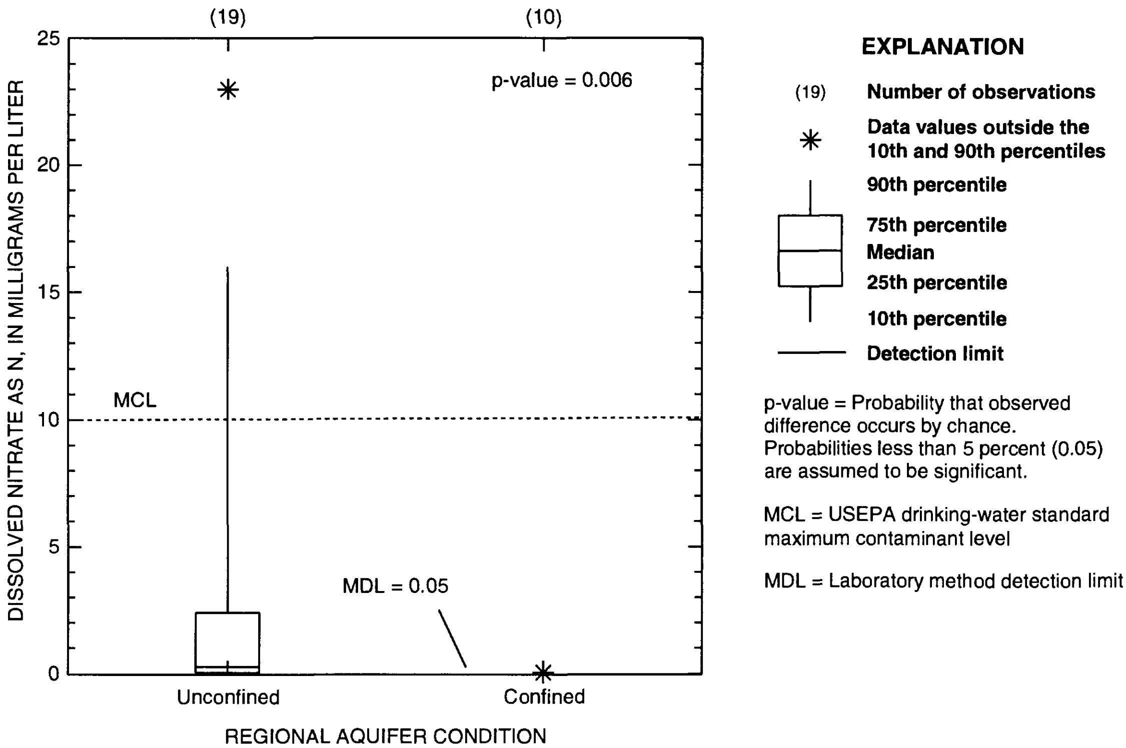


Figure 16. Boxplots of concentration of dissolved nitrate, by regional aquifer condition, in water from sampled wells.

ples from the regionally unconfined part of the study area. The highest concentrations were detected in samples from the agricultural southwestern part of the study area from relatively shallow wells that produced modern water. Dissolved ammonium concentrations were significantly higher in samples from the regionally confined part of the study area and probably resulted from nitrate reduction.

Seven pesticides or metabolites were detected in ground-water samples, and at least one pesticide was detected in samples from 24 percent (7 of 29) of wells. Most of the pesticides were detected at low concentrations and were from wells in the regionally unconfined, agricultural, southwest part of the study area. Atrazine was the most commonly detected pesticide and was typically detected in samples from wells that produced modern water.

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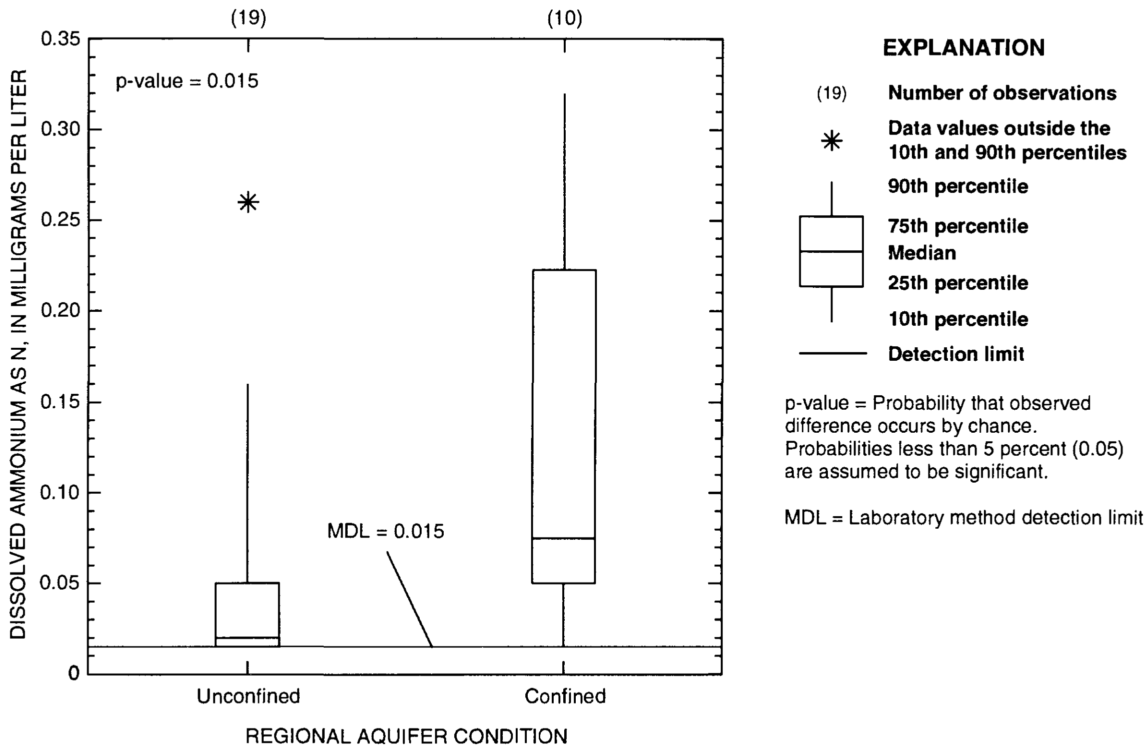

Figure 17. Boxplots of concentration of dissolved ammonium, by regional aquifer condition, in water from sampled wells.

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APPENDIXES 1–2

Appendix 1. Water-quality constituents analyzed in ground-water samples from wells in the western part of the Cambrian-Ordovician aquifer

[na, not applicable; µS/cm, microsiemens per centimeter; °C, degrees Celsius; mg/L, milligrams per liter; µg/L, micrograms per liter; pCi/L, picocuries per liter]

Constituent	Parameter code	Number of samples/ number of detections	Laboratory method detection limit (MDL)
FIELD MEASUREMENTS			
Bicarbonate, whole water, mg/L as HCO_3^-	00450	29 / 29	na
Dissolved oxygen, mg/L	00300	28 / 28	na
pH (standard units)	00400	29 / 29	na
Specific conductance (µS/cm at 25°C)	00095	29 / 29	na
Water temperature (°C)	00010	29 / 29	na
INORGANICS			
Total dissolved solids, (residue at 180°C)	70300	29 / 29	1.0
Major ions (sample passed through 0.45-micron filter; MDL in mg/L unless otherwise noted)			
Bromide	71870	29 / 27	0.01
Calcium	00915	29 / 29	0.02
Chloride	00940	29 / 29	0.1
Fluoride	00950	29 / 18	0.1
Iron	01046	29 / 22	3.0 µg/L
Magnesium	00925	29 / 29	0.01
Manganese	01056	29 / 21	1.0 µg/L
Potassium	00935	29 / 29	0.1
Silica	00955	29 / 29	0.01
Sodium	00930	29 / 29	0.2
Sulfate	00945	29 / 29	0.1
Nutrients (sample passed through 0.45-micron filter; MDL in mg/L)			
Ammonia, as N (described as ammonium in text and appendix 2)	00608	29 / 21	0.015
Ammonia plus organic, as N (described as ammonium plus organic in text and appendix 2)	00623	29 / 7	0.2
Nitrite, as N	00613	29 / 3	0.01
Nitrite plus nitrate, as N	00631	29 / 12	0.05
Orthophosphorus, as P (described as orthophosphate in text and in appendix 2)	00671	29 / 2	0.01
Phosphorus, as P	00666	29 / 8	0.01
Radionuclides (whole water sample; MDL in pCi/L)			
Radon-222	82303	29 / 29	24
Tritium	07000	29 / 27	0.3
ORGANICS			
Dissolved organic carbon (sample passed through 0.45-micron silver filter)	00681	28 / 28	0.1 mg/L
Pesticides or metabolites (Schedules 2001 and 2010; sample passed through 0.7-micron filter; MDL in µg/L)			
Acetochlor	49260	29 / 0	0.002
Alachlor	46342	29 / 1	0.002
Atrazine	39632	29 / 6	0.001
Atrazine, deethyl[1]	04040	29 / 6	0.002
Azinphos, methyl-[1]	82686	29 / 0	0.001

Appendix 1. Water-quality constituents analyzed in ground-water samples from wells in the western part of the Cambrian-Ordovician aquifer—Continued

Constituent	Parameter code	Number of samples/ number of detections	Laboratory method detection limit (MDL)
Pesticides or metabolites (Schedules 2001 and 2010)—Continued			
Benfluralin	82673	29 / 0	0.002
Butylate	04028	29 / 0	0.002
Carbaryl (Sevin)[1]	82680	29 / 0	0.003
Carbofuran[1]	82674	29 / 0	0.003
Chlorpyrifos	38933	29 / 0	0.004
Cyanazine	04041	29 / 0	0.004
DCPA (Dacthal)	82682	29 / 0	0.002
DDE, p,p'-	34653	29 / 0	0.006
Diazinon	39572	29 / 0	0.002
Dieldrin	39381	29 / 0	0.001
Diethylaniline, 2'6-	82660	29 / 0	0.003
Disulfoton	82677	29 / 0	0.017
EPTC (Eptam)	82668	29 / 0	0.002
Ethalfluralin	82663	29 / 0	0.004
Ethoprop	82672	29 / 0	0.003
Fonofos	04095	29 / 0	0.003
HCH, alpha	34253	29 / 0	0.002
Lindane	39341	29 / 0	0.004
Linuron	82666	29 / 0	0.002
Malathion	39532	29 / 0	0.005
Meto!achlor	39415	29 / 1	0.002
Metribuzin	82630	29 / 0	0.004
Molinate	82671	29 / 0	0.004
Napropamide	82684	29 / 0	0.003
Parathion, ethyl-	39542	29 / 0	0.004
Parathion, methyl-	82667	29 / 0	0.006
Pebulate	82669	29 / 0	0.004
Pendimethalin	82683	29 / 0	0.004
Permethrin, cis-	82687	29 / 0	0.005
Phorate	82664	29 / 0	0.002
Prometon	04037	29 / 1	0.018
Pronamide	82676	29 / 0	0.003
Propachlor	04024	29 / 0	0.007
Propanil	82679	29 / 0	0.004
Propargite	82685	29 / 0	0.013
Simazine	04035	29 / 1	0.005
Thiobencarb	82670	29 / 0	0.002
Tebuthiuron	82665	29 / 0	0.01
Terbacil[1]	82675	29 / 0	0.007
Terbufos	82681	29 / 0	0.013
Triallate	82678	29 / 0	0.001
Trifluralin	82661	29 / 0	0.002

Appendix 1. Water-quality constituents analyzed in ground-water samples from wells in the western part of the Cambrian-Ordovician aquifer—Continued

Constituent	Parameter code	Number of samples/ number of detections	Laboratory method detection limit (MDL)
Pesticides or metabolites (Schedules 2050 and 2051; sample passed through 0.7-micron filter, MDL in µg/L)			
2,4,5-T	39742	29 / 0	0.035
2,4-D	39732	29 / 0	0.035
2,4-DB	38746	29 / 0	0.035
Acifluorfen (Blazer)	49315	29 / 0	0.035
Aldicarb	49312	29 / 0	0.016
Aldicarb sulfone	49313	29 / 0	0.016
Aldicarb sulfoxide	49314	29 / 0	0.021
Bentazon	38711	29 / 0	0.014
Bromacil	04029	29 / 0	0.035
Bromoxynil	49311	29 / 0	0.035
Carbaryl (Sevin)	49310	29 / 0	0.008
Carbofuran	49309	29 / 0	0.028
Carbofuran, 3-hydroxy-	49308	29 / 0	0.014
Chloramben (Ambien)	49307	29 / 0	0.011
Chlorothalonil[1]	49306	29 / 0	0.035
Clopyralid	49035	29 / 0	0.05
Dacthal, mono-acid-	49304	29 / 0	0.017
Dicamba	38442	29 / 0	0.035
Dichlobenil[1]	49303	29 / 1	0.02
Dichlorprop	49302	29 / 0	0.032
Dinoseb	49301	29 / 0	0.035
Diuron	49300	29 / 0	0.02
DNOC[1]	49299	29 / 0	0.035
Esfenvalerate[1]	49298	29 / 0	0.019
Fenuron	49297	29 / 0	0.013
Fluometuron	38811	29 / 0	0.035
Linuron	39478	29 / 0	0.018
MCPA	38482	29 / 0	0.05
MCPB	38487	29 / 0	0.035
Methiocarb	38501	29 / 0	0.026
Methomyl	49296	29 / 0	0.017
1-Naphthol[1]	49295	29 / 0	0.007
Neburon	49294	29 / 0	0.015
Norflurazon	49293	29 / 0	0.024
Oryzalin	49292	29 / 0	0.019
Oxamyl	38866	29 / 0	0.018
Picloram	49291	29 / 0	0.05
Propham	49236	29 / 0	0.035
Propoxur	38538	29 / 0	0.035
Silvex	39762	29 / 0	0.021
Triclopyr	49235	29 / 0	0.05

Appendix 1. Water-quality constituents analyzed in ground-water samples from wells in the western part of the Cambrian-Ordovician aquifer—Continued

Constituent	Parameter code	Number of samples/ number of detections	Laboratory method detection limit (MDL)
Volatile organic compounds (whole water sample; MDL in µg/L)			
Benzene	34030	26 / 0	0.2
Benzene, 1,2,3-trichloro-	77613	26 / 0	0.2
Benzene, 1,2,4-trichloro-	34551	26 / 0	0.2
Benzene, 1,2,4-trimethyl-	77222	26 / 0	0.2
Benzene, 1,2-dichloro-	34536	26 / 0	0.2
Benzene, 1,3,5-trimethyl-	77226	26 / 0	0.2
Benzene, 1,3-dichloro-	34566	26 / 0	0.2
Benzene, 1,4-dichloro-	34571	26 / 0	0.2
Benzene, 1-chloro-2-methyl-	77275	26 / 0	0.2
Benzene, 1-chloro-4-methyl-	77277	26 / 0	0.2
Benzene, isopropyl-	77223	26 / 0	0.2
Benzene, bromo-	81555	26 / 0	0.2
Benezene, chloro-	34301	26 / 0	0.2
Benzene, dimethyl- (Xylene)	81551	26 / 0	0.2
Benzene, ethyl-	34371	26 / 0	0.2
Benzene, 1-methyl-4-isopropyl-	77356	26 / 0	0.2
Benzene, methyl- (Toluene)	34010	26 / 0	0.2
Benzene, n-butyl-	77342	26 / 0	0.2
Benzene, n-propyl-	77224	26 / 0	0.2
Benzene, sec-butyl-	77350	26 / 0	0.2
Benzene, tert-butyl-	77353	26 / 0	0.2
Ethane, 1,1,1,2-tetrachloro-	77562	26 / 0	0.2
Ethane, 1,1,1-trichloro-	34506	26 / 0	0.2
Ethane, 1,1,2,2-tetrachloro-	34516	26 / 0	0.2
Ethane, 1,1,2-trichloro-	34511	26 / 0	0.2
Ethane, 1,1-dichloro-	34496	26 / 0	0.2
Ethane, 1,2-dibromo-	77651	26 / 0	0.2
Ethane, 1,2-dichloro-	32103	26 / 0	0.2
Ethane, chloro-	34311	26 / 0	0.2
Ethane, trichlorotrifluoro-	77652	26 / 0	0.2
Ethylene, 1,1-dichloro-	34501	26 / 0	0.2
Ethylene, chloro- (Vinyl chloride)	39175	26 / 0	0.2
Ethylene, cis-1,2-dichloro-	77093	26 / 0	0.2
Ethylene, tetrachloro-	34475	26 / 0	0.2
Ethylene, trans-1,2-dichloro-	34546	26 / 0	0.2
Ethylene, trichloro-	39180	26 / 0	0.2
Hexachlorobutadiene	39702	26 / 0	0.2
Methane, bromo-	34413	26 / 0	0.2
Methane, bromochloro-	77297	26 / 0	0.2

Appendix 1. Water-quality constituents analyzed in ground-water samples from wells in the western part of the Cambrian-Ordovician aquifer—Continued

Constituent	Parameter code	Number of samples/ number of detections	Laboratory method detection limit (MDL)
Volatile organic compounds—Continued			
Methane, chloro- (methyl chloride)	34418	26 / 0	0.2
Methane, dibromo-	30217	26 / 0	0.2
Methane, dibromochloro-	32105	26 / 0	0.2
Methane, dichloro- (methylene chloride)	34423	26 / 2	0.2
Methane, dichlorobromo-	32101	26 / 0	0.2
Methane, dichlorodifluoro-	34668	26 / 0	0.2
Methane, tetrachloro-	32102	26 / 0	0.2
Methane, tribromo-	32104	26 / 0	0.2
Methane, trichloro- (chloroform)	32106	26 / 0	0.2
Methane, trichlorofluoro-	34488	26 / 0	0.2
Naphthalene	34696	26 / 0	0.2
Propane, 1,2,3-trichloro-	77443	26 / 0	0.2
Propane, 1,2-dibromo-3-chloro-	82625	26 / 0	1.0
Propane, 1,2-dichloro-	34541	26 / 0	0.2
Propane, 1,3-dichloro-	77173	26 / 0	0.2
Propane, 2,2-dichloro-	77170	26 / 0	0.2
Propene, 1,1-dichloro-	77168	26 / 0	0.2
Propene, 2-methoxy-2-methyl- (MTBE)	78032	26 / 0	0.2
Propene, cis-1,3-dichloro-	34704	26 / 0	0.2
Propene, trans-1,3-dichloro-	34699	26 / 0	0.2
Styrene	77128	26 / 0	0.2

[1] These pesticides or metabolites demonstrated variable recoveries and are reported as estimated values in appendix 2 if measured concentrations were above the MDL.

Appendix 2a. Selected water-quality data for sampled wells in the western part of the Cambrian-Ordovician aquifer

[All concentrations are in milligrams per liter unless otherwise indicated. Additional information about each constituent can be found in appendix 1. yyyy, year; mm, month; dd, day; °C, degrees Celsius; µS/cm, microsiemens per centimeter; --, no data]

Well number	Sample date (yyyymmdd)	Sample time	Temperature (°C)	Specific conductance (µS/cm at 25°C)	Dissolved oxygen	pH (standard units)	Bicarbonate, as HCO_3^-
Well 1a	19950612	1700	10.8	196	9.9	7.1	439
Well 1b	19950612	1140	16.0	278	8.7	7.1	493
Well 2	19950613	1345	11.0	387	5.6	7.6	229
Well 3a	19950612	1100	9.7	549	.2	7.0	286
Well 3b	19950613	0940	10.1	315	7.3	7.6	181
Well 4a	19950613	1000	9.6	1,010	2.4	7.0	466
Well 4b	19950613	1800	10.5	678	8.9	7.3	329
Well 5a	19950613	1630	10.5	460	.2	7.7	222
Well 5b	19950613	1330	11.4	349	.1	8.1	222
Well 6	19950621	1500	9.8	804	.3	7.1	381
Well 7a	19950614	1500	10.1	624	.2	7.2	349
Well 7b	19950615	0930	9.4	593	.2	7.3	390
Well 8	19950614	1200	10.3	641	3.7	7.0	390
Well 9	19950614	0930	9.7	546	2.8	7.3	356
Well 10a	19950824	1200	15.0	685	2.3	7.2	181
Well 10b	19950831	1400	12.6	3,010	.3	7.1	117
Well 11	19950612	1300	10.5	605	2.6	7.1	376
Well 14	19950614	1300	12.5	2,410	--	7.0	172
Well 15	19950621	1020	15.1	657	.9	7.5	203
Well 16	19950615	1030	10.4	578	.3	7.3	322
Well 18	19950619	1400	8.5	509	.1	7.4	300
Well 19	19950615	1430	10.6	2,960	.3	7.6	110
Well 25	19950615	1330	8.7	470	.2	7.4	320
Well 26a	19950620	1030	10.0	450	.1	7.3	251
Well 26b	19950620	1340	9.8	454	.1	7.4	295
Well 27	19950620	1600	9.9	441	.1	7.3	273
Well 28	19950620	1000	8.0	453	.3	7.7	268
Well 29	19950620	1330	8.8	385	8.5	7.3	242
Well 30	19950620	1645	7.6	317	4.8	7.7	190

Appendix 2b. Selected water-quality data for sampled wells in the western part of the Cambrian-Ordovician aquifer

[All concentrations are in milligrams per liter unless otherwise indicated. Additional information about each constituent can be found in appendix 1. µg/L, micrograms per liter;<, less than]

Well number	Bromide	Calcium	Chloride	Fluoride	Iron, in µg/L	Magnesium	Manganese, in µg/L	Potassium	Silica	Sodium
Well 1a	0.03	68	1.6	<0.1	<3.0	37	<1.0	0.4	13	1.5
Well 1b	.07	91	37	.1	<3.0	47	<1.0	1.0	11	21
Well 2	<.01	42	1.2	<.1	7.0	25	<1.0	.6	14	2.1
Well 3a	.06	61	6.3	.1	770	34	9.0	1.0	15	3.7
Well 3b	.02	35	3.0	<.1	<3.0	19	<1.0	.5	14	1.9
Well 4a	.05	110	49	<.1	<3.0	62	2.0	1.9	20	13
Well 4b	.06	73	17	<.1	<3.0	36	<1.0	1.1	14	13
Well 5a	.01	43	7.7	.2	<3.0	33	36	1.5	13	5.5
Well 5b	.03	15	1.9	1.4	29	22	7.0	2.1	16	30
Well 6	.05	96	30	<.1	100	42	26	1.6	15	6.2
Well 7a	.03	70	20	<.1	750	39	20	1.0	19	4.5
Well 7b	.05	71	.9	.2	240	39	65	1.2	12	1.3
Well 8	.03	78	1.6	.3	680	38	34	3.0	16	3.2
Well 9	.03	61	1.5	.1	<3.0	38	<1.0	1.4	17	2.7
Well 10a	.23	70	56	.8	500	19	44	3.3	11	46
Well 10b	.83	530	200	.8	3,200	44	66	12	6.9	130
Well 11	.05	68	5.9	.2	5.0	39	<1.0	1.1	15	3.5
Well 14	1.4	330	270	1.9	1,000	55	54	16	7.5	150
Well 15	.22	61	35	2.5	120	22	17	6.4	6.9	31
Well 16	.06	59	8.7	<.1	430	32	32	2.4	8.1	5.1
Well 18	.09	64	2.9	<.1	1,200	28	32	.8	11	1.9
Well 19	.43	550	71	1.7	360	130	39	7.9	22	69
Well 25	.03	61	4.4	.2	170	24	24	2.5	12	3.9
Well 26a	.06	55	5.4	.2	370	22	18	3.3	12	5.1
Well 26b	.05	53	6.5	.3	240	21	4.0	3.5	8.7	9.5
Well 27	.03	58	.8	.2	550	21	16	3.3	7.9	2.7
Well 28	.04	53	2.7	.4	84	23	6.0	2.9	7.2	6.8
Well 29	<.01	54	1.1	<.1	280	18	19	.9	13	1.7
Well 30	.01	37	.9	<.1	5.0	18	<1.0	.8	11	1.7

Appendix 2c. Selected water-quality data for sampled wells in the western part of the Cambrian-Ordovician aquifer

[All concentrations are in milligrams per liter unless otherwise indicated. Additional information about each constituent can be found in appendix 1. pCi/L, picocuries per liter; <, less than]

Well number	Sulfate	Total dissolved solids	Ammonium, as N	Ammonium plus organic, as N	Nitrite, as N	Nitrite plus nitrate, as N	Ortho phosphate, as P	Phosphorus, as P	Tritium, in pCi/L	Radon-222, in pCi/L
Well 1a	15	317	<0.015	0.30	<0.01	1.3	<0.01	0.03	37	270
Well 1b	25	507	<.015	<.20	<.01	16.0	<.01	<.01	48	170
Well 2	14	210	<.015	<.20	<.01	1.3	<.01	<.01	40	180
Well 3a	59	329	.02	<.20	<.01	<.05	<.01	<.01	7.6	230
Well 3b	5.7	171	<.015	<.20	<.01	2.4	.03	.03	30	150
Well 4a	54	608	<.015	<.20	.01	16	<.01	<.01	48	1,000
Well 4b	23	412	<.015	<.20	<.01	23	<.01	<.01	58	220
Well 5a	34	263	<.015	<.20	.16	3.2	<.01	<.01	62	540
Well 5b	5.3	192	.13	<.20	<.01	<.05	.01	.01	.6	770
Well 6	67	472	.02	.20	.01	.21	<.01	<.01	140	600
Well 7a	41	366	.02	<.20	<.01	<.05	<.01	<.01	150	590
Well 7b	6.8	331	.04	<.20	<.01	<.05	<.01	.01	.9	740
Well 8	93	385	.10	<.20	<.01	<.05	<.01	<.01	4.4	1,100
Well 9	11	302	.02	<.20	<.01	.95	<.01	<.01	3.0	740
Well 10a	130	457	<.015	<.20	<.01	<.05	<.01	<.01	6.3	1,300
Well 10b	1,500	2,680	.32	<.20	<.01	<.05	<.01	<.01	.3	130
Well 11	27	345	.02	<.20	<.01	1.4	<.01	.03	12	850
Well 14	830	1,850	.19	<.20	<.01	.05	<.01	<.01	<.3	230
Well 15	110	399	.07	<.20	<.01	<.05	<.01	<.01	.9	320
Well 16	19	295	.05	<.20	<.01	<.05	<.01	.01	6.8	690
Well 18	16	272	.04	<.20	<.01	<.05	<.01	<.01	14	640
Well 19	1,700	2,800	.32	.30	<.01	<.05	<.01	.02	1.7	620
Well 25	12	262	.26	.30	<.01	<.05	<.01	.01	9.0	580
Well 26a	14	245	.16	.20	<.01	<.05	<.01	<.01	.3	680
Well 26b	16	246	.16	.20	<.01	<.05	<.01	<.01	<.3	220
Well 27	12	235	.06	<.20	<.01	<.05	<.01	<.01	1.1	290
Well 28	17	245	.07	<.20	<.01	<.05	<.01	<.01	.4	750
Well 29	1.8	226	.08	.30	<.01	<.05	<.01	<.01	.8	410
Well 30	10	171	.03	<.20	<.01	.27	<.01	<.01	44	1,400

Appendix 2d. Selected water-quality data for sampled wells in the western part of the Cambrian-Ordovician aquifer

[All concentrations are in milligrams per liter unless otherwise indicated. Additional information about each constituent can be found in appendix 1. μg/L, micrograms per liter; pCi/L, picocuries per liter; <, less than; E, estimated; --, no data]

Well number	Dissolved organic carbon (DOC)[1]	Alachlor, in μg/L	Atrazine, in μg/L	Deethyl atrazine, in μg/L	Dichlobenil, in μg/L	Metolachlor, in μg/L	Prometon, in μg/L	Simazine, in μg/L	Methylene chloride, in μg/L[2]
Well 1a	2.5	<0.002	0.083	E 0.039	<0.02	<0.002	<0.018	<0.005	<0.2
Well 1b	1.4	<.002	.012	E .02	<.02	<.002	<.018	<.005	<.2
Well 2	.5	<.002	<.001	<.002	<.02	<.002	<.018	<.005	<.2
Well 3a	.6	<.002	<.001	<.002	<.02	<.002	<.018	<.005	<.2
Well 3b	.3	<.002	.007	E .062	<.02	<.002	<.018	<.005	<.2
Well 4a	.9	<.002	.15	E .23	<.02	<.002	.14	<.005	<.2
Well 4b	1.2	.096	2.6	E 2.0	<.02	1.2	<.018	.017	<.2
Well 5a	1.2	<.002	<.001	<.002	<.02	<.002	<.018	<.005	<.2
Well 5b	.6	<.002	<.001	<.002	<.02	<.002	<.018	<.005	<.2
Well 6	--	<.002	<.001	<.002	<.04	<.002	<.018	<.005	<.2
Well 7a	.7	<.002	<.001	<.002	<.04	<.002	<.018	<.005	<.2
Well 7b	.5	<.002	<.001	<.002	<.02	<.002	<.018	<.005	<.2
Well 8	1.2	<.002	<.001	<.002	<.02	<.002	<.018	<.005	<.2
Well 9	.5	<.002	<.001	<.002	<.02	<.002	<.018	<.005	<.2
Well 10a	.9	<.002	<.001	<.002	<.02	<.002	<.018	<.005	<.2
Well 10b	.5	<.002	<.001	<.002	<.02	<.002	<.018	<.005	<.2
Well 11	.4	<.002	.003	E .006	<.02	<.002	<.018	<.005	--
Well 14	.3	<.002	<.001	<.002	<.02	<.002	<.018	<.005	.3
Well 15	2.1	<.002	<.001	<.002	<.04	<.002	<.018	<.005	--
Well 16	1.1	<.002	<.001	<.002	<.02	<.002	<.018	<.005	--
Well 18	1.0	<.002	<.001	<.002	<.02	<.002	<.018	<.005	<.2
Well 19	.3	<.002	<.001	<.002	<.02	<.002	<.018	<.005	<.2
Well 25	1.3	<.002	<.001	<.002	<.02	<.002	<.018	<.005	<.2
Well 26a	1.4	<.002	<.001	<.002	<.02	<.002	<.018	<.005	<.2
Well 26b	1.2	<.002	<.001	<.002	<.02	<.002	<.018	<.005	<.2
Well 27	.8	<.002	<.001	<.002	E .06	<.002	<.018	<.005	<.2
Well 28	1.1	<.002	<.001	<.002	<.02	<.002	<.018	<.005	<.2
Well 29	5.7	<.002	<.001	<.002	<.04	<.002	<.018	<.005	<.2
Well 30	2.0	<.002	<.001	<.002	<.04	<.002	<.018	<.005	.2

[1]DOC was detected in field blank samples at concentrations ranging from .2 to 4.6 mg/L. For this reason measured DOC concentrations in ground-water samples may be questionable.

[2]Methylene chloride concentrations above the MDL may be due to laboratory contamination of those samples.

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