Hydrology, Water Quality, and Effects of Drought in Monroe County, Michigan

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 94-4161

Prepared in cooperation with
MONROE COUNTY,
THE TOWNSHIPS OF MONROE COUNTY,
THE CITY OF PETERSBURG,
THE CITY OF MONROE, AND THE
MICHIGAN DEPARTMENT OF NATURAL RESOURCES,
GEOLOGICAL SURVEY DIVISION

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By J.R. Nicholas, Gary L. Rowe, and J.R. Brannen

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Lansing, Michigan
1996

DEPARTMENT OF THE INTERIOR
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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	2.590	square kilometer
acre	0.4047	square hectometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
ton	0.9072	megagram
ton per acre-foot (ton/acre-ft)	0.07358	megagram per cubic hectometer

Temperature is given in degrees Celsius (°C), which 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 used in this report: 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.

Specific conductance of water is expressed in microsiemens per centimeter at 25 degrees Celsius (µS/cm). This unit is equivalent to micromhos per centimeter at 25 degrees Celsius (µmho/cm), formerly used by the U.S. Geological Survey.

Stable isotope ratios are indicated by use of the delta symbol(δ) and are expressed in parts per thousand (permil).

Tritium concentration is expressed in tritium units (TU); one tritium unit is equal to one tritium atom per 101^{8} hydrogen atoms; it is also equivalent to 3.24 picocuries per liter. Carbon-14 activities are reported as percent modern carbon (pmc).

Concentrations of bacteria are expressed in number of colonies per 100 milliliters of sample (col./100mL).

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ABSTRACT

Monroe County relies heavily on its aquifers and streams for drinking water, irrigation, and other uses; however, increased water use, high concentrations of certain constituents in ground water, and droughts may limit the availability of water resources. Although the most densely populated parts of the county use water from the Great Lakes, large amounts of ground water are withdrawn for quarry dewatering, domestic supply, and irrigation.

Unconsolidated deposits and bedrock of Silurian and Devonian age underlie Monroe County. The unconsolidated deposits are mostly clayey and less than 50 feet thick. Usable amounts of ground water generally are obtained from thin, discontinuous surficial sand deposits or, in the northwestern part of the county, from deep glaciofluvial deposits. In most of the county, however, ground water in unconsolidated deposits is highly susceptible to effects of droughts and to contamination.

The bedrock is mostly carbonate rock, and usable quantities of ground water can be obtained from fractures and other secondary openings throughout the county. Transmissivities of the Silurian-Devonian aquifer range from 10 to 6,600 feet squared per day. Aquifer tests and historical information indicate that the Silurian-Devonian aquifer is confined throughout most of the county. The major recharge area for the Silurian-Devonian aquifer in Monroe County is in the southwest, and ground-water flow is mostly southeastward toward Lake Erie. In the northeastern and southeastern parts of the county, the potentiometric surface of the Silurian-Devonian aquifers has been lowered by pumpage to below the elevation of Lake Erie.

Streams and artificial drains in Monroe County are tributary to Lake Erie. Most streams are perennial because of sustained discharge from the sand aquifer and the Silurian-Devonian aquifer; however, the lower reaches of River Raisin and Plum Creek lost water to the Silurian-Devonian aquifer in July 1990.

The quality of ground water and of streamwater at low flow is suitable for most domestic uses, irrigation, and recreation. In ground water, dissolved solids and hydrogen sulfide are present at concentrations objectionable to some users. Indicators of ground-water contamination from agricultural activities—pesticides and nitrates—were not present at detectable concentrations or were below U.S. Environmental Protection Agency (USEPA) limits. In streamwater, some treatment to remove bacteria may be necessary in summer months; nitrate concentrations, however, were found to be below USEPA limits.

Tritium concentrations indicative of recent recharge to the Silurian-Devonian aquifer are present in a southwest-to-northeast-trending band from Whiteford to Berlin Townships. Generally, where glacial deposits are thicker than 30 feet, recharge takes more than 40 years. Carbon isotope data indicate that some of the ground water in the Silurian-Devonian aquifer is more than 14,000 years old.

Mild droughts are common in Michigan, but long severe droughts, such as those during 1930-37 and 1960-67, are infrequent. The most recent drought, during 1988, was severe but short. Ground-water levels declined throughout the county; the largest declines were probably in the southwest. Shallow bedrock wells completed in only the upper part of the Silurian-Devonian aquifer and near large uses of ground water were especially susceptible to the effects of drought. Deep bedrock wells continued to produce water through the drought of 1988.

During droughts, streamflow is reduced because of low ground-water levels and high consumptive uses of surface water. In 1988, annual discharge on the River Raisin was near normal, but monthly averages were below normal from March through August. The quality of surface water during droughts is similar to that during normal low-flow conditions.

INTRODUCTION

Monroe County, Michigan relies heavily on its aquifers and streams for drinking water, irrigation, and water for other uses. In parts of the county, however, ground water at moderate depths can contain objectionable amounts of hydrogen sulfide or can be highly mineralized, and aquifers that yield water of suitable quality for most uses are heavily stressed. Historically, droughts in Monroe County have limited the availability of ground water. Although surface-water resources are usually sufficient in the county and of suitable quality for most uses, these resources also are susceptible to the effects of drought.

The recent short-duration drought of 1988 emphasized the need for an improved understanding of the water resources in Monroe County. Consequently, the U.S. Geological Survey (USGS) began a study to provide additional detail about quantity and quality of water in Monroe County. The study, which took place during 1989-92, was done in cooperation with Monroe County, the townships of Monroe County, the cities of Petersburg and Monroe, and the Geological Survey Division of the Michigan Department of Natural Resources.

Purpose and Scope

This report describes the results of the USGS study in Monroe County. The report focuses on (1) ground-water occurrence and quality in unconsolidated deposits and the freshwater part of the bedrock and (2) the quantity and quality of water in streams. Particular emphasis is given to water in the bedrock aquifer. The effects of drought on ground water and surface water are discussed on the basis of historical information from drought periods and on findings from this study.

Thirty-two observation wells were installed in the bedrock, and one was installed in the unconsolidated deposits. Geologic and hydrologic information—including drill cuttings, borehole-geophysical logs, water levels, hydraulic-test data, and water-quality samples—were collected from these wells. Water-quality samples were also collected from 10 domestic wells. The report includes ground-water-level data collected by the Monroe County Health Department from 1992 through July 1993.

Stream stage was measured continuously during the study at two gaging stations, the River Raisin near Monroe and Otter Creek near LaSalle. Streamflow was measured at 22 other locations during low-flow periods in 1990. Samples for water-quality analysis were collected at these 24 locations. The report includes fecal coliform data from surface-water samples collected and analyzed by the Monroe County Health Department in 1990-91.

Acknowledgments

The authors thank Jim Neorr, Larry Pickens and other staff at the Monroe County Health Department for providing assistance in the field and office, and they thank Royce Maniko and his staff at the Monroe County Planning Commission and Department for providing needed information. Without their support, this study would not have been accomplished. Appreciation is also is expressed to the owners of domestic wells in Monroe County who made their wells available for measurement of water levels and collection of ground-water samples.

DESCRIPTION OF STUDY AREA

Monroe County is in southeastern Michigan (fig. 1). Lake Erie forms the eastern border of the county, and the Huron River forms the northeastern border. The remaining borders are political: Lenawee, Washtenaw, and Wayne Counties and the State of Ohio. The River Raisin, which drains most of the northwestern part of the county, flows into Lake Erie at the city of Monroe. Most of the county is a plain with low relief that slopes southeastward toward Lake Erie. Land-surface altitude ranges from 572 ft above sea level at Lake Erie to about 740 ft in the northwestern part of the county (fig. 2).

Monroe County has a semimarine type of climate because of the influence of Lake Erie (Blumer and others, 1991). Lake Erie is a regional source of moisture for precipitation and has a moderating effect on temperature. Average annual precipitation at the city of Monroe from 1970 through 1990 was 33.58 in. (National Oceanic and Atmospheric Administration, 1970-90). Mean monthly precipitation for the same period at Monroe ranged from 1.54 in. in January to 3.69 in. in June. Mean monthly temperatures ranged from 23.3 °F in January to 74.6 °F in July.

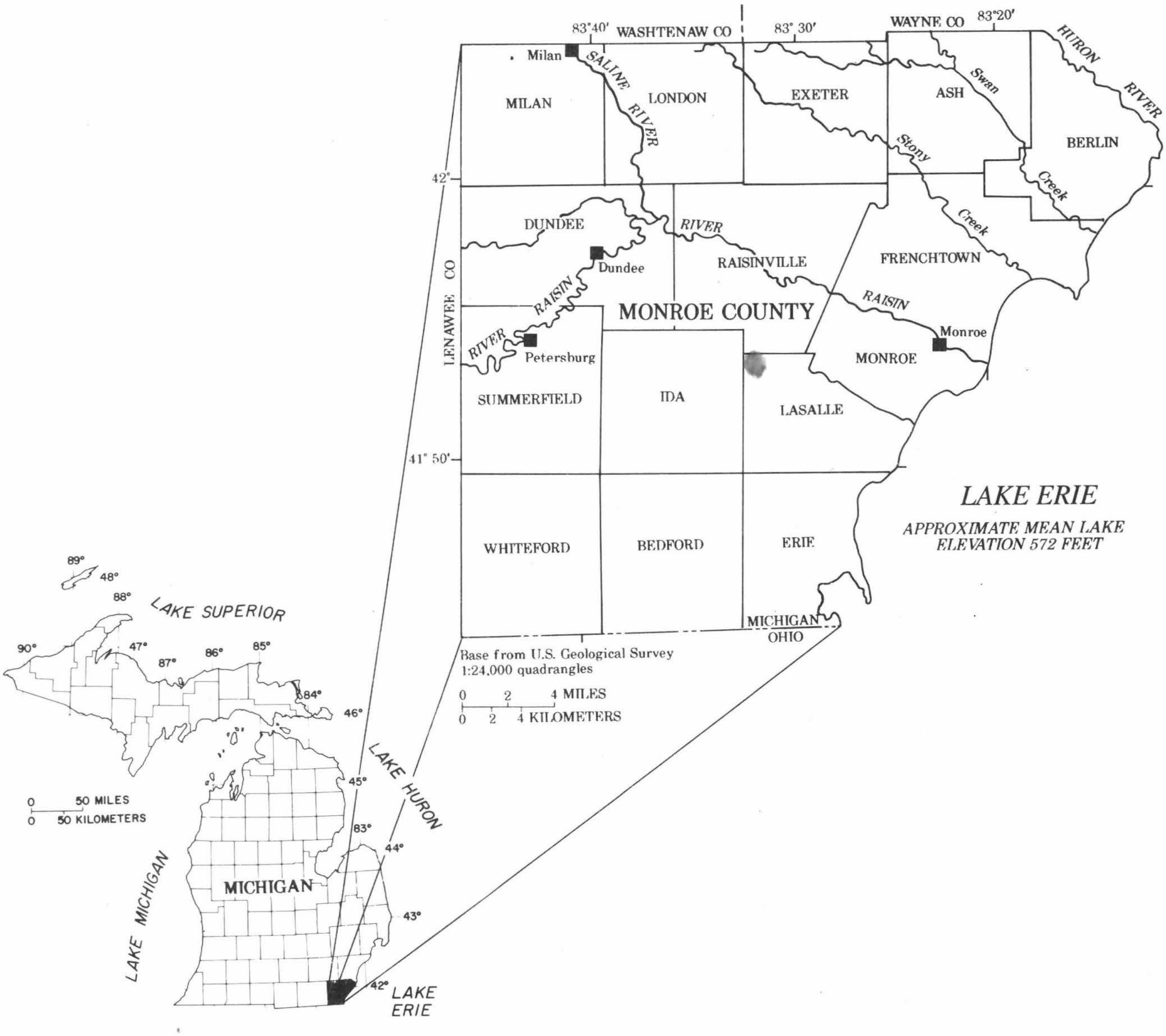
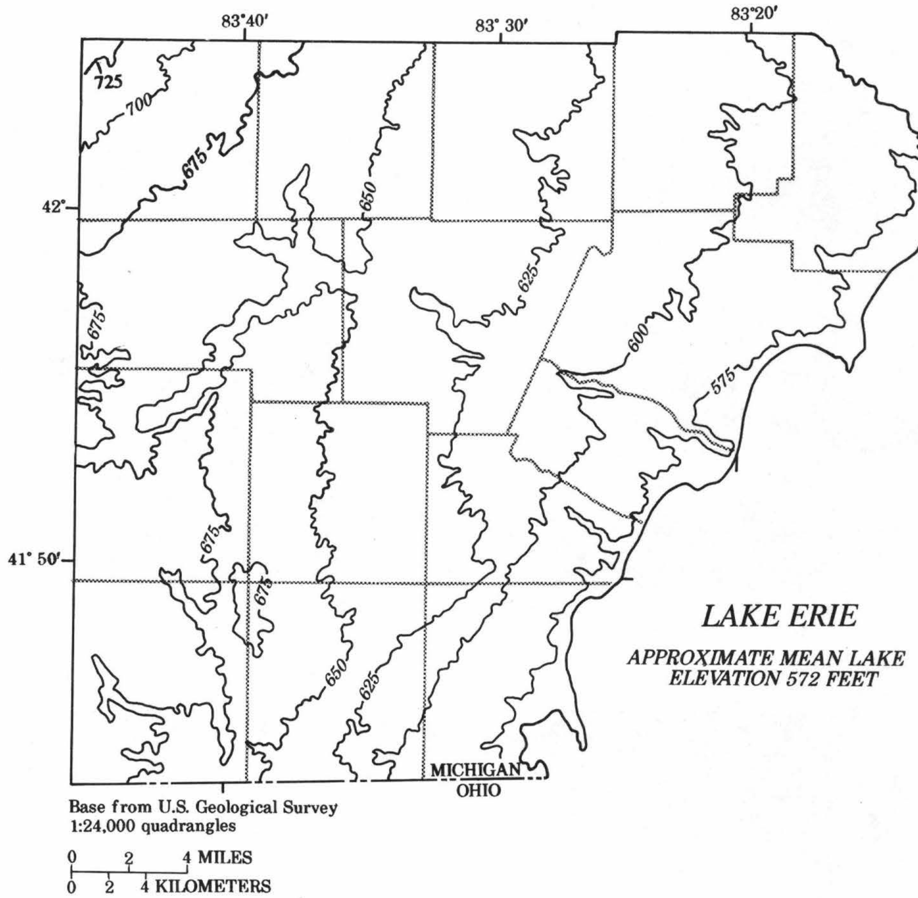


Figure 1. Location of Monroe County, Michigan.

Land Use and Water Use

The county comprises about 562 mi^2, of which three-quarters is agricultural land, mostly field crops (Monroe County Planning Commission and Department, written commun., 1993). Forest, urban and residential, and open land account for 9, 8, and 3 percent of land use, respectively. Remaining land uses are less than 1 percent each. Land use by township is shown on figure 3.

About 134,000 people live in Monroe County (U.S. Bureau of the Census, 1991). The largest community is the city of Monroe which has a population of 23,000. More than half of the people in the county live in Bedford, Frenchtown, and Monroe Townships; Bedford is the most populated township.



EXPLANATION

—— *575* —— LINE OF EQUAL ALTITUDE OF LAND SURFACE--Contour interval 25 feet. Datum is sea level

Figure 2. Topography of Monroe County, Michigan.

Residents in the most densely populated parts of Monroe County depend on surface water from three major municipal suppliers (Monroe County Planning Department, 1985). The city of Monroe supplies itself and parts of Frenchtown, Raisinville, and Monroe Townships. The city of Toledo (Ohio) supplies parts of Bedford, Erie, and LaSalle Townships. The Detroit Metropolitan Water Board supplies parts of Ash and Berlin Townships. Daily water use in all of these areas is about 12 Mgal/d (Monroe County Planning Department, 1985).

Residents in the remainder of Monroe County depend on municipal ground-water or surface-water supplies or on individual wells. Milan and Petersburg have municipal wells; Dundee uses water from the River Raisin. Daily water use in these three municipalities is about 1.3 Mgal/d, of which about 0.3 Mgal/d is surface water (Monroe County Planning Department, 1985). Daily water use from individual wells is about 2 Mgal/d (T. E. Behrendt, U.S. Geological Survey, written commun., 1993).

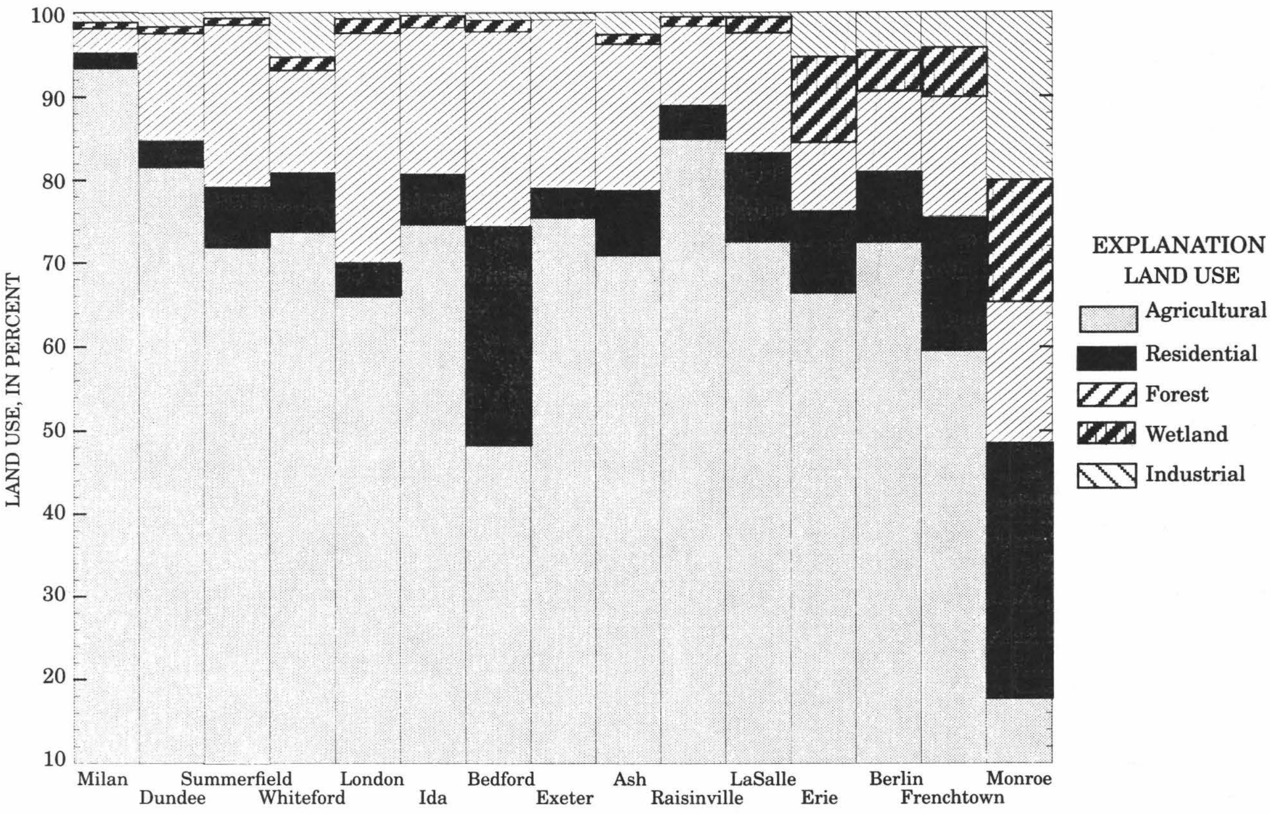


Figure 3. Land use by percentage of township, Monroe County, Michigan.

Farming is an important part of the county's economy, and most crops can be raised satisfactorily if rainfall is normal. Irrigation, however, increases yields and sustains crop growth during dry periods. In 1977, about 2,200 acres of agricultural land was irrigated with 387 Mgal of water by 27 irrigators (Bedell and Van Til, 1979). Ground water and surface water were used nearly equally for irrigation. In 1987, about 2,400 acres of agricultural land was irrigated (Paul Marks, Monroe County Agricultural Extension Service, oral commun., 1993). Most of the irrigation was in southern Dundee Township, Summerfield Township, and northern Bedford Township (Monroe County Health Department, oral commun., 1993).

Although quarries are not a major land use (0.4 percent), large amounts of ground water are pumped from them during mining. From January 1991 through October 1992, an average of 9.2 Mgal/d—about 70 percent of the ground-water use in the county—was pumped from six active quarries in Monroe County (Monroe County Health Department, written commun., 1993) (pl. 1).

Geologic Setting

Monroe County is underlain by sedimentary rock of Silurian and Devonian age, mostly carbonate rock and sandstone. Unconsolidated deposits, the result of Pleistocene continental glaciation and high stages of ancestral Lake Erie, overlie the bedrock surface throughout most of the county.

The Silurian and Devonian bedrock units consists of, in ascending order, the Salina Group, the Bass Islands Dolomite, the Detroit River Dolomite, the Dundee Formation, the Traverse Group, and the Antrim Shale (fig. 4). In Monroe County, the Detroit River Dolomite has been informally subdivided into the basal Sylvania Sandstone and the upper Detroit River Dolomite by Mozola (1970), and this division is used throughout this report. Because the county is on the southeastern rim of the Michigan Basin, the bedrock subcrops are oldest in the southeast part of the county and youngest in the northwest. Bedrock units strike northeast-southwest and dip about 50 ft/mi to the northwest (Mozola, 1970). All of the bedrock units are fractured, and sinkholes are present in the southwestern part of the county.

Thirty-two USGS observation wells were drilled into the bedrock in Monroe County. Borehole-geophysical logs were run in five of the wells (Appendix 1). Lithologic descriptions in the following paragraphs are based on logs of drill cuttings from the USGS wells (Appendix 2).

The oldest rock unit in Monroe County is the Salina Group. The Salina Group is a subcrop in the southeastern part of the county in Bedford, Erie, LaSalle and Monroe Townships. The rock unit is not reported to crop out in the county (Mozola, 1970). Two USGS wells (G32, and G33; pl. 1) were drilled into the Salina Group. Drill cuttings indicate that the Salina Group is composed of interbedded limestone, shale, and dolomite. The limestone is brown and gray and has small vugs. The dolomite is also brown and gray and has a microcrystalline to sucrosic texture. Porosity occurs as fractures and vugs. Calcite and celestite crystals are present in some vugs. Some drill cuttings from the dolomite had petroliferous odors.

The Bass Islands Dolomite unconformably overlies the Salina Group (Dorr and Eschman, 1970). The Bass Islands Dolomite is a subcrop in Whiteford, Summerfield, Bedford, Ida, Erie, LaSalle, Monroe, Raisinville, Frenchtown, Ash, and Berlin Townships. The Bass Islands Dolomite crops out in LaSalle Township (Mozola, 1970), near S19 (pl. 1) on South Otter Creek; near S22 (pl. 1) on North Ten Mile Creek; and in Muddy Creek, Swan Creek, Stony Creek, and the River Raisin (Sherzer, 1900). The Bass Islands Dolomite is being quarried in Whiteford and Monroe Townships, and a sinkhole has been reported in Bedford Township (Mozola, 1970). Eight USGS wells (G2, G15, G16, G17, G18, G29, G30 and G31, pl. 1) were drilled into the Bass Islands Dolomite. The Bass Islands Dolomite is composed of interbedded limestone and dolomite. The limestone is brown and gray and has small vugs. The dolomite is also brown and gray and has a dense microcrystalline texture. Porosity occurs as fractures and vugs. Calcite and celestite crystals are present in some vugs. Native sulfur is present in shallow fractures but not in deeper fractures. Some drill cuttings from the dolomite had petroliferous odors.

The Sylvania Sandstone unconformably overlies the Bass Islands Dolomite (Dorr and Eschman, 1970). The Sylvania Sandstone is a subcrop in Whiteford, Summerfield, Bedford, Ida, Erie, LaSalle, Monroe, Raisinville, Frenchtown, Ash, Exeter, and Berlin Townships. The Sylvania Sandstone crops out along the River Raisin near SLTO (see pl. 1); near well G14 (Mozola, 1970); and in Stony Creek, Sandy Creek, Plum Creek, Otter Creek, Little Lake Creek, and Tamarack Creek (Sherzer, 1900). The Sylvania Sandstone is being quarried in Berlin Township south of Rockwood. Six USGS wells (G1, G3, G4, G14, G19, G27, and pl. 1) were drilled into the Sylvania Sandstone. Drill cuttings indicate that the Sylvania Sandstone is white to light gray quartz sandstone. The grains are moderately to well sorted and held together by a friable, calcitic cement. Pyrite was noted in samples from well G4. Native sulfur, calcite, and celestite have been reported in geodes from the Sylvania Sandstone (Mozola, 1970).

The Detroit River Dolomite conformably overlies the Sylvania Sandstone (Mozola, 1970). The Detroit River Dolomite is a subcrop in Whiteford, Summerfield, Dundee, Ida, London, Exeter, Milan, Raisinville, Ash, and Berlin Townships. According to Mozola (1970), the Detroit River Dolomite does not crop out in the county; however, Sherzer (1900) reported outcrops along the River Raisin upstream from Petersburg and at the mouth of Macon Creek. The Detroit River Dolomite is being quarried in London Township and near the City of Maybee, and sinkholes have been reported in Whiteford and Ida Townships (Mozola, 1970).

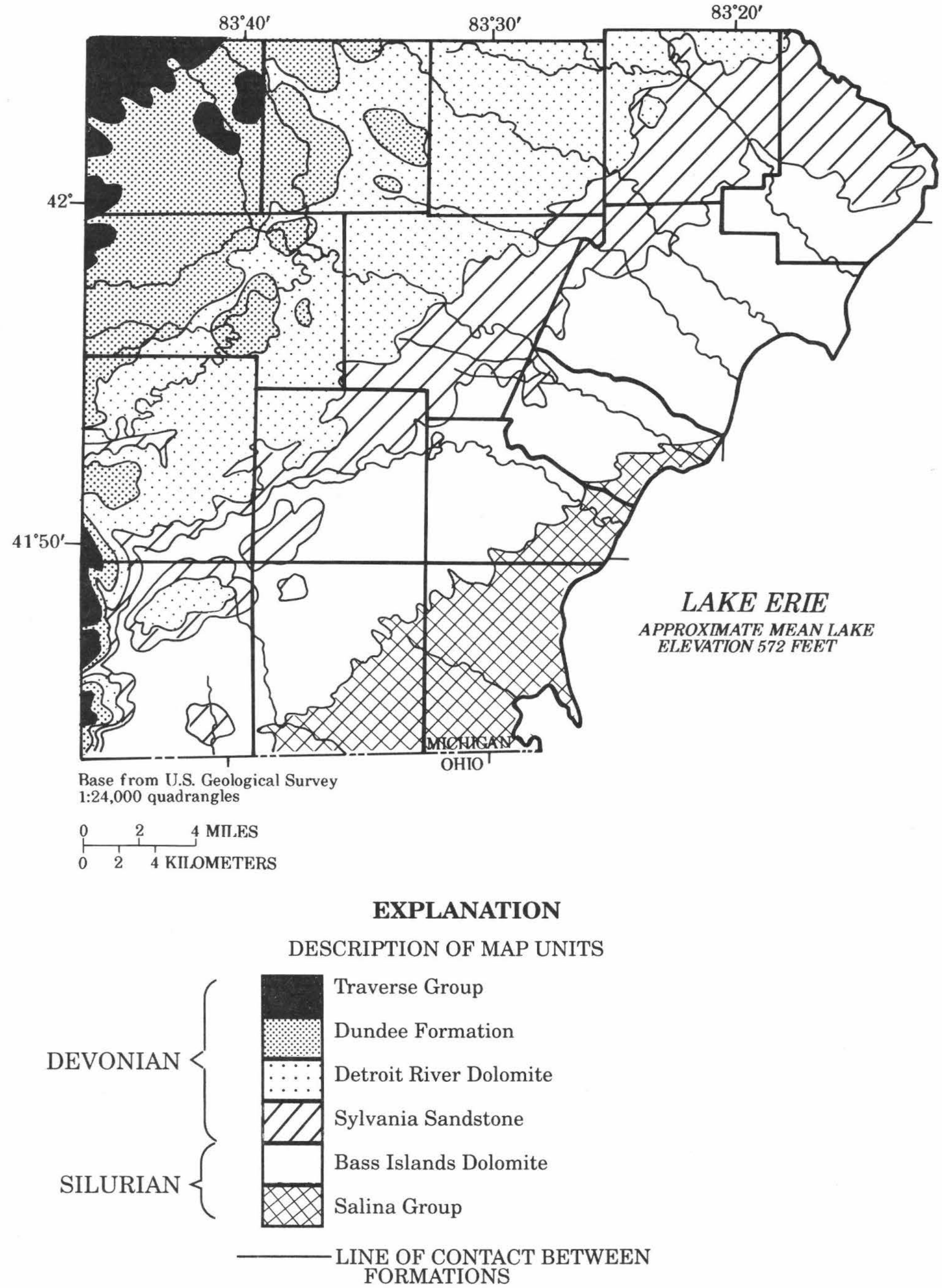


Figure 4. Bedrock geology of Monroe County, Michigan. (The Antrim Shale, which unconformably overlies a small part of the Traverse Group, is not depicted. Geology modified from Mozola, 1970.)

Sixteen USGS wells (G3, G4, G5, G6, G7, G12, G13, G14, G20, G21, G22, G23, G24, G25, G26, and G27; pl. 1) were drilled into the Detroit River Dolomite. Drill cuttings indicate that the Detroit River Dolomite is composed of interbedded limestone and dolomite. The limestone is brown and gray and has small vugs. The dolomite is also brown and gray and has a dense microcrystalline texture. Porosity occurs as fractures and vugs. Calcite and celestite crystals are present in some vugs. Native sulfur is present in shallow fractures but not in deep fractures. Some drill cuttings from the dolomite had petroliferous odors.

The Dundee Formation unconformably overlies the Detroit River Dolomite (Dorr and Eschman, 1970). The Dundee Formation is a subcrop in Whiteford, Summerfield, Dundee, London, and Milan Townships. According to Mozola (1970), the Dundee Formation does not crop out in the county; however, Sherzer (1900) reported outcrops along the River Raisin at Dundee and Petersburg and along Macon Creek northeast of Dundee. The Dundee Formation is being quarried near Dundee. Three USGS wells (G8, G9, and G11; pl. 1) were drilled into the Dundee Formation. Drill cuttings indicate that the Dundee Formation is composed of interbedded limestone and dolomite. The limestone is brown and gray and has small vugs. The dolomite is also brown and gray and has a dense microcrystalline texture. Porosity occurs as fractures and vugs. Calcite and celestite crystals are present in some vugs. Native sulfur is present in shallow fractures but not in deep fractures. Some cuttings from the dolomite had petroliferous odors.

The Traverse Group unconformably overlies the Dundee Formation (Dorr and Eschman, 1970). The Traverse Group is a subcrop in Whiteford, Summerfield, Dundee, and Milan Townships. The rock unit is not reported to crop out in the county (Mozola, 1970). None of the USGS wells were drilled into the Traverse Group; however, Mozola (1970) describes the lithology as consisting of shale, limestone, and dolomite. Pyrite is common throughout the unit.

The Antrim Shale conformably overlies the Traverse Group (Dorr and Eschman, 1970). The Antrim Shale is a subcrop in Whiteford Township. The rock unit is reported to subcrop only along the western edge of section 18 in Whiteford Township (Mozola, 1970) and is not shown on figure 4. None of the USGS wells were drilled into the Antrim Shale; however, Mozola (1970) describes the lithology as fissile bituminous shale. Pyrite and marcasite are common.

Erosion of the bedrock surface has resulted in a bedrock topography that generally slopes toward the southeast and northwest from a high in central and southwestern Monroe County (fig. 5). The altitude of the bedrock surface ranges from more than 650 ft above sea level in Whiteford Township to less than 550 ft along Lake Erie and in Milan Township (Mozola, 1970). Preglacial stream valleys eroded into the bedrock surface generally drained to the southeast, except in northwestern Monroe County, where they drained to the northwest.

Unconsolidated deposits in the county include till, glaciofluvial deposits, alluvium, and glaciolacustrine deposits. Till overlies the bedrock throughout most of the county and is composed mostly of silty clay (Mozola, 1970). Small, isolated glaciofluvial deposits are present in the subsurface in Monroe County and are composed mostly of sand and gravel. Some preglacial bedrock valleys are partially filled with glaciofluvial deposits. In northwestern Milan Township, thick glaciofluvial deposits overlie the bedrock surface.

Glaciolacustrine deposits overlie the till and are at the land surface throughout Monroe County except where bedrock crops out (Mazola, 1970). They are composed of clay or sand (fig. 6). In parts of Bedford and Whiteford Townships sand is at land surface and directly overlies bedrock. Small deposits of sand are present in the county, but are not shown in figure 6. Alluvium is present in narrow bands along most of the major streams and is composed mostly of sand and gravel.

The thickness of unconsolidated deposits in the county is varied, ranging from 0 ft along reaches of some streams to more than 150 ft in the northwest. Throughout most of the county glacial deposits are less than 50 ft thick (fig. 7). A southwest-to-northeast-trending band of thin drift, mostly less than 20 ft thick, is found from Whiteford to Ash Townships atop the bedrock high. The thickest deposits are where preglacial valleys have been filled northwest and southeast of the bedrock high. In parts of Milan and London Townships unconsolidated deposits are more than 150 ft thick, and in parts of Bedford and Erie Townships they are more than 90 ft thick (Mozola, 1970).

Although these generalizations are useful for understanding the occurrence of unconsolidated deposits in Monroe County, the complexity of their distribution and lithology must be emphasized. The type of deposit or the lithology of a deposit can differ considerably over very short distances. Many deposits have been reworked by successive ice advances, by meltwater, or by recent erosion. Consequently, the exact vertical sequence of lithology at any location within Monroe County can be determined only by drilling or excavating.

HYDROLOGY

Ground Water

The occurrence and flow of ground water in Monroe County is complex because of the lithologic heterogeneity of the unconsolidated deposits and the fractured bedrock. To simplify discussion of Monroe County ground-water hydrology, the authors define two aquifers in this report. The sand aquifer is composed of saturated unconsolidated

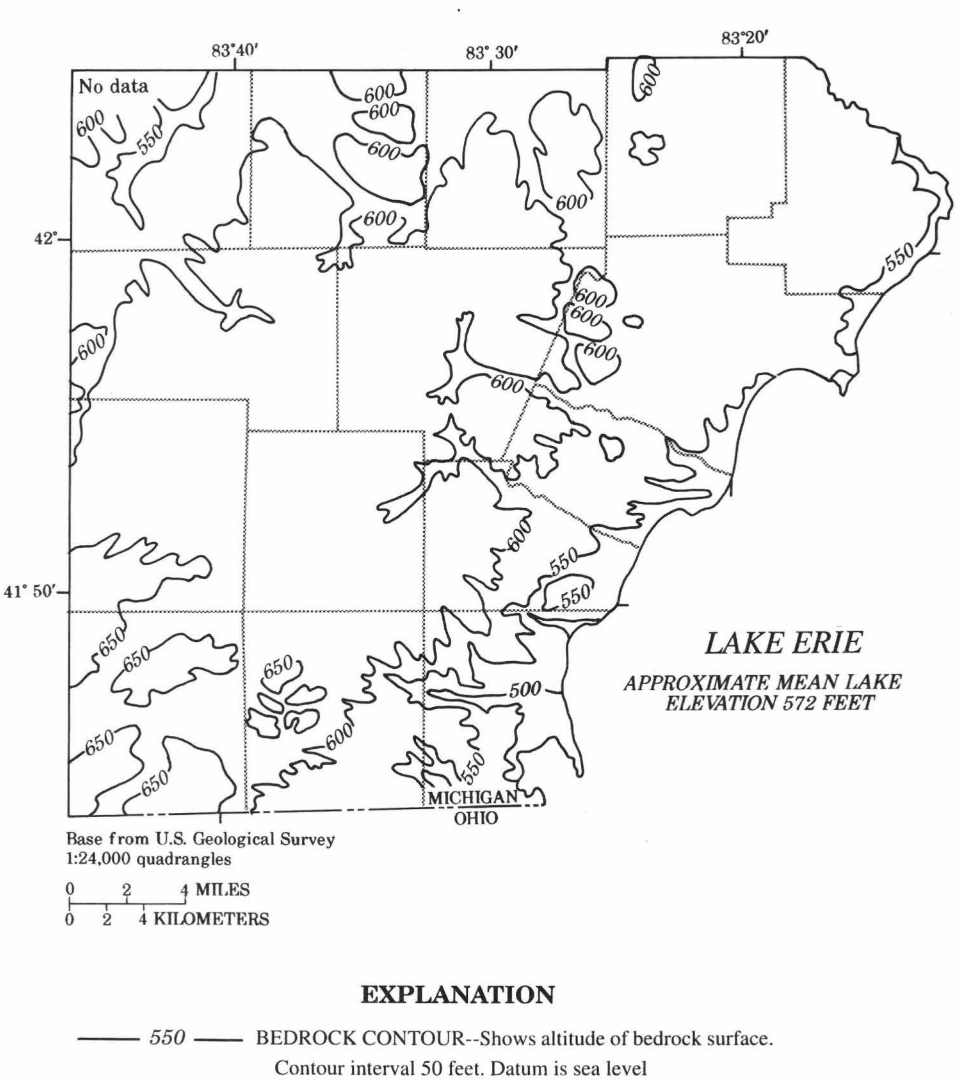


Figure 5. Altitude of bedrock surface, Monroe County, Michigan. (Modified from Mozola, 1970.)

deposits that will yield usable quantities of water to wells. The Silurian-Devonian aquifer (Olcott, 1992) is composed of all saturated bedrock units that yield freshwater to wells. Most of the ground water for domestic and municipal uses is withdrawn from the Silurian-Devonian aquifer. Thirty-three observation wells were drilled for the USGS during this study (table 1; Appendix 2). Thirty-two were completed in the Silurian-Devonian aquifer; one was completed in the sand aquifer.

Sand Aquifer

The sand aquifer in Monroe County consists of isolated saturated sand deposits. These deposits may be present at any depth above the bedrock surface, but they are usually near the land surface, except in the northwestern part of the county where they are at depths greater than 100 ft in places. The sand aquifer is not a uniform, continuous resource. Where present, the sand aquifer yields small quantities of water sufficient for most domestic uses. Higher, more sustainable yields can

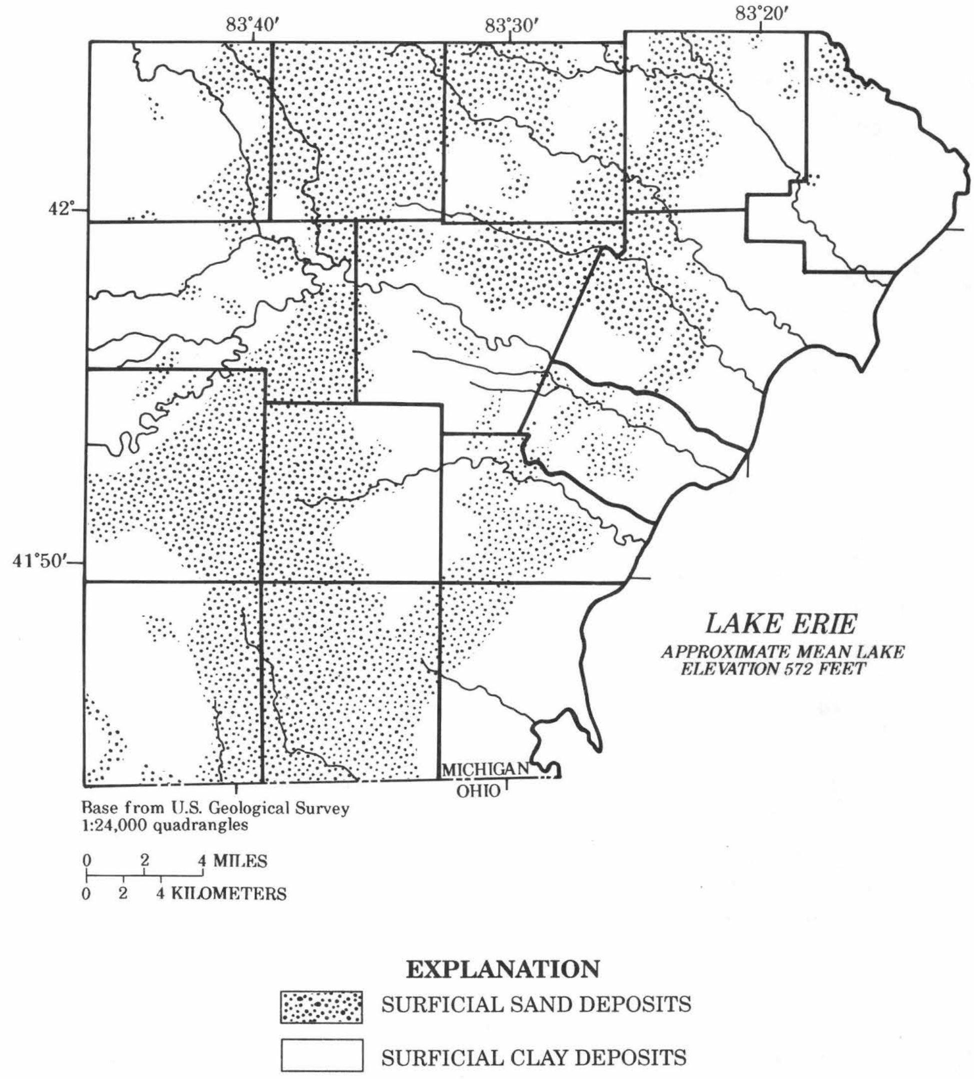
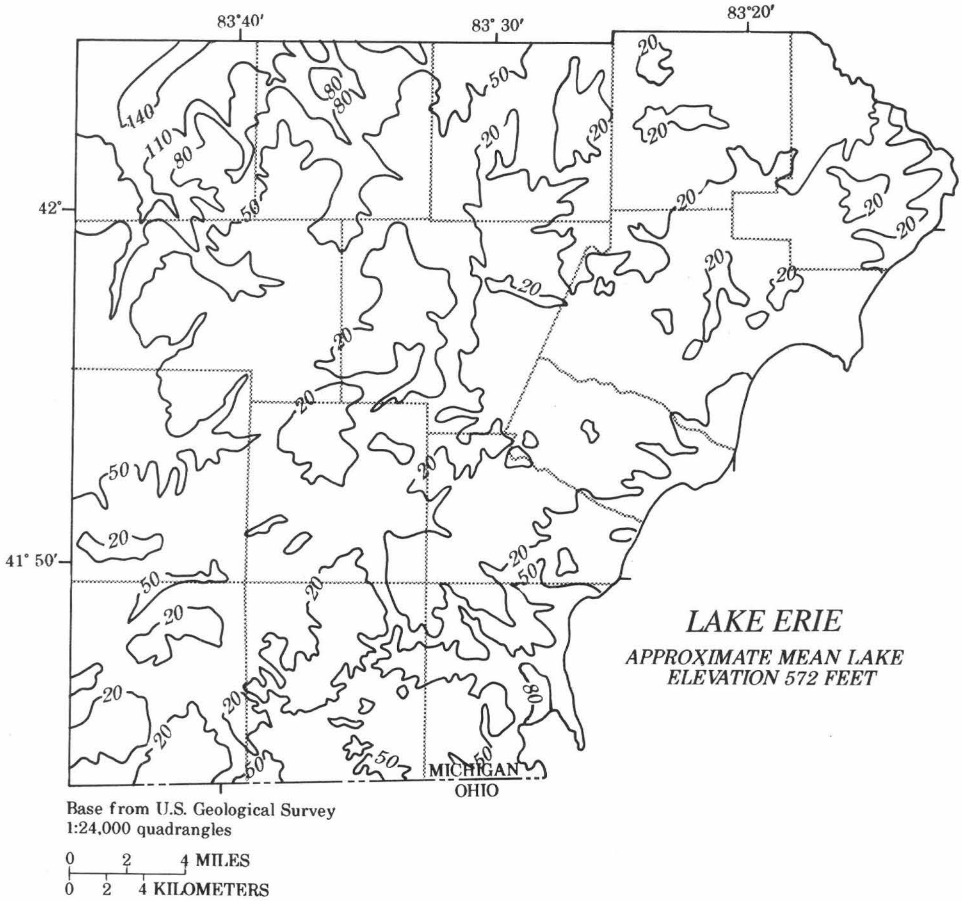


Figure 6. Areal distribution of surficial deposits, Monroe County, Michigan. (Modified from Sherzer, 1900.)

be obtained from thicker deposits of sand and gravel that fill bedrock valleys. The USGS well completed in the sand aquifer (G10, pl. 1, Appendix 2) was constructed where the aquifer is composed of thick glaciofluvial deposits.

Perched ground water is common in Monroe County and has occasionally been used for domestic purposes. Perched ground water is ground water that is above the water table and is separated from the water table by an unsaturated zone. Perched ground water can occur where sand overlies a clayey deposit. The clayey deposit impedes infiltration of precipitation, and ground water accumulates in the sand. A perched aquifer is formed if the amount of ground water is sufficient to yield water to wells and may occur in areas of surficial sand in Monroe County. Because of the high potential for contamination, perched aquifers are no longer an approved source of water in Monroe County (Monroe County Health Department, written commun., 1993). Perched ground-water levels can be significantly lowered by discharge to



EXPLANATION

—— *50* —— LINE OF EQUAL THICKNESS OF UNCONSOLIDATED DEPOSITS, IN FEET--Contour interval 30 feet

Figure 7. Thickness of unconsolidated deposits, Monroe County, Michigan. (Modified from Mozola, 1970.)

drainage ditches and quarries and by periods of low recharge. Consequently, perched ground water is an unreliable resource.

In much of Monroe County, the water table is in the sand aquifer. However, differentiating perched aquifers from water-table aquifers and mapping the water table are difficult because of the few wells screened across the water table, the heterogeneity of the unconsolidated deposits, and the relief on the bedrock surface. In general, the horizontal component of ground-water flow in the sand aquifer tends to be from topographically high areas to topographically low areas. Exceptions to this generalization are the result of withdrawals and contrasts in lithology. In coarse-grained deposits, the horizontal component of ground-water flow is greater than the vertical component, whereas in fine-grained deposits, the vertical component is commonly greater.

Ground-water levels in the sand aquifer fluctuate in response to seasonal variations in recharge and discharge (G10; fig. 8). Typically, recharge

Table 1. Selected data for wells, Monroe County, Michigan
[--, no data. Well locations are on Plate 1]

Well number	Date drilled	Site identifier	Land location	Altitude of land surface (feet)	Well depth (feet below land surface)	Well diameter (inches)	Casing length (feet)	Depth to water (feet below measuring point)	Estimated transmissivity (feet squared per day)	Estimated yield (gallons per minute)	Bedrock unit and top (feet below land surface)
G1	11-07-90	4244070831304	5S10E26BAB	575	50	5	29	35.86	--	0.5	Sylvania Sandstone (24)
G2	11-06-90	4200550831756	5S10E31BCDC	592	60	5	27	19.5	--	8	Bass Islands Dolomite (23)
G3	11-14-90	4205030831921	5S9E1CBCC	605	85	5	36	21.59		3-5	Detroit River Dolomite (30) Sylvania Sandstone (60)
G4	11-08-90	4203440832257	5S9E17AADB	615	65	5	35	24.4	480	25	Sylvania Sandstone (34)
G5	01-07-91	4204280832703	5S8E2DCC	629	80	5	42	15.6	Oscillatory	70-80	Detroit River Dolomite (36)
G6	01-04-91	4201230833000	5S8E29ADA	635	185	5	30	25.7	--	20	Detroit River Dolomite (14)
G7	11-28-90	4204140833515	5S7E10BBA	665	95	5	72	49.2	Oscillatory	50	Detroit River Dolomite (65)
G8	11-26-90	4202480833726	5S7E20CCA	670	110	5	71	60.0	940	5	Dundee Formation (61)
G9	01-09-91	4201070834032	5S6E26DAA	671	200	5	90	56.8	--	10-15	Dundee Formation (77)
G10	11-27-90	4203250834409	5S6E8ADD	708	110	5	107	17.4	360	15-20	Glacial drift
G11	12-03-90	4156480834056	6S6E23BDDD	667	110	5	42	42.8	30	5-6	Dundee Formation (32)
G12	12-05-90	4155270834020	6S6E35AAAA	676	100	5	51	40.5	190	25	Detroit River Dolomite (46)
G13	11-15-90	4157210833316	6S7E13CCC	644	110	5	26	16.2	40	8-10	Detroit River Dolomite (12)
G14	11-14-90	4159230832721	6S8E2DBC	627	65	5	25	20.6	150	5-8	Sylvania Sandstone (11)
G15	11-09-90	4258390832215	6S9E16BAAB	604	50	5	25	10.6	130	1	Bass Islands Dolomite (11)
G16	11-21-90	4157100831925	6S9E23DDBB	586	90	5	40	--	60	8-10	Bass Islands Dolomite (32)
G17	11-12-90	4154000832628	7S8E2DCDA	605	95	5	26	--	--	3-5	Bass Islands Dolomite (12)

Table 1. Selected data for wells, Monroe County, Michigan--Continued

Well number	Date drilled	Site identifier	Land location	Altitude of land surface (feet)	Well depth (feet below land surface)	Well diameter (inches)	Casing length (feet)	Depth to water (feet below measuring point)	Estimated transmissivity (feet squared per day)	Estimated yield (gallons per minute)	Bedrock unit and top (feet below land surface)
G18	11-16-90	4151330832748	7S8E22CAAD	605	50	5	32	12.4	1,200	40-50	Bass Islands Dolomite (24)
G19	12-17-90	4154310833432	7S7E3AAD	640	80	5	55	12.6	870	20	Sylvania Sandstone (28)
G20	12-18-90	4152370833656	7S7E17AACC	655	70	5	34	23.8	6,600	20-25	Detroit River Dolomite (22)
G21	12-06-90	4154370834130	6S6E34DDD	677	75	5	54	44.5	990	20-25	Detroit River Dolomite (42)
G22	01-02-91	4152440834152	7S6E15ABB	680	87	5	58	38.5	Oscillatory	40-50	Detroit River Dolomite (53)
G23	12-27-90	4152340834138	7S6E15ADB	679	90	5	58	40.5	Oscillatory	40-50	Detroit River Dolomite (50)
G24	12-21-90	4152360834140	7S6E15AAD	680	87	5	5	41.0	--	25-30	Detroit River Dolomite (48)
G25	12-19-90	4152390834129	7S6E15AAD	679	87	5	57	41.5	930	10-15	Detroit River Dolomite (52)
G26	12-07-90	415150834415	7S6E17DCC	682	80	5	60	48.1	--	10-12	Detroit River Dolomite (52)
G27	01-14-91	4151150834002	7S6E24CCA	676	208	5	40	42.6	180	12-15	Detroit River Dolomite (30) Sylvania Sandstone (48) Bass Island Group (87)
G28	12-11-90	4147310834501	8S6E7DDB	688	75	5	40	44.8	--	40-50	Detroit River Dolomite (12)
G29	12-10-90	4144520833852	8S7E31BBB	662	71	5	38.5	21.2	3,400	50-60	Bass Islands Dolomite (23)
G30	12-12-90	4146010833758	8S7E19DCA	670	155	5	36	23.6	10	1-2	Bass Islands Dolomite (26)
G31	12-14-90	4148290833456	8S7E3CDC	647	80	5	30	14.7	190	10	Bass Islands Dolomite (12)
G32	11-19-90	4147480833055	8S8E8CCAD	600	75	5	50	2	160	15-20	Salina Group (42)
G33	11-20-90	4145090832910	8S8E28CCAD	574	85	5	77	6.6	880	15	Salina Group (38)
GLTO	10-17-78	4152360834145	7S6E15ACA	680	72.5	6	53	40.35	--	--	Detroit River Dolomite (52)
D1	08-12-76	4151550834412	7S6E20DCCD	682	60	5	48	40	--	--	Detroit River Dolomite (42)

Table 1. Selected data for wells, Monroe County, Michigan--Continued

Well number	Date drilled	Site identifier	Land location	Altitude of land surface (feet)	Well depth (feet below land surface)	Well diameter (inches)	Casing length (feet)	Depth to water (feet below measuring point)	Estimated transmissivity (feet squared per day)	Estimated yield (gallons per minute)	Bedrock unit and top (feet below land surface)
D2	11-23-68	4151500834419	7S6E17CDC	683	69	4	52	40	--	--	Dundee Formation (52)
D3	05-28-79	4204140833510	5S7E10ABAC	672	25	1.25	10	23	--	8	Glacial drift
D4	11-11-91	4152280832424	7S8E13DDD	577	100	5	56	5	-	--	Salina Group (25)
D5	02-12-92	4148540833822	8S7E6AAC	669	57	4	30	34	--	--	Unknown (29)
D6	12-04-76	4145590833255	8S7E24CCCB	608	72	5	41	20	-	--	Salina Group (30)
D7	10-23-91	4201230832138	5S9E28DDA	606	59	5	32	25	-	--	Sylvania Sandstone (24) Bass Islands Dolomite (56)
D8	04-14-92	4158240831629	6S10E17BDB	581	61	5	26	20	--	--	Bass Islands Dolomite (13)
D9	11-27-90	4202460832859	5S8E15CCA	629	38	4	37	16	--	--	Detroit River Dolomite (33)
D10	11-16-91	4157490832820	6S8E150BDC	624	66	4	30	20	--	--	Sylvania Sandstone (27)
D11	07-9-91	4257540834209	6S6E15BAC	667	65	5	62	45	--	--	Dundee Formation (60)
D12	01-09-91	4143530834228	9S6E4AAB	674	110	5	46	30	--	--	Bass Islands Dolomite (9)
D13	05-15-90	4152040833231	7S7E13DCCC	632	70	5	36	2	--	--	Bass Islands Dolomite (30)

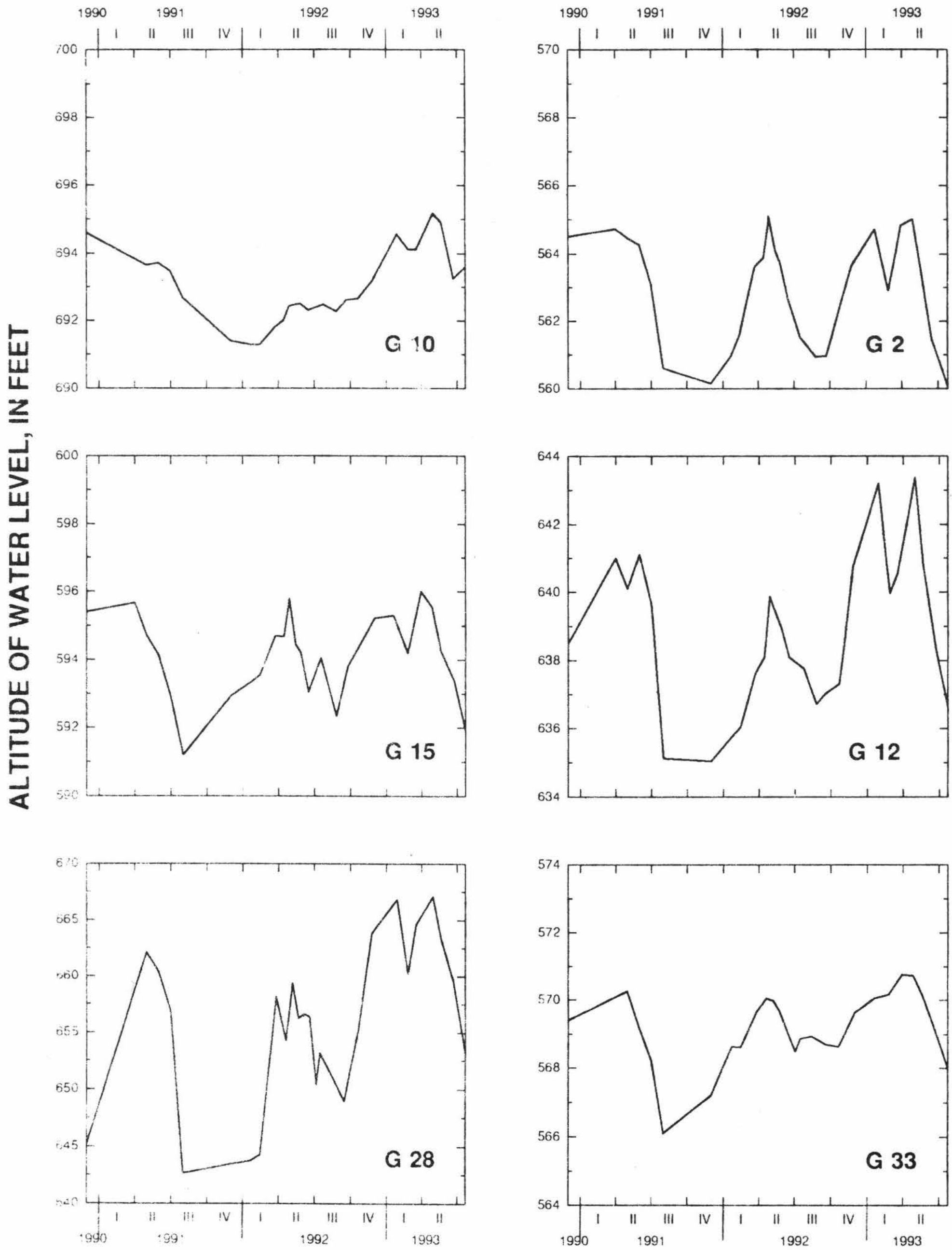


Figure 8. Hydrographs of selected U.S. Geological Survey observation wells, Monroe County, Michigan.

exceeds discharge during fall through spring, causing ground-water levels to rise. Discharge exceeds recharge during the growing season, causing ground-water levels to decline. Recharge to the sand aquifer in Monroe County is from precipitation, losing reaches of streams, and ground-water flow from Lenawee, Washtenaw, and Wayne Counties. Ground water discharges from the sand aquifer to the Silurian-Devonian aquifer, wells, streams, Lake Erie, drainage ditches, and quarries or other excavations; ground water also discharges to the atmosphere through evapotranspiration.

Silurian-Devonian Aquifer

In Monroe County most of the ground water withdrawn from the Silurian-Devonian aquifer comes from secondary openings, principally solutionally enlarged fractures and bedding-plane partings. Although the primary openings store more water than the secondary openings, the primary openings typically are poorly connected and conduct water very slowly compared to the secondary openings. Where the Sylvania Sandstone is poorly cemented, ground water may be stored and withdrawn from primary openings. Throughout Monroe County, secondary openings in carbonate rock tend to be larger and more conductive near the bedrock surface. In this report, the zone near the bedrock surface is referred to as the "weathered zone." Wells open only to the weathered zone are common.

Aquifers such as the Silurian-Devonian aquifer, which are fractured and have significant secondary openings, are typically heterogeneous and anisotropic with respect to transmissivity and storage; that is, these aquifer properties may be varied in different locations (heterogeneity) or in different directions (anisotropy). For instance, in areas of Whiteford Township where sinkholes have formed, the Silurian-Devonian aquifer likely has a higher transmissivity than in northwestern Monroe County where the aquifer is not karstic and contains more shale. In addition, as a result of subvertical fractures, transmissivity is probably greater along the strike and dip of the rocks than at an angle to the strike and dip. Common tools used for analysis of aquifers—interpretation of water-level maps and aquifer-test data—typically require the assumptions of homogeneity and isotropy. These tools are useful in the analysis of aquifer properties, provided that the assumptions are recognized.

Slug-test data for Monroe County demonstrate the heterogeneity of the Silurian-Devonian aquifer with respect to transmissivity. Slug tests were done in 24 USGS observation wells (table 1). Transmissivities estimated from the slug-test data by use of the analytical method of Cooper and others (1967) range from 10 to 6,600 ft^2/d The median transmissivity is 200 ft^2/d. Transmissivities at two wells that are within 2 mi of each other, G29 and G30, differ by two orders of magnitude. In several of the wells, water levels oscillated during the tests; such oscillation is characteristic of highly transmissive fractured rock.

Although the slug-test data in table 1 are useful for showing heterogeneity, the estimated transmissivities should be used with caution. Slug tests stress only a small part of the aquifer, and results are strongly affected by hydraulic properties in the immediate vicinity of the borehole. Well drilling and development sometimes alter hydraulic properties near the borehole.

Data from multiple-well aquifer tests can be used to make better estimates of transmissivity than can data from slug tests. Furthermore, the storage properties of an aquifer (storage coefficient) can be estimated from multiple-well tests. On June 24, 1992, the USGS did a multiple-well aquifer test in the Petersburg State Game Area in Summerfield Township. Well G23 was pumped at 80 gal/min for about 20 hours while water levels were measured in four observation wells. The data were normalized for distance from the pumped well, and the Theis (1935) method of analysis was used to compute transmissivity and storage coefficient (T and S on fig. 9). The late-time responses of water levels in G24, G25, and GLTO are similar, resulting in a computed transmissivity of 1,300 ft^2/d and a storage coefficient of 0.00012. The late-time response of the water level in G22 resulted in a computed transmissivities of 1,000 ft^2/d and a storage coefficient of 0.000083. These transmissivity values are similar to that estimated for well G25 from slug-test data, 930 ft^2/d. The early-time data from the four wells could not be quantitatively interpreted; these data indicate an additional source of recharge to the well and, perhaps, wellbore storage effects. The advantage of normalizing the data for distance from the pumped well is that the resulting graph clearly shows whether the aquifer is homogeneous and isotropic with respect to transmissivity. If the aquifer is homogeneous and isotropic, all of the data will plot on a single type-curve. Considering the late-time data only, the responses in wells G24, G25, and GLTO are indicative of a homogeneous, isotropic aquifer; however, the response in G22 is different, indicating heterogeneity. The variable response to pumping illustrates the difficulty in predicting the effects of quarry dewatering and high-capacity irrigation wells on water levels in the Silurian-Devonian aquifer.

Results from a two-well aquifer test done in section 30 of Bedford Township by a private company in 1963 were similar to those from the USGS test in the Petersburg State Game Area. The wells were 212 ft deep, completed in the Silurian-Devonian

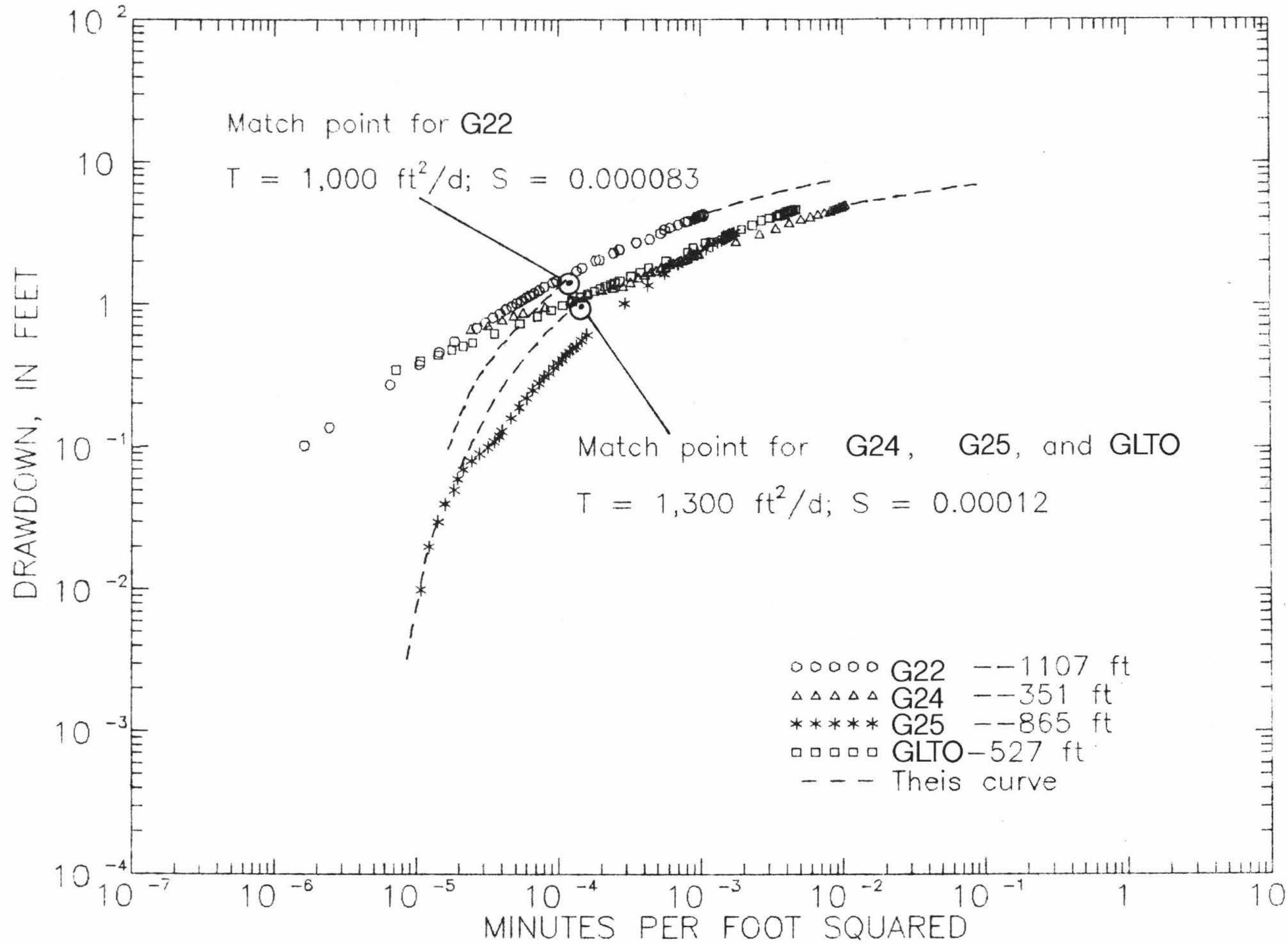
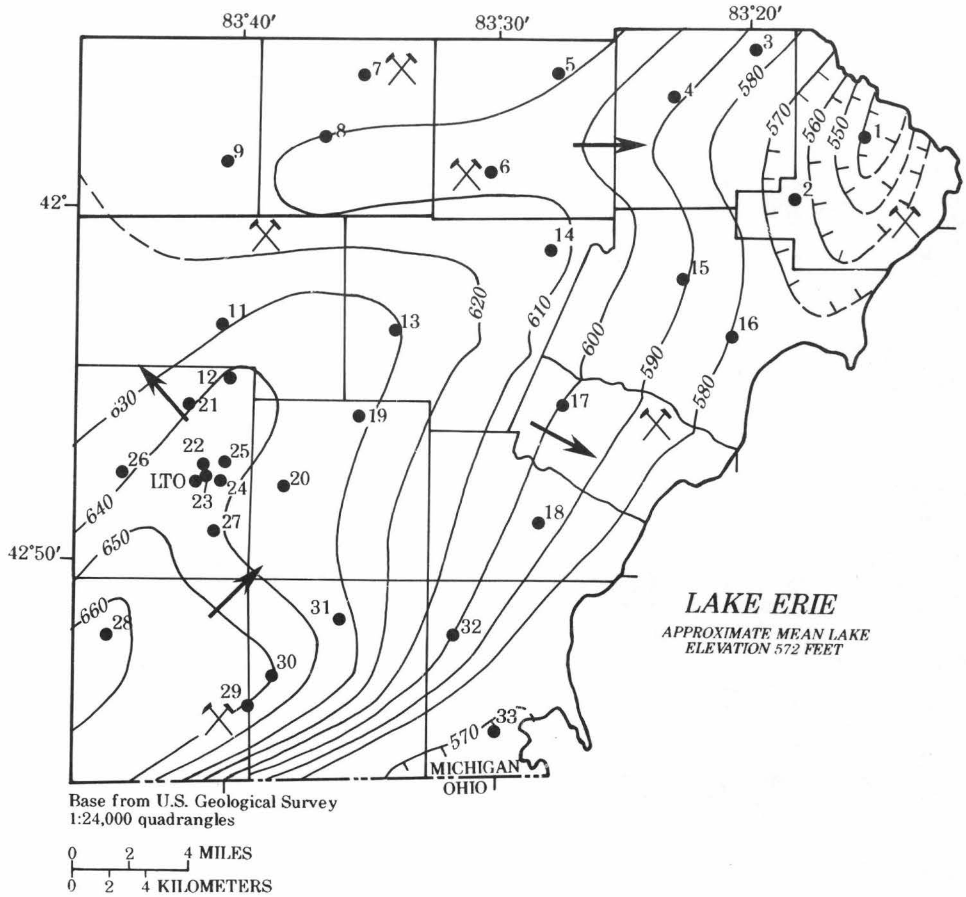


Figure 9. Results of aquifer test by U.S. Geological Survey at Petersburg State Game Area, Monroe County, Michigan, June 24, 1992.

aquifer, and 1,000 ft apart. One well was pumped at 40 gal/min for 24 hours while water levels were measured in the second well. The Theis (1935) method of analysis was used to compute a transmissivity of 3,800 ft^2/d and a storage coefficient of 0.0001.

Ground-water flow

Directions of ground-water flow in the Silurian-Devonian aquifer in Monroe County can be inferred from a potentiometric map—a map of contoured water-levels. The potentiometric map in figure 10 was based on water levels measured in January 1993 in USGS wells completed in the Silurian-Devonian aquifer. Although measurements of depth to water in the wells are accurate to 0.01 ft, the altitudes of the measuring points on the wells were estimated from topographic maps and are accurate within only 5 ft. Water levels in Ohio (Breen and Dumouchelle, 1991) were used to guide placement of potentiometric contours in southern Monroe County.



EXPLANATION

—*600*— POTENTIOMETRIC CONTOUR--Shows altitude of water level, January, 1993. Dashed where approximately located. Contour interval 10 feet. Datum is sea level

→ GROUND-WATER FLOW--Arrow indicates direction of ground-water flow if the aquifer was isotropic and homogeneous with respect to transmissivity

● 1 WELL AND IDENTIFIER--Prefix the letter G to number

⚒ QUARRY--Active in 1992

Figure 10. Potentiometric surface in the Silurian-Devonian aquifer, Monroe County, Michigan, January 1993.

Ground water flows from areas where water levels are high to areas where water levels are lower. If the Silurian-Devonian aquifer was isotropic with respect to transmissivity, horizontal ground-water-flow directions would be exactly perpendicular to the ground-water-level contours. In anisotropic aquifers, the direction of ground-water flow is not necessarily parallel to the direction of the hydraulic gradient. Despite probable anisotropy, flow perpendicular to the contours is a reasonable assumption on a countywide scale for the purpose of understanding the general pattern of flow. For specific locations, however, ground-water-flow directions cannot be accurately determined from the potentiometric map.

The potentiometric surface of the Silurian-Devonian aquifer in Monroe County is highest in the southwest (fig. 10). Most ground water flows southeastward to Lake Erie and Ohio. Some ground water flows northward and northwestward before flowing eastward to Berlin Township. In addition, some ground water enters northern Monroe County from Washtenaw and Lenawee

Counties. The arrows in figure 10 are intended as a guide to general directions of ground-water flow, and their placement assumes isotropy and homogeneity. Locally, ground water also flows toward active quarries and wells; however, flow at such small scales cannot be determined from the 32 observation wells used to construct figure 10.

Ground-water levels in eastern Monroe County are below the mean altitude of Lake Erie (572 ft). Consequently, water potentially could move from Lake Erie to the Silurian-Devonian aquifer in these two areas. Measurements of flow in the River Raisin indicate that the river loses water to the Silurian-Devonian aquifer downstream from SLTO (pl. 1). Therefore, downstream deflections were drawn in potentiometric contours in Raisinville, Monroe, and Frenchtown Townships (fig. 10).

The predevelopment configuration of the potentiometric surface (fig. 11) can be approximated from ground-water-level data and locations

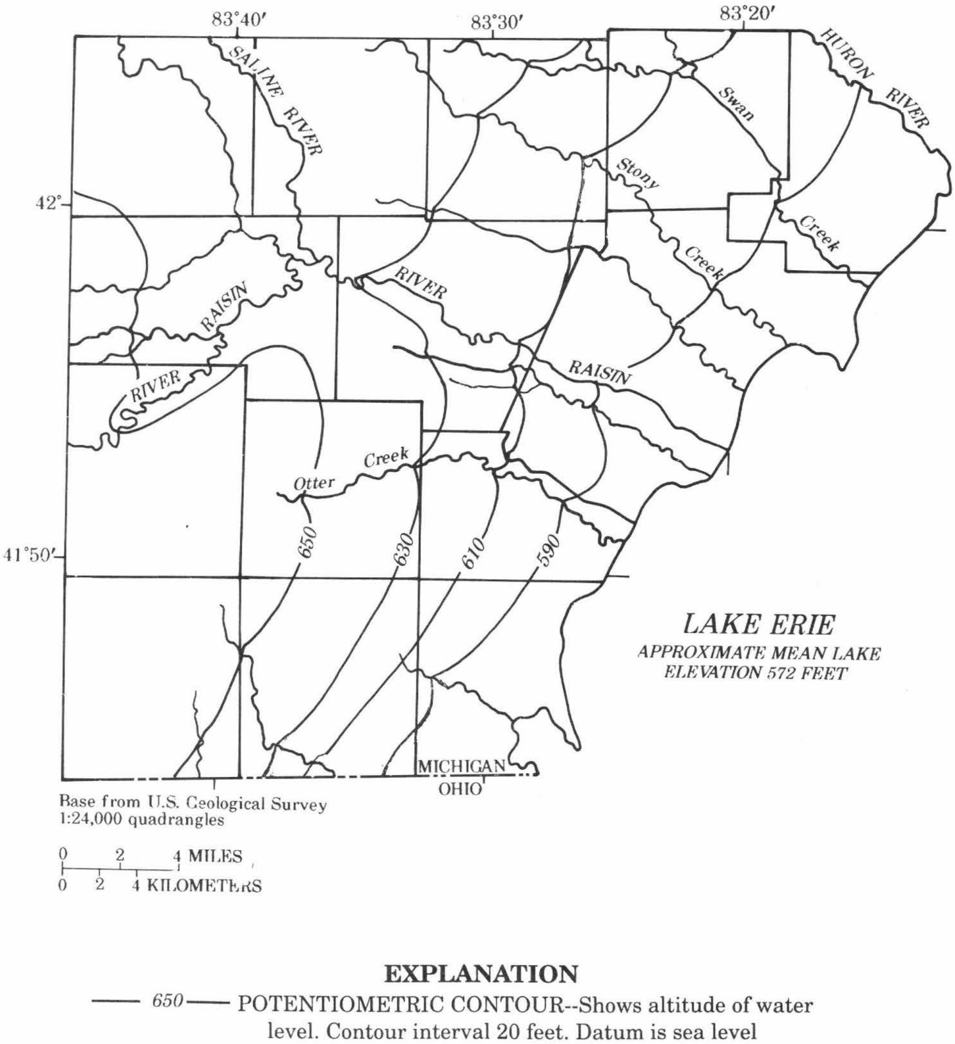


Figure 11. Estimated water levels in the Silurian-Devonian aquifer before development, Monroe County, Michigan. (Based on Sherzer, 1900, and Leverett and others, 1906.)

of springs reported by Sherzer (1900) and Leverett and others (1906). Potentiometric contours at streams are drawn with upstream deflections to indicate assumed flow from the Silurian-Devonian aquifer into streams. Figures 10 and 11 have similar features. The major recharge area is in the southwest, most ground-water flow is toward the southeast, and gradients are steeper in the southeast than in the northwest. Comparison of figures 10 and 11 also shows major changes in the pattern of ground-water flow since predevelopment times. In figure 11, no cones of depression are evident, and ground-water levels are not below Lake Erie.

Recharge to the ground-water-flow system occurs throughout Monroe County; however, the amount of recharge varies with depth to the water table and the hydraulic conductivity of the materials above the water table. Recharge is highest where surficial materials are sandy and the water table is near land surface. Recharge is lowest where surficial materials are clayey and the water table is deep. Gillespie and Dumouchelle (1989) used base-flow duration to estimate that recharge in southeastern Michigan ranges from about 1.5 in./yr where lacustrine clays are at the surface to about 7 in./yr where coarse sand is at the surface.

D.J. Holtschlag (U.S. Geological Survey, written commun., 1993) estimated recharge in Monroe County to be 6 in./yr using baseflow separation of streamflow records and regression. If 6 in. of annual recharge is multiplied by the area of the county (562 mi^2), then the rate can also be expressed as 160 Mgal/d, a convenient unit for comparison to ground-water use in the county. As mentioned previously, ground-water use is about 12.9 Mgal/d or 8 percent of the estimated annual recharge.

In Monroe County, recharge to the Silurian-Devonian aquifer is probably greatest in the parts of Summerfield, Ida, Whiteford, and Bedford Townships where the bedrock is near land surface and surficial deposits are sandy. In the remainder of the report, this area is referred to as "the recharge area." Recharge is probably least in northwestern and southeastern Monroe County, where the bedrock is overlain by more than 50 ft of clayey deposits.

The effects of drain tiles and ditches on recharge cannot be quantified by use of available data. However, these artificial drainage features are designed to lower the water table in order to increase arable land. Consequently, they locally reduce the amount of recharge to aquifers in Monroe County.

The hydraulic gradient is markedly varied throughout the county. Variation in hydraulic gradient is the result of variations in hydraulic conductivity, variations in recharge or discharge, or a combination of both. High hydraulic gradients in southeastern and northeastern Monroe County are associated with cones of depression on the potentiometric surface. The cones of depression are the result of pumpage near the Wayne-Monroe County line and near Toledo, Ohio. The low gradients in the major recharge area probably result from the high hydraulic conductivity typically associated with carbonate rock that has solutionally enlarged fractures. The very low gradients in northwestern Monroe County probably result from low rates of recharge through the thick clayey deposits. Water-level contours in this area are only approximately located because of the small difference in water levels; in some places, the difference is less than the uncertainty in the altitude of the measuring points.

Confining conditions

Most of the Silurian-Devonian aquifer in Monroe County is confined. In a confined aquifer, the potentiometric surface is above the top of the aquifer and a unit of significantly lower hydraulic conductivity (confining unit) restricts flow of water into and out of the aquifer. In an unconfined aquifer, the water table (the potentiometric surface in an unconfined aquifer) is below the top of the aquifer. In an unconfined aquifer, a confining unit may still overlie the water table; however, unsaturated material is present between the water table and the bottom of the confining unit. A confining unit composed of clay or till overlies most of the Silurian-Devonian aquifer in Monroe County; however, the aquifer is unconfined locally at bedrock highs, where the potentiometric surface is below the top of the aquifer. Where the Silurian-Devonian aquifer is unconfined, the potentiometric surface is the water table. Where the Silurian-Devonian aquifer is confined, the water table is in the overlying unconsolidated deposits and its altitude is unknown. If the bedrock surface in Monroe County was smooth and uniformly overlain by clayey unconsolidated deposits, determining confinement of the Silurian-Devonian aquifer on the basis of water levels would be simple. However, the complexity of bedrock topography and the lithologic heterogeneity of the unconsolidated deposits makes this determination difficult.

A fence diagram of Monroe County was constructed to aid in determining locations of confined and unconfined conditions in the Silurian-Devonian aquifer (pl. 2). The geologic information on the fence diagram is from 547 drillers' logs and Mozola's bedrock surface map (1970); the potentiometric surface is from figure 14. The fence diagram shows that the aquifer is unconfined either at bedrock highs, principally in the recharge area in southwestern Monroe County, or in northeastern Monroe County where ground-water levels have been lowered by pumping.

Locations of unconfined and confined conditions can also be determined from comparison of the bedrock surface and water levels in observation wells. Ground water was unconfined throughout the period of the study in nine of the USGS wells (G1, G2, G6, G11, G13, G14, G21, G27, and G28) and was unconfined seasonally during the period of the study in an additional six USGS wells (G15, G17, G20, G26, G29, and G31). Ground water was confined throughout the period of study in the other 17 USGS wells completed in the bedrock.

A map of approximate areas of confined and unconfined conditions was constructed by combining information from the fence diagram and the well data (fig. 12). In most of the county, the Silurian-Devonian aquifer is confined. In northeastern Monroe County, the aquifer is unconfined because of pumping. In southwestern Monroe County, the aquifer is unconfined at bedrock highs, but otherwise is confined. Local unconfined conditions have been found in Monroe County in areas too small to be depicted in figure 12. The Silurian-Devonian aquifer is unconfined near all quarries (pl. 1) and near wells whose rates of pumpage cause water levels to decline below the top of the bedrock surface.

Historical information other than water-level data indicates that the Silurian-Devonian aquifer in Berlin Township was formerly confined. Sherzer (1900) reports that water levels in wells in Berlin, Ash, and Exeter Townships rose significantly just before storms. Increased heads (higher water levels) in response to reduced barometric pressure are indicative of confined conditions.

Storage coefficients computed from aquifer tests indicate confined conditions at the Petersburg State Game Area and in southwest Bedford Township. The typical range of storage coefficient in confined aquifers is from 0.00005 to 0.005 (Freeze and Cherry, 1979), and the computed storage coefficients from the aquifer tests ranged from 0.000083 to 0.00012. The storage term for unconfined aquifers (specific yield) is significantly higher, typically in the range from 0.01 to 0.3 (Freeze and Cherry, 1979). The higher the storage terms, the more water an aquifer can release from storage to wells. Consequently, the cone of depression caused by pumpage from an unconfined aquifer is smaller and shallower than the cone of depression caused by pumpage from a confined aquifer, provided that both aquifers have the same transmissivity.

In fractured carbonate rock, subhorizontal fractures may have discrete potentiometric surfaces that are vertically separated by unfractured or sparsely fractured rock (Sherrill, 1978; Johnson, 1962). In these rocks, the subhorizontal fractures function as confined aquifers and the intervening rocks function as confining units. Where ground water in the upper fracture or fractures of the Silurian-Devonian aquifer is unconfined in Monroe County, ground water in deeper fractures is probably confined.

Water-level changes

Water levels change continuously in response to changes in recharge to or discharge from the Silurian-Devonian aquifer. When recharge exceeds discharge, ground-water levels rise; when discharge exceeds recharge, they fall. Seasonal and year-to-year variation in precipitation—the principal source of recharge in Monroe County—causes short- and long-term regional changes in water levels. Ground-water discharge in Monroe County occurs naturally and as a result of pumpage. Seasonal and year-to-year variation in natural discharge causes short- and long-term regional changes in water levels, whereas seasonal pumpage causes short-term local change in water levels. The effect of long-term pumpage, however, is long-term decline in water levels.

Water levels in the Silurian-Devonian aquifer in Monroe County were measured approximately monthly in 32 USGS wells from December 1990 through July 1993 (Appendix 3) and continuously in one well (GLTO) from 1978 through 1993. Seasonal fluctuations of water levels in Monroe County are typical (figs. 8 and 13). Water levels are highest in early spring, when recharge from precipitation and snowmelt is high, water use is low, and evapotranspiration is low. Water levels generally decline throughout the summer and fall as water use and evapotranspiration increase. In late fall, when the first heavy frosts limit evapotranspiration, water levels begin to rise. At USGS well

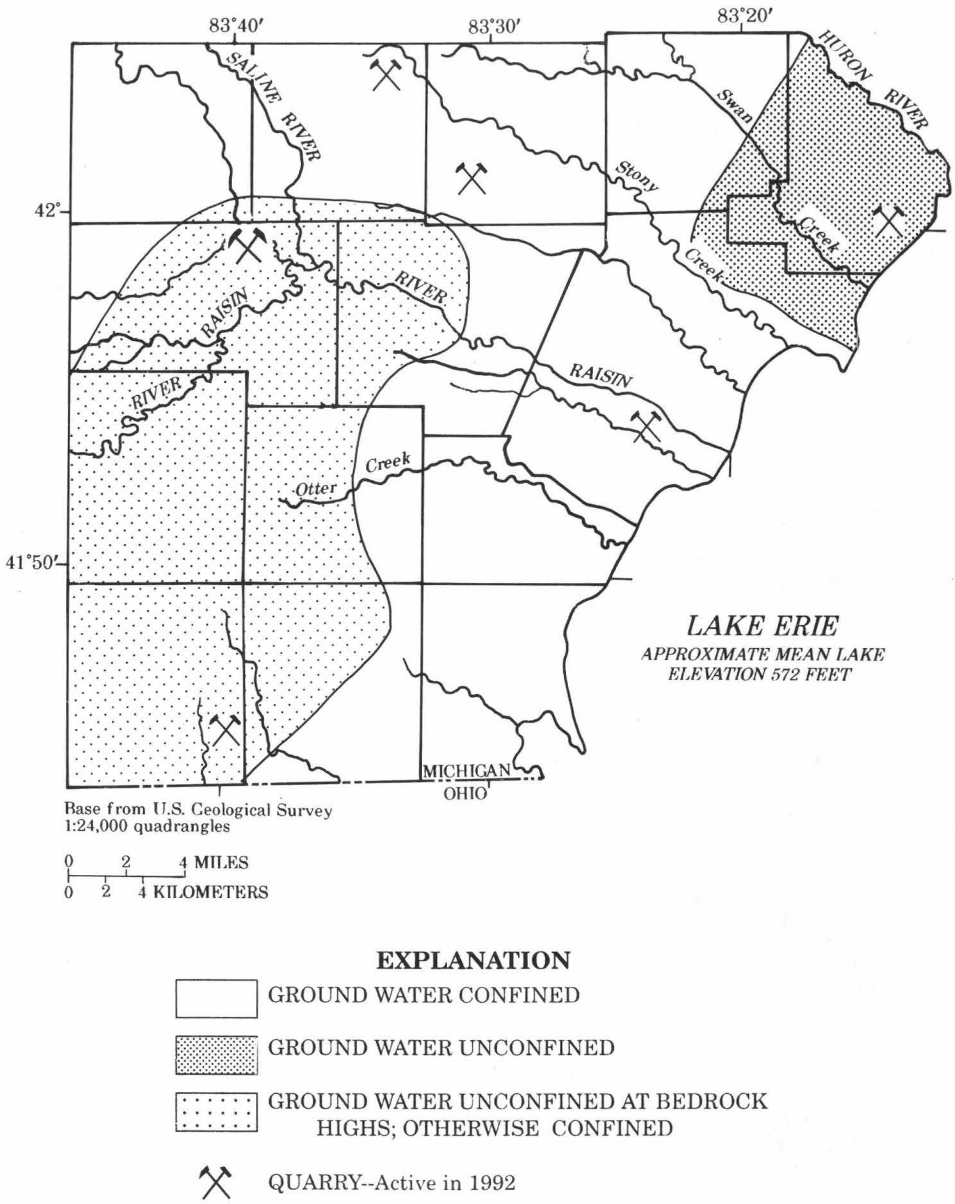


Figure 12. Areas where the Silurian-Devonian aquifer is confined or unconfined, Monroe County, Michigan.

G28, a 24-ft water-level difference was recorded during the study, a much greater difference than at any other USGS well. This unusually large difference may result from locally high recharge through sinkholes or thin, coarse glacial deposits or from a locally low aquifer storage coefficient.

Water levels fluctuate seasonally throughout the county, but the general pattern of flow does not change (compare fig. 14 to fig. 10); however, the amount of water-level fluctuation tends to be greatest in the recharge areas in southwestern Monroe County (fig. 15). Seasonal, regional changes in water level are caused by climatic variability. A succession of wet or dry years results in a regional raising or lowering of ground-water levels over which the seasonal fluctuations are superimposed (fig. 13).

Local, short-term declines in water level generally are a result of pumping. Daily or seasonal increases in pumping result from domestic, municipal, and irrigation pumpage and quarry dewatering. Most of these uses tend to be greatest in the

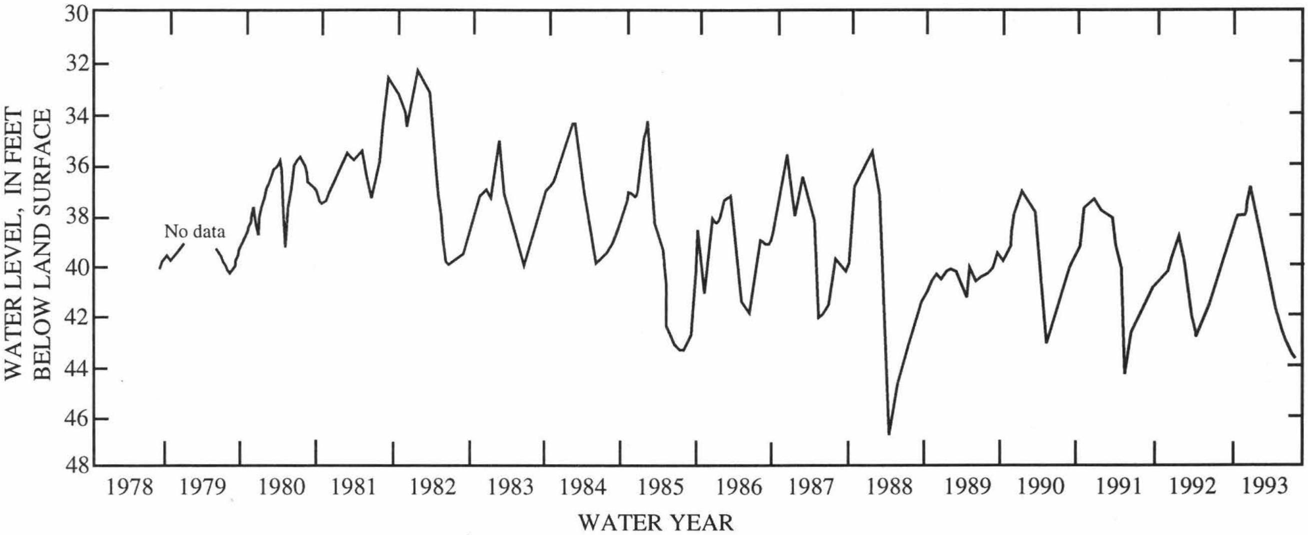


Figure 13. Hydrograph for well GLTO in Petersburg State Game Area, Monroe County, Michigan, 1978-93.

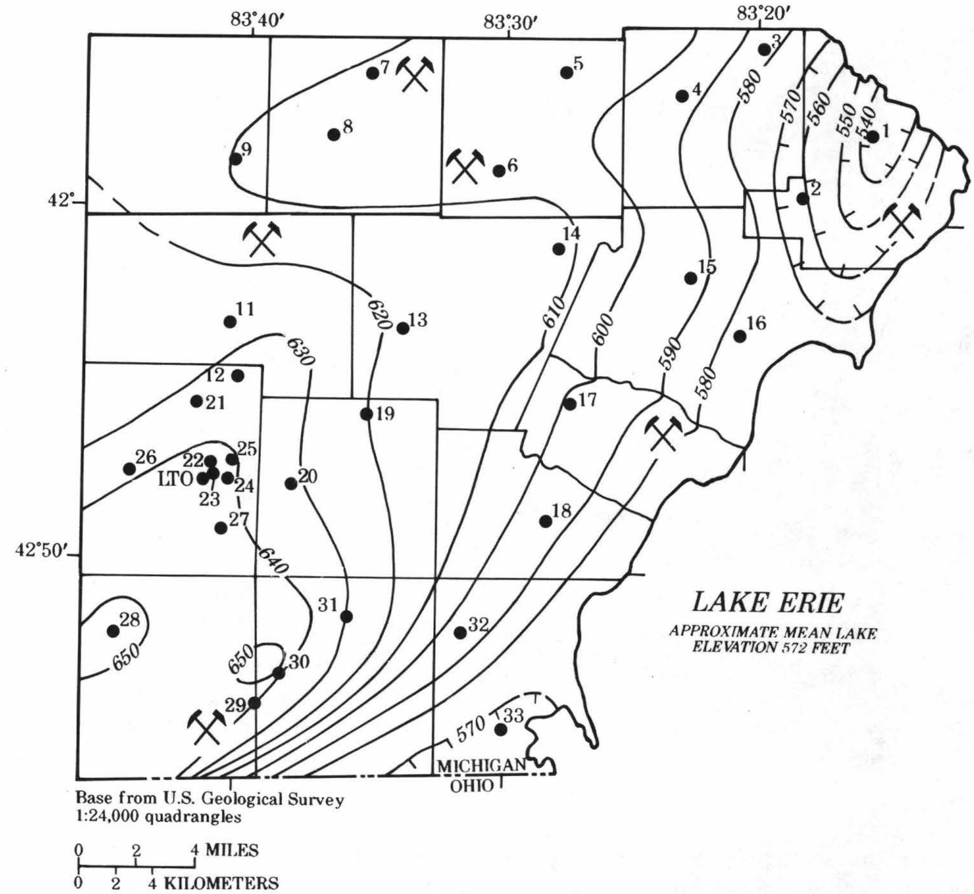
summer, when regional water levels are lowest. The size of the area affected by these types of pumpage is directly related to the rate of pumpage, the duration of pumpage, and aquifer transmissivity and indirectly related to the aquifer storage coefficient.

Local, long-term declines in water level have also resulted from pumpage. The cones of depression in Berlin Township and in southern Erie Township at the Michigan-Ohio State line are the result of long-term pumpage. The 12-year decline in water levels at GLTO (fig. 13) may have resulted either from long-term pumpage or from a long-term decline in recharge.

Regional, long-term changes in water levels in Monroe County have resulted from pumpage and perhaps from the extensive network of artificial drains and drainage tile. The differences between the predevelopment and present potentiometric surfaces were discussed previously. One can also compare flowing-well districts drawn by Sherzer (1900) to depths to water measured during this study. The flowing-well districts (fig. 16) represent areas where the depth to water in the Silurian-Devonian aquifer was equal to or less than zero. The depths to water contoured in figure 16 were not all measured on the same date; rather, they are the maximum depth to water measured during the period of the study. No contour line represents a depth to water of 0 ft; therefore, water levels in much of Monroe County have declined 10 ft or more since 1900.

Surface Water

Streams in Monroe County (pl. 1) flow to Lake Erie. The streams are either directly tributary to Lake Erie or are in the Huron River Basin, the River Raisin Basin, or the Ottawa River Basin. Because of the gentle slope of the land and the large amount of agricultural land use, Monroe County has a dense network of artificial drains. Most basins are underlain by fine-grained unconsolidated deposits; however, bedrock crops out in parts of some streambeds as discussed previously. Streams are hydraulically connected to perched aquifers, the sand aquifer, and the Silurian-Devonian aquifer. There are no natural lakes in the county, but lakes formed when some abandoned quarries filled with water. Only streams are discussed in this report.



EXPLANATION

—— *600* —— POTENTIOMETRIC CONTOUR--Shows altitude of water level, July, 1993. Dashed where approximately located. Contour interval 10 feet. Datum is sea level

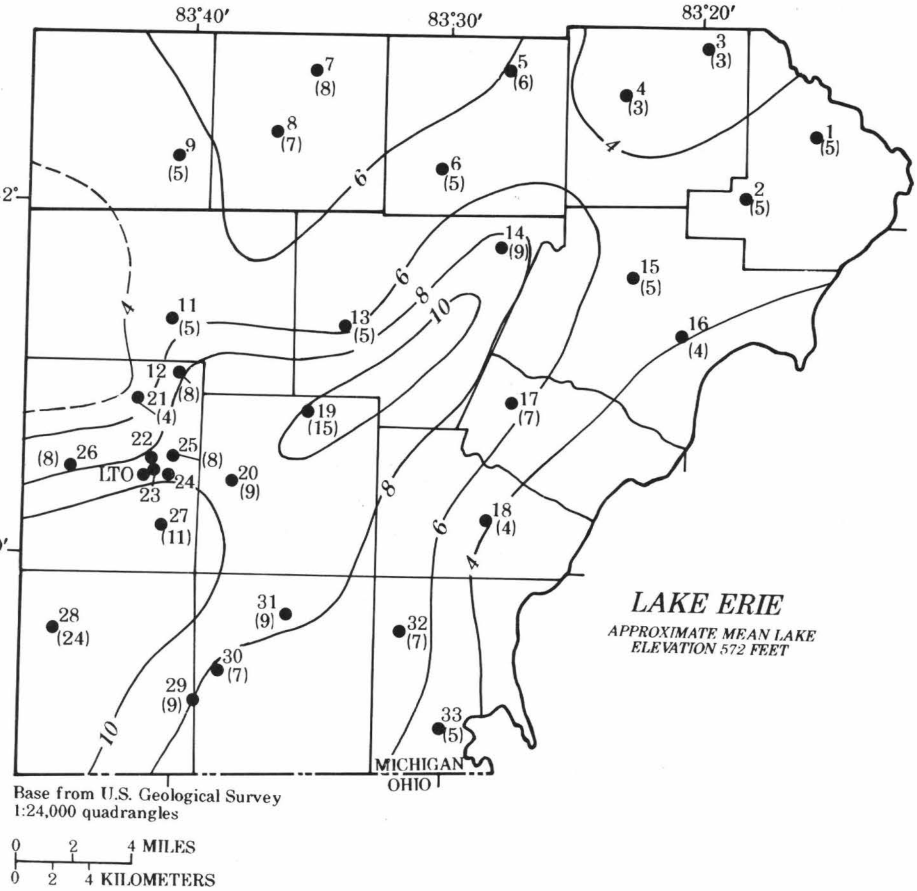
● 1 WELL AND IDENTIFIER--Prefix the letter G to number

⚒ QUARRY--Active in 1992

Figure 14. Potentiometric surface in the Silurian-Devonian aquifer, Monroe County, Michigan, July 1993.

The Huron River has a drainage area of 908 mi^2 (Larson and others, 1975), but only a few square miles are in Monroe County, principally in northeast Berlin Township. The surficial material in the Huron River Basin in Monroe County is mostly clay (Bowman, 1981).

The River Raisin has a drainage area of 1,072 mi^2 (Knutilla and Allen, 1975). In Monroe County, the River Raisin drains the northwestern half of Summerfield Township, most of Milan and Dundee Townships, and the western third of London Township. Surficial deposits in the River Raisin Basin in Monroe County are mostly clay, although sand is found near drainage divides and as small isolated deposits. The River Raisin is characterized by wide meanders in a broad flood plain from Lenawee County downstream to the mouth of the Saline River near the village of Dundee (Knutilla and Allen, 1975). From Dundee to Lake Erie, the River Raisin Basin is narrow. Major tributaries in Monroe County are the Saline River,



EXPLANATION

—*3*— LINE OF EQUAL CHANGE IN WATER LEVEL, IN FEET--Contour interval 2 feet. Dashed where approximately located. Datum is sea level

●1 WELL AND IDENTIFIER--Prefix the letter G to number

(15) DIFFERENCE BETWEEN HIGHEST AND LOWEST WATER LEVEL, IN FEET

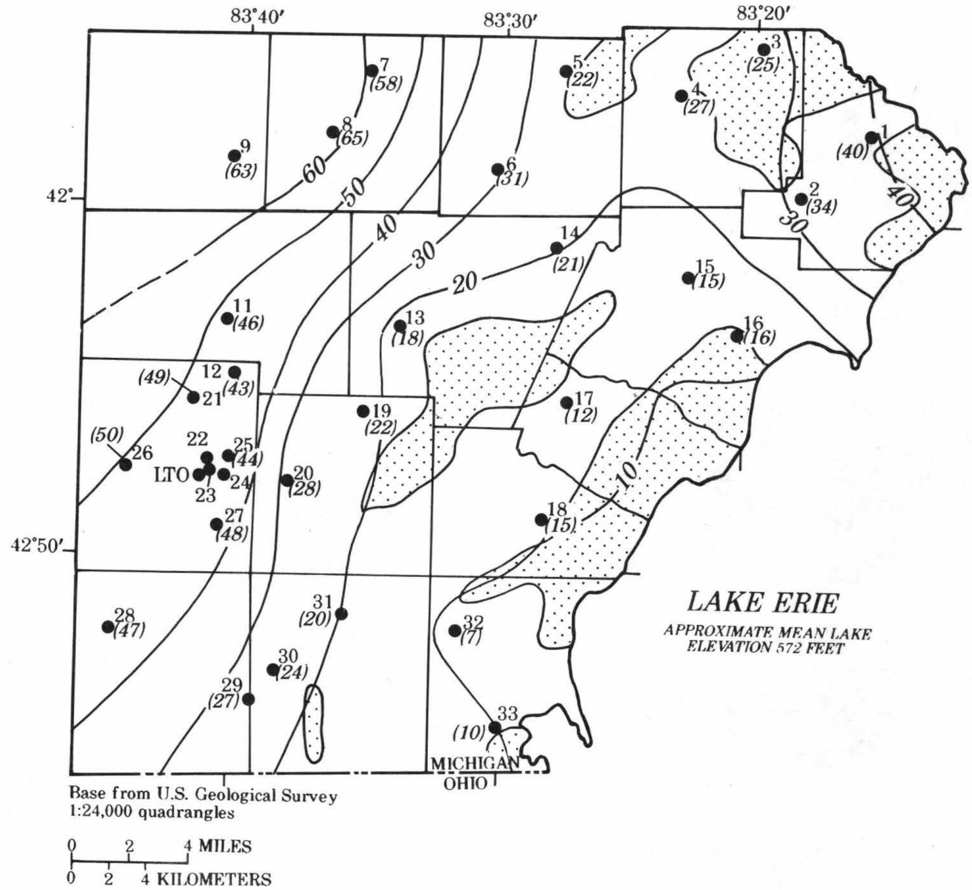
Figure 15. Range of water-level fluctuations in the Silurian-Devonian aquifer, Monroe County, Michigan, 1990-93.

Macon Creek, and Little River Raisin. Streams in the River Raisin Basin are perennial, except for Middle Branch Macon Creek and artificial drains.

Many small streams and artificial drains that are directly tributary to Lake Erie are between the Huron River Basin and the River Raisin Basin (Twenter and others, 1975). Drainage basins for these streams and drains include Ash Township and most of London, Berlin, Frenchtown, and Raisinville Townships. In the western part of the drainage basins, surficial deposits are mostly sand (Bowman, 1981), whereas in the eastern part of the drainage basins, surficial deposits are clay (Bowman, 1981). The largest streams—Sandy Creek, Swan Creek, and Stony Creek—are perennial.

The southwestern part of Whiteford Township is in the Ottawa River Basin. Most of the surficial material is clay (Bowman, 1981), and the streams are intermittent.

A second group of small streams and artificial drains that are directly tributary to Lake Erie is between the Ottawa River Basin and the River



EXPLANATION

FLOWING-WELL DISTRICT--Modified from Sherzer, 1900

10 LINE OF EQUAL DEPTH TO WATER BASED ON MAXIMUM DEPTH TO WATER MEASURED IN DECEMBER 1990 THROUGH JULY 1993-- Dashed where approximately located

● 1 WELL AND IDENTIFIER--Prefix the letter G to number

(18) MAXIMUM DEPTH TO WATER, IN FEET, DECEMBER 1990 THROUGH JULY 1993

Figure 16. Flowing-well districts before development and depth to water in the Silurian-Devonian aquifer, Monroe County, Michigan.

Raisin Basin (Twenter and others, 1975). Drainage basins for these streams and drains include all of Erie, Ida, LaSalle, and Bedford Townships and most of Whiteford, Summerfield, and Monroe Townships. In the western part of the drainage basins, surficial deposits are sand, whereas in the eastern part of the drainage basins, surficial deposits are clay (Bowman, 1981). Otter Creek, Halfway Creek, Plum Creek, Indian Creek, Bragden Ditch, Bay Creek, and Lapoint Drain are perennial.

Daily discharge record at River Raisin near Monroe has been collected by the USGS since 1937. Monthly mean discharges for water years 1988 through 1992 are shown on figure 17. Seasonal fluctuations in discharge are similar to seasonal

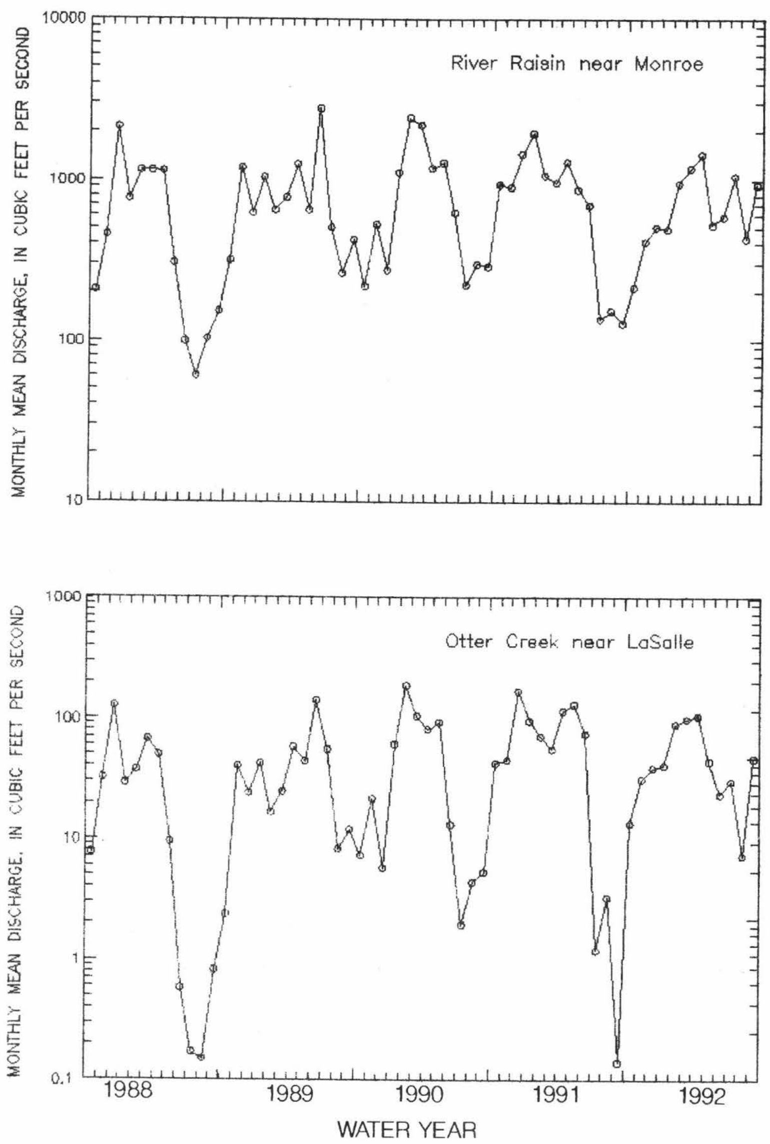


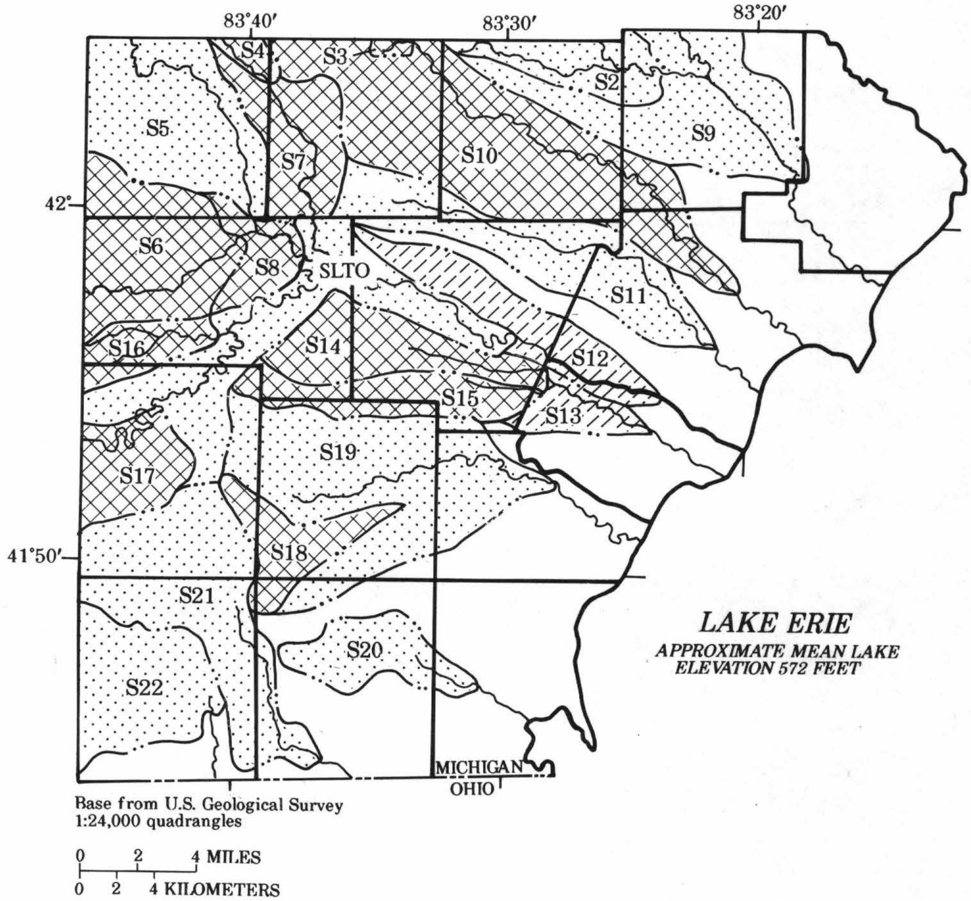
Figure 17. Monthly mean discharge at River Raisin near Monroe and Otter Creek near LaSalle, Monroe County, Michigan, water years 1988-92.

fluctuations in ground-water levels (fig. 8); typically, discharge is highest in the spring and lowest in the summer. Mean annual discharge for the period of record is 736 ft^3/s. The maximum discharge, 15,300 ft^3/s, was in March 1982; the minimum discharge, 2 ft^3/s, was in September 1938 and September 1941. During the drought of 1988, a minimum discharge of 24 ft^3/s was recorded on July 14 and 17. From October 1986 through September 1992, the minimum discharge for the River Raisin near Monroe was 24 ft^3/s, and the maximum was 8,280 ft^3/s.

Daily discharge record on Otter Creek near LaSalle has been collected since 1987. Monthly mean discharges for water years 1988 through 1992 are shown on figure 17. The maximum discharge, 2,050 ft^3/s, was in February 1990; streamflow ceased for a period of 26 days in 1988 and a period of 30 days in 1991. During periods of above-average precipitation, as in the summers of 1989 and 1992, flow is usually greater than 2 ft^3/s.

Discharge was measured at 24 sites in Monroe County in summer 1990 (See table 3, at back of report, p. 83). Measurements were made during low flow, when streamflow was all or mostly ground-water discharge. The measurements were made to (1) determine gaining and losing reaches of streams and (2) complement sampling for water quality of base flow.

The discharge measurements from July 1990 were normalized by drainage area and converted to inches per year. The lower reaches of River Raisin (S12) and Plum Creek (S13) were losing, indicating flow from the stream to the Silurian-Devonian aquifer (fig. 18). Normalized discharge at the other sites ranged from 0.22 in/yr in Macon Creek (S8) to 14.7 in/yr in Little Lake Creek (S20). No relation between normalized discharge and hydrogeology is apparent.



EXPLANATION

NORMALIZED DISCHARGE, IN INCHES PER YEAR

No data

Less than 0

0 to 0.9

Greater than or equal to 1.0

BASIN BOUNDARY

S2 SITE NUMBER--Site name listed in table 4

Figure 18. Drainage area and normalized discharge for surface-water sites, Monroe County, Michigan, July 1990.

WATER QUALITY

The water-quality-sampling program was designed to provide a general assessment of current water quality in Monroe County and to evaluate natural and human processes that affect ground- and surface-water quality. Additional goals were to examine lithologic controls on major and minor element chemistry in the Silurian-Devonian aquifer, to use geochemical and isotopic data to evaluate ground-water flow, and to relate surface-water quality to ground-water quality. A list of water-quality properties and constituents determined for this study, applicable drinking-water regulations, and a brief discussion of each property or constituent with respect to its implications for human health, domestic and industrial use, and natural geochemical processes is given in Appendix 4. Sampling and analytical procedures are describe in Appendix 5.

Ground-water samples were collected from November 1991 through May 1992 from 31 USGS wells and 10 domestic wells (table 2, at back of report, p. 78). Thirty-nine wells were completed in the Silurian-Devonian aquifer. Two wells, G10 and D3, were completed in the sand aquifer. Ground-water samples from all wells were analyzed for pH, dissolved oxygen (DO), specific conductance, turbidity, dissolved solids, hydrogen sulfide (H_2S), major and minor cations and anions, and dissolved organic carbon (DOC). Ground-water samples from selected wells were analyzed for stable isotopes of oxygen ($^{18}O/^{16}O$) and hydrogen (D/H), for dissolved sulfur ($^{34}S/^{32}S$) and inorganic carbon ($^{13}C/^{12}C$) species, and for the radioactive isotopes of hydrogen (^{3}H) and carbon (^{14}C). In addition, the Michigan Department of Agriculture (MDA) analyzed 21 ground-water samples collected from 10 USGS observation wells (G7, G8, G10, G11, G13, G19, G26, G28, G29, and G31) and 11 domestic wells (including three used in this study, D1, D2, and D3) for 32 pesticides. (No pesticides were detected in any of the samples. A list of the 31 pesticides analyzed for and the detection limits for each, as reported by MDA, is given in Appendix 6.)

Surface-water quality samples were collected to assess low-flow water-quality conditions in streams during the summers of 1990 and 1991 (See table 3, at back of report, p. 83). During low flow periods, most or all of the water is ground water discharged to the stream. Low-flow samples may also include constituents from point and nonpoint sources upstream from the site. Surface-water samples collected in late June and early July 1990 were analyzed for pH, specific conductance, temperature, DO, nitrite, nitrate, sulfate, and chloride. Samples collected in August 1990 and July, September, October 1991 were analyzed for basic cations and anions. Sampling by the Monroe County Health Department for fecal coliform bacteria in streams was done four times in 1990 and twice in 1991.

The charge balance between positively and negatively charged ions was calculated to assess the quality of analytical results for major dissolved ions for all ground-water samples and for surface-water samples analyzed for all major cations and anions. In most samples, analytical charge-balance errors were less than 3 percent, although charge-balance errors from 5 to 12 percent were found in several samples (tables 2 and 3, at back of report, pp. 78 and 83). This range of charge-balance errors is acceptable for evaluation of summary water-quality statistics and equilibrium speciation calculations. The ground-water sample from well D10, however, had an analytical charge-balance error of 90 percent; such a large error indicates major analytical errors, so the sample from well D10 is not considered in subsequent discussions.

General Characteristics

Summary water-quality statistics were calculated for ground-water samples from the Silurian-Devonian aquifer (table 4) and for surface-water samples collected in August 1990 (table 5). The summary statistics describe the ranges and distributions of values for selected water-quality characteristics. Distributions are summarized on the basis of their lower quartile (25th-percentile), median (50th percentile), and upper quartile (75th percentile). For example, the lower quartile corresponds to a value that was not exceeded by 25 percent of the sample values. In many samples, concentrations are below the reporting limits for determinations of trace elements and other minor constituents. For these constituents, means and standard deviations were calculated according to statistical methods designed for use with censored data sets (Helsel and Gilliom, 1986).

Ground Water

The major-ion composition and dissolved-solids concentration of ground-water samples collected in Monroe County indicate that the Silurian-Devonian aquifer contains water of highly varied composition. This variability can be attributed to the areal and vertical hydraulic and lithologic

Table 4. Water-quality statistics for the Silurian-Devonian aquifer of Monroe County, Michigan, 1991-92

[MCL, maximum contaminant level; SMCL, secondary maximum contaminant level (MCL's and SMCL's from U.S. Environmental Protection Agency, 1992); mg/L, milligrams per liter, μg/L, micrograms per liter; μs/cm, microsiemens per centimeter; °C, degrees Celsius; $CaCO_3$, calcium carbonate; NTU, nephelometric turbidity units. Dashes indicate no limit established or insufficient data to calculate statistic. Less-than symbol (<) indicates value is less than laboratory reporting limit. Asterisk indicates statistics estimated by the method developed by Helsel and Gilliom (1986)]

Property or constituent and unit	Number of analyses	Number of detections	Mean	Standard deviation	Range	MCL or SMCL	Number of samples that equal or exceed the MCL or SMCL	Sample values that were less than or equal to the: Lower quartile	Median	Upper quartile
Specific conductance (μs/cm at 25°C)	39	39	1,320	825	341-3,900	--	--	600	1,160	2,090
pH- field	38	38	7.4	.3	7.0-8.0	6.5-8.5	--	7.2	7.3	7.5
pH-whole lab (standard units)	39	39	7.4	.3	7.0-8.2	6.5-8.5	0	7.1	7.3	7.6
Temperature (°C)	13	13	11.5	.8	10.0-13.5	--	--	11.0	11.5	12.0
Turbidity (NTU)	39	39	46.2	125	.4-450	--	--	.7	2.8	17
Oxygen, dissolved (mg/L)	37	37	1.1	1.5	.1-5.9	--	--	.2	.4	1.6
Hardness (mg/L as $CaCO_3$)	39	39	735	532	110-1,800	--	--	270	470	1,300
Alkalinity-lab (mg/L as $CaCO_3$)	39	39	236	66	101-486	--	--	197	226	261
Solids, residue at 180°C (mg/L)	39	39	1,030	780	207-2,430	500	24	360	740	1,800
Solids, sum of constituents (mg/L)	39	39	946	694	203-2,700	500	24	371	704	1610
Calcium, dissolved (mg/L)	39	39	186	141	29-460	--	--	63	130	130
Magnesium, dissolved (mg/L)	39	39	60	46	6.1-150	--	--	21	37	100
Sodium, dissolved (mg/L)	39	39	30	40	3.0-250	--	--	8.7	22	36
Potassium, dissolved (mg/L)	39	39	2.7	1.7	.5-9.8	--	--	1.4	2.4	3.4
Sulfate, dissolved (mg/L)	39	39	470	471	<.1-1,400	250	20	61	250	950
Sulfide, total (mg/L as S)	38	19	*8.8	*20	<.5-96	--	--	*<.5	*5	*4.8
Chloride, dissolved (mg/L)	39	39	41	97	1.1-600	250	1	6.5	12	38
Fluoride, dissolved (mg/L)	39	39	1.0	.5	.1-2.7	2.0-4.0	1	.7	1.0	1.3
Silica, dissolved (mg/L as SiO_2)	39	39	13.3	3.8	6.3-27	--	--	11	13	15
Nitrite, dissolved (mg/L as N)	39	0	--	--	all < .01	1.0	0	--	--	--
Nitrite + nitrate, ($NO_2 + NO_3$) dissolved (mg/L as N)	39	4	--	--	< .01-.31	10.0	0	--	--	--
Aluminum, dissolved (μg/L)	39	27	*18	*9.5	< 10-50	50-200	1	*10	*20	*20
Arsenic, dissolved (μg/L)	39	3	--	--	< 1-1	50	0	--	--	--
Barium, dissolved (μg/L)	39	39	11	12	6-320	1,000	0	1	5	16
Beryllium, dissolved (μg/L)	39	6	*1.0	*6	< .5-2	4.0	0	*< 1.0	*< 1.0	*1.2
Cadmium, dissolved (μg/L)	39	1	--	--	all < 5.0	5.0	0	--	--	--
Chromium, dissolved (μg/L)	39	11	*.8	*.9	< 1-5	50	0	*< 1.0	*< 1.0	*1.0
Cobalt, dissolved (μg/L)	39	0	--	--	all < 20	--	--	--	--	--
Copper, dissolved (μg/L)	39	4	--	--	< 1-2	1,300	0	--	--	--
Iron, dissolved (μg/L)	39	37	*230	*470	< 3-2,600	300	8	*15	*50	*200
Lead, dissolved (μg/L)	39	1	--	--	< 1-7	50	0	--	--	--
Lithium, dissolved (μg/L)	39	36	*36	*39	< 4-200	--	--	*11	*25	*45
Manganese, dissolved (μg/L)	39	36	*18	*34	< 1-170	50	3	*4.5	*7	*11
Molybdenum, dissolved (μg/L)	39	4	--	--	all < 30	--	--	--	--	--
Nickel, dissolved (μg/L)	39	8	*.6	*1.3	< 1-7	100	0	*< 1.0	*< 1.0	*< 1.0
Silver, dissolved (μg/L)	39	0	--	--	all < 1.0	--	--	--	--	--
Strontium, dissolved (μg/L)	39	39	17	12	170-50,000	--	--	9.6	14	22
Vanadium, dissolved (μg/L)	39	0	--	--	all < 30	--	--	--	--	--
Zinc, dissolved (μg/L)	39	28	*25	*39	< 3-120	5,000	0	*7.7	*15	*23
Carbon, organic dissolved (mg/L)	39	39	2.7	1.8	.8-10	--	--	1.8	2.2	3.0
Sodium adsorption ration (SAR)	39	39	.54	.49	.05-2.59	--	--	.19	.37	.84

Table 5.--Water-quality statistics for surface water, Monroe County, Michigan, August 1990

[MCL, maximum contaminant level; SMCL, secondary maximum contaminant level (MCL's and SMCL's from U.S. Environmental Protection Agency, 1992); mg/L, milligrams per liter, µg/L, micrograms per liter; µs/cm, microsiemens per centimeter at 25 degrees Celsius; °C, degrees Celsius; $CaCO_3$, calcium carbonate; NTU, nephelometric turbidity units; Dashes indicate no limit established or insufficient data calculate statistic. Less than symbol (<) indicates value is less than laboratory reporting limit. Asterisk indicates statistics estimated by the method developed by Helsel and Gilliom (1986)]

Property or constituent and unit	Number of analyses	Number of detections	Mean	Standard deviation	Range	MCL or SMCL	Number of samples that equal or exceed the MCL or SMCL	Sample values that were less than or equal to the quartiles shown below: Lower quartile	Median (50%)	Upper quartile
Specific conductance (µs/cm at 25°C)	23	23	1,074	737	545-3,150	--	--	657	741	1230
pH	23	23	8.2	0.3	7.6-8.6	6.5-8.5	5	7.9	8.3	8.4
Temperature (°C)	23	23	20.1	2.9	15.5-27.0	--	--	18.0	19.0	22.5
Oxygen, dissolved (mg/L)	23	23	8.3	1.9	4.0-11.0	--	--	7.0	8.7	10.0
Hardness (mg/L as $CaCO_3$)	23	23	520	460	200-1,800	--	--	280	310	480
Alkalinity, (mg/L as $CaCO_3$)	23	23	191	45	59-262	--	--	161	204	225
Solids, residue at 180°C (mg/L)	23	23	812	769	334-2,820	500	9	387	445	782
Calcium, dissolved (mg/L)	23	23	150	145	54-510	--	--	73	88	130
Magnesium, dissolved (mg/L)	23	23	33	24	15-120	--	--	22	24	37
Sodium, dissolved (mg/L)	23	23	34	15	14-65	--	--	24	28	44
Potassium, dissolved (mg/L)	23	23	4.7	1.8	2.4-8.6	--	--	3.5	4.3	5.6
Sulfate, dissolved (mg/L)	22	22	259	400	34-1,500	250	5	66	86	225
Chloride, dissolved (mg/L)	23	23	68	24	33-120	250	0	46	60	81
Fluoride, dissolved (mg/L)	23	23	.3	.2	<.1-0.8	2.0-4.0	0	.2	.2	.4
Silica, dissolved (mg/L as SiO_2)	23	23	6.3	3.0	.8-11.0	--	--	4.0	5.7	9.1
Nitrite, dissolved (mg/L as N)*	23	10	<.01	--	<.01-0.2	1.0	0	<.01	0.01	<.01
Nitrite + Nitrate, (NO_2 + NO_3) dissolved (mg/L as N)*	23	16	.7	.6	<.05-1.7	10.0	0	.2	.4	1.0

heterogeneity of the aquifer. Most USGS wells have open intervals sufficiently long to sample several fractures; hence, samples from a single well may reflect a mixture of water obtained from several depths. The sampling program and the presentation in this report was designed primarily to describe areal trends. Therefore, in most cases, vertical variability is not quantified.

In the county, the major cation in ground water is calcium; the major anions are sulfate and bicarbonate (table 4). Strontium, which is usually considered a minor element, is found at concentrations exceeding 10 mg/L in about 75 percent of the samples (table 4). Dissolved-solids concentrations of ground water ranged from 207 to 2,430 mg/L. Ground-water samples from the Silurian-Devonian aquifer had a median pH of 7.3, were generally anoxic (DO < 0.5 mg/L), and commonly contained measurable concentrations of iron, manganese, and hydrogen sulfide (H_2S).

The most common water types in the Silurian-Devonian aquifer are calcium magnesium sulfate and calcium magnesium bicarbonate (fig. 19). Mixed-cation bicarbonate waters that contain significant concentrations of sodium (and strontium) also are common. Bicarbonate sulfate waters (hereafter called mixed-anion waters) fall along a mixing trend defined by dilute bicarbonate waters and the more concentrated sulfate waters. The sample from the glacial aquifer (G10) is classified as a mixed-cation bicarbonate water.

Sulfate water is the most common type in the Silurian-Devonian aquifer in eastern Monroe County (fig. 20). Bicarbonate waters are common in the north-central and northwestern parts of the county, whereas mixed waters are scattered throughout the south-central and southwestern parts of the county. The distribution of water types cannot be correlated with any individual geologic formation; multiple water types are found in different locations of each formation. The lack of correlation is not unexpected, because each formation is spatially and vertically varied in lithology and hydrogeologic properties. Furthermore, many sampled wells are open to more than one formation, and water from these wells represents a mixture of waters from more than one formation.

Water type and dissolved-solids concentration are related in the Silurian-Devonian aquifer (fig. 21). Waters with dissolved-solids concentrations less than 500 mg/L are mostly bicarbonate type. Waters with dissolved-solids concentrations greater than 500 mg/L are either mixed-anion type or sulfate type. Waters with dissolved-solids concentrations greater than 1,000 mg/L are mostly sulfate type.

Dissolved-solids concentrations are positively correlated with dissolved-sulfate concentrations in the Silurian-Devonian aquifer (fig. 22). The correlation is strong: regression analysis yields a line with a slope of 1.61 and a correlation coefficient of 0.97 (fig. 22). This correlation holds for all waters except for the sample collected from well G4, which is a mixed-anion water with the highest chloride concentration (600 mg/L) found in this study. The correlation between dissolved-solids concentration and dissolved sulfate is consistent with hypotheses involving mixing of dilute bicarbonate water with sulfate-rich waters or progressive addition of sulfate to ground water by dissolution of sulfate-bearing minerals in the aquifer matrix. These hypotheses are explored in detail in subsequent sections.

Surface Water

Summary statistics calculated for the August 1990 samples (table 5) indicate that median pH and dissolved-oxygen concentrations of streams in Monroe County are higher than those for ground water from the Silurian-Devonian aquifer. Median specific conductances and dissolved-solids concentrations, however, are significantly less than those in ground water. Median concentrations of major cations and anions are generally similar, although most cation and anion concentrations in surface water are slightly less than those in ground water (table 5); however, median concentrations of sodium, potassium, chloride, and nitrate are higher than those in the ground-water samples, a pattern that is consistent with local applications of deicing salts and nitrate-based fertilizers.

Mixed-anion waters, including bicarbonate chloride, bicarbonate sulfate and bicarbonate chloride sulfate waters, are nearly 70 percent of surface-water samples collected in August 1990 (fig. 23). Bicarbonate, however, is the dominant anion in most waters classified as mixed-anion waters. Most of the samples are of the mixed-cation type. The dominant cations in the surface-water samples are calcium, magnesium, and sodium. The dominance of mixed-cation and mixed-anion water types at low flow reflects contributions of sodium, chloride and, to a lesser extent, sulfate derived from anthropogenic sources to dilute bicarbonate ground water discharging from shallow glacial

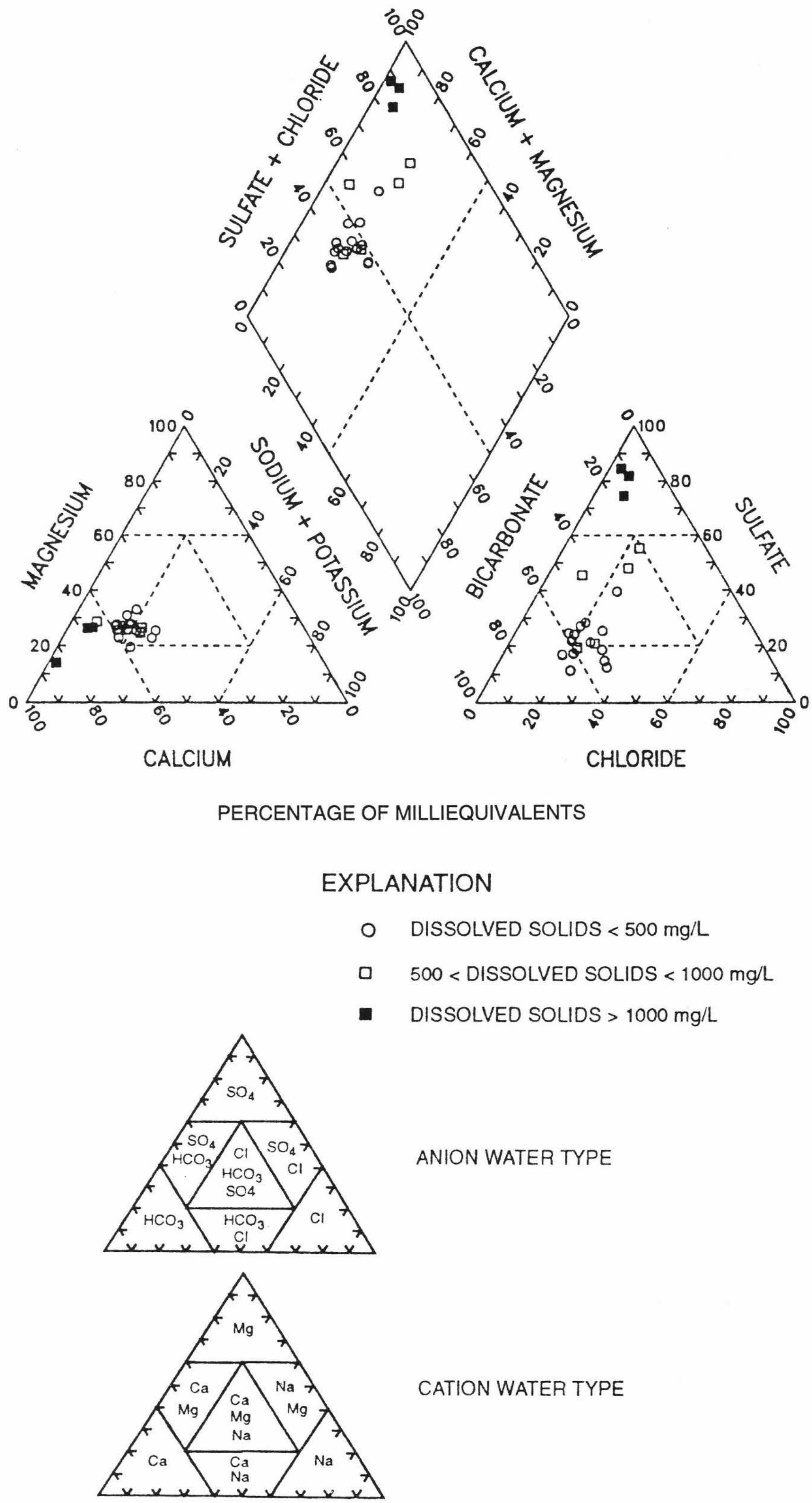
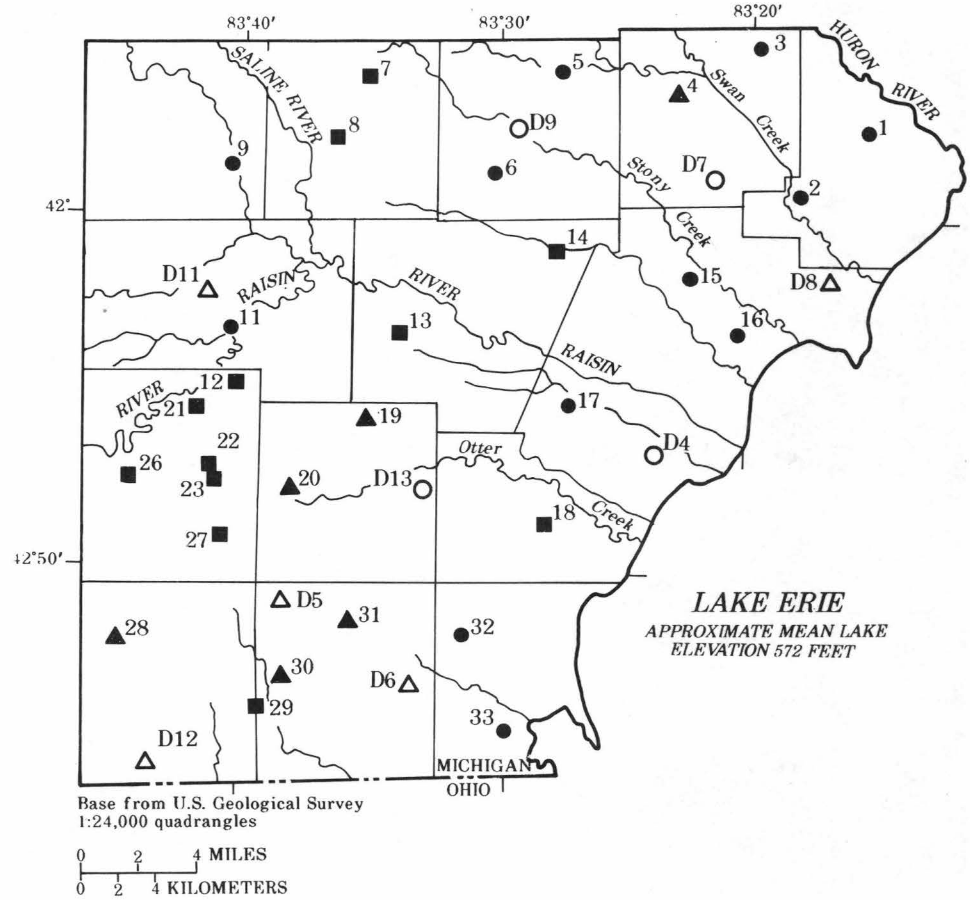


Figure 19. Water types for ground-water samples, Monroe County, Michigan, 1991-92.



EXPLANATION

D12 WELL IDENTIFIER--D prefix indicates domestic well

WATER TYPE IN WELL--Filled symbol indicates U.S. Geological Survey well. Unfilled symbol indicates domestic well

- ● Sulfate water
- ■ Bicarbonate water
- ▲ Mixed water

Figure 20. Areal distribution of major water types in the Silurian-Devonian aquifer, Monroe County, Michigan, 1991-92.

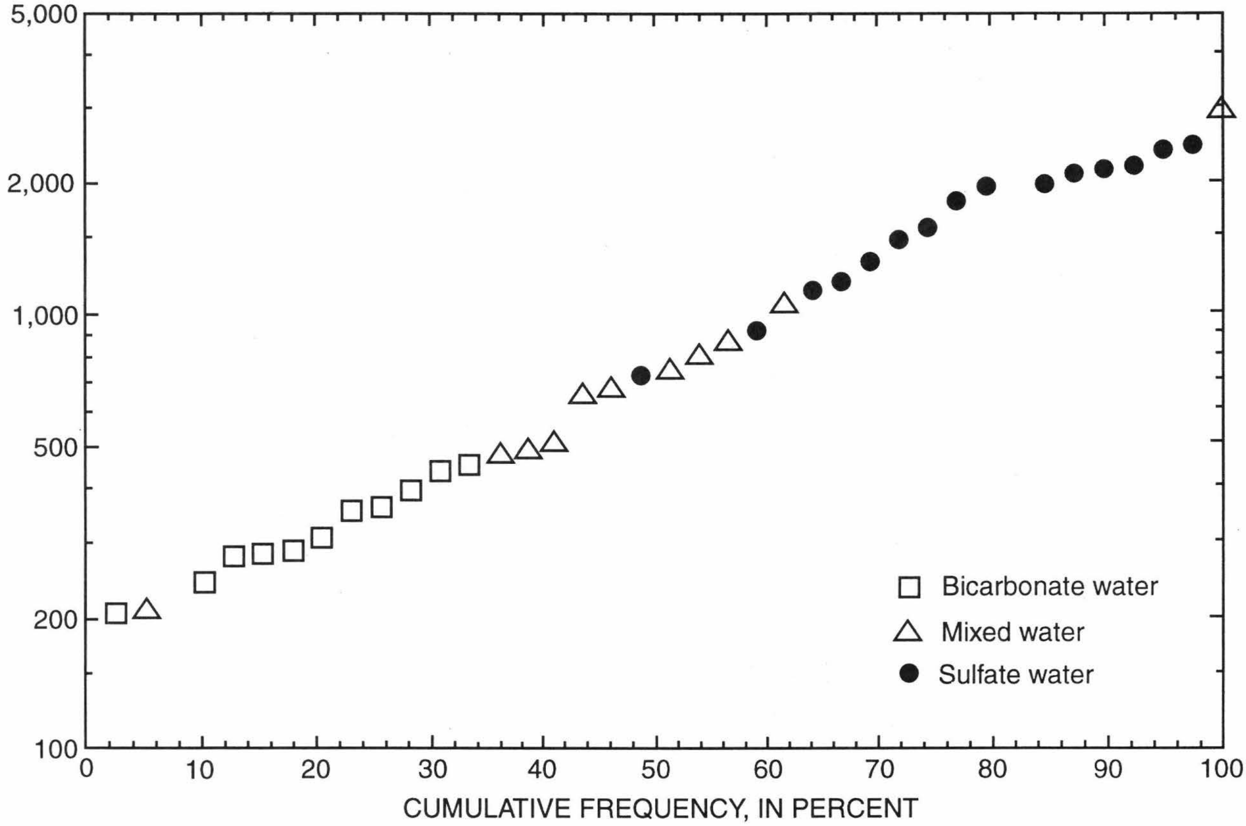


Figure 21. Cumulative frequency of dissolved-solids concentration for ground-water samples, Monroe County, Michigan, 1991-92.

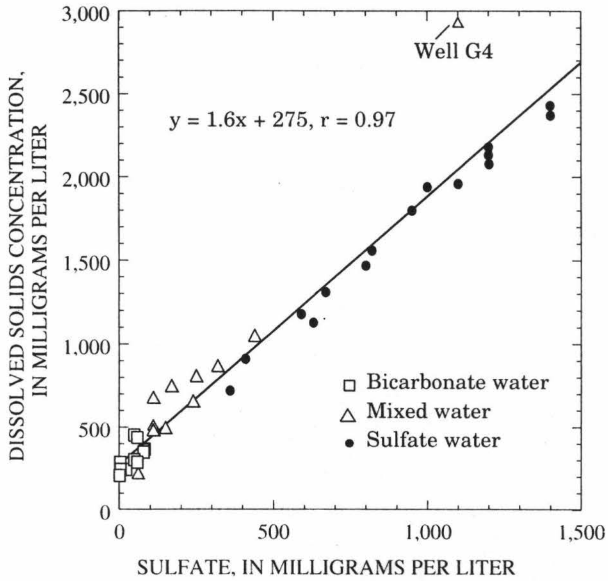


Figure 22. Dissolved-solids concentration as a function of dissolved-sulfate concentration for ground-water samples, Monroe County, Michigan, 1991-92.

sediments or the underlying carbonate rocks. Similar to ground water, surface-water compositions change from bicarbonate and mixed-anion waters to sulfate waters with increasing dissolved-solids concentrations (fig. 23). High-sulfate water at low-flow is associated with streams receiving discharge from quarry-dewatering operations (table 5; pl. 1).

Suitability for Use

The quality of water determines the suitability of water for drinking, irrigation, or other uses. In Monroe County, the most important chemical factors that can limit the use of water are hardness, high concentrations of sulfate and dissolved solids, and in ground water, high concentrations of hydrogen sulfide (H_2S), iron, or manganese. Concentrations of objectionable constituents in ground water are largely controlled by natural geochemical processes and the mineralogy in the Silurian-Devonian aquifer. Surface-water quality is less affected by natural geochemical process, although base-flow water quality reflects conditions in the aquifer discharging to the stream. When streamflow is greater than base flow, objectional effects on surface-water quality are mostly related to human activities. In ground water and surface water of Monroe County, however, most trace elements and agrichemicals (nitrates and pesticides) are not present at levels that would affect domestic use (tables 4 and 5).

In this section, the occurrence of constituents that affect the suitability of water for use in Monroe County are discussed primarily in terms of drinking-water regulations set by the U. S. Environmental Protection Agency (1992). These regulations consist of enforceable, health-based limits (maximum contaminant levels or MCL's) and non-enforceable, secondary limits that are set according to aesthetic criteria (secondary maximum contaminant levels or SMCL's) (U. S. Environmental Protection Agency, 1992; Appendix 4). Constituents and water-quality properties for which no regulatory limits have been established, such as hardness, also are discussed.

Ground Water

The most common ground-water-quality problem in Monroe County is high dissolved-solids concentrations. Dissolved-solids concentrations in excess of the SMCL can cause mineral deposition in plumbing fixtures and water heaters, can affect the taste of water, and can induce laxative effects in people who do not normally drink the water. The SMCL for dissolved solids is 500 mg/L. Dissolved-solids concentrations in the Silurian-Devonian aquifer ranged from 207 to 2,920 mg/L; the median dissolved-solids concentrations was 740 mg/L. The SMCL was exceeded in 24 samples.

Water with sulfate concentrations greater than 400 to 500 mg/L, the proposed MCL, (U.S. Environmental Protection Agency, 1993), has a marked laxative effect on infants and people who do not consume such water on a regular basis (for example, travelers). Because such waters do not affect most of the local population, USEPA is considering applying the regulation only to businesses that regularly serve short-term visitors (for example, hotels and restaurants). The median sulfate concentration of ground water in the Silurian-Devonian aquifer is 250 mg/L, equivalent to the SMCL for sulfate. Sulfate concentrations in calcium sulfate and calcium magnesium sulfate waters commonly exceed 1,000 mg/L. The distribution of high-sulfate water is similar to that for dissolved solids; sulfate concentrations exceeding the SMCL are mostly in the eastern third of the county (fig. 24).

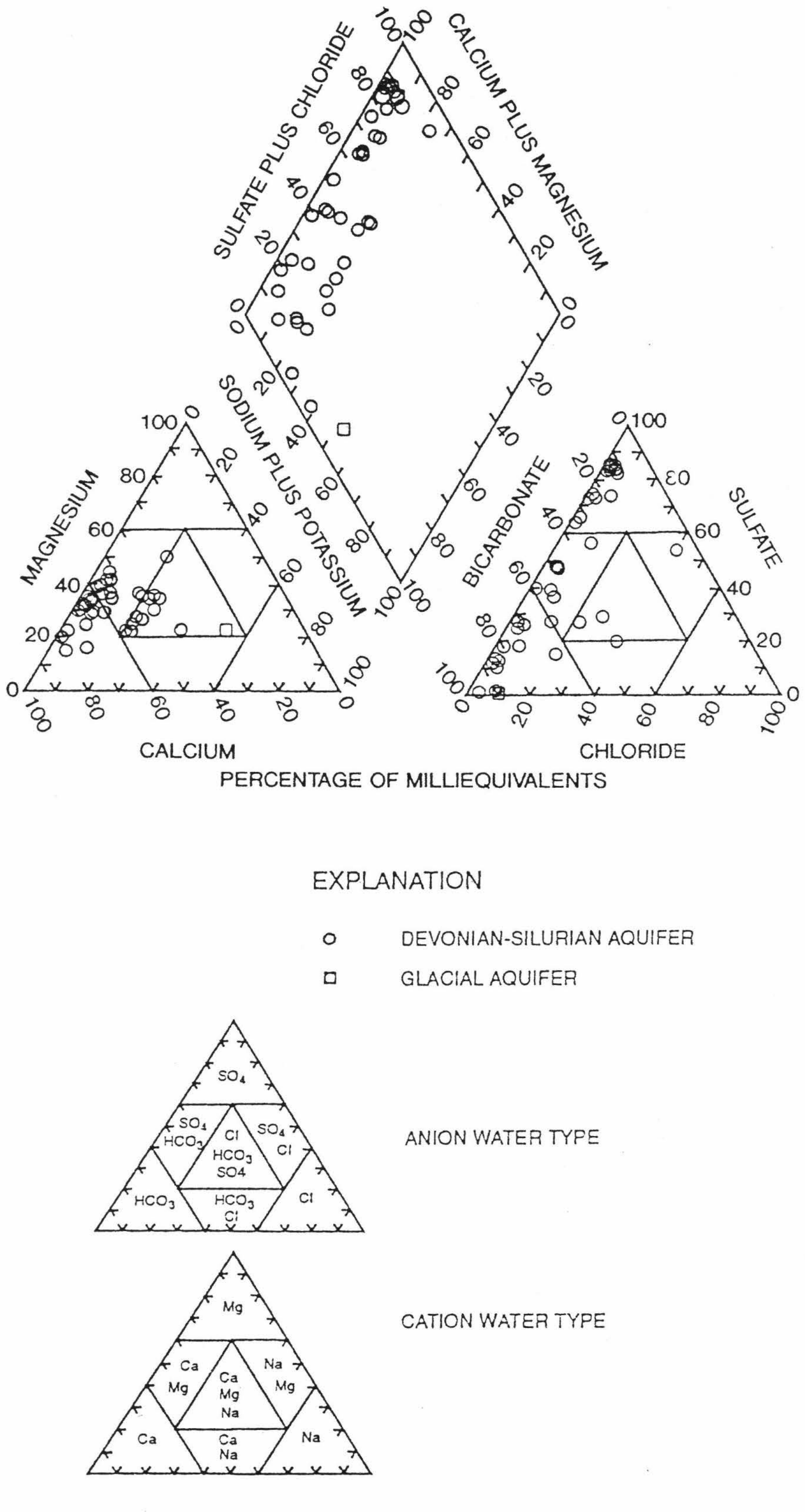
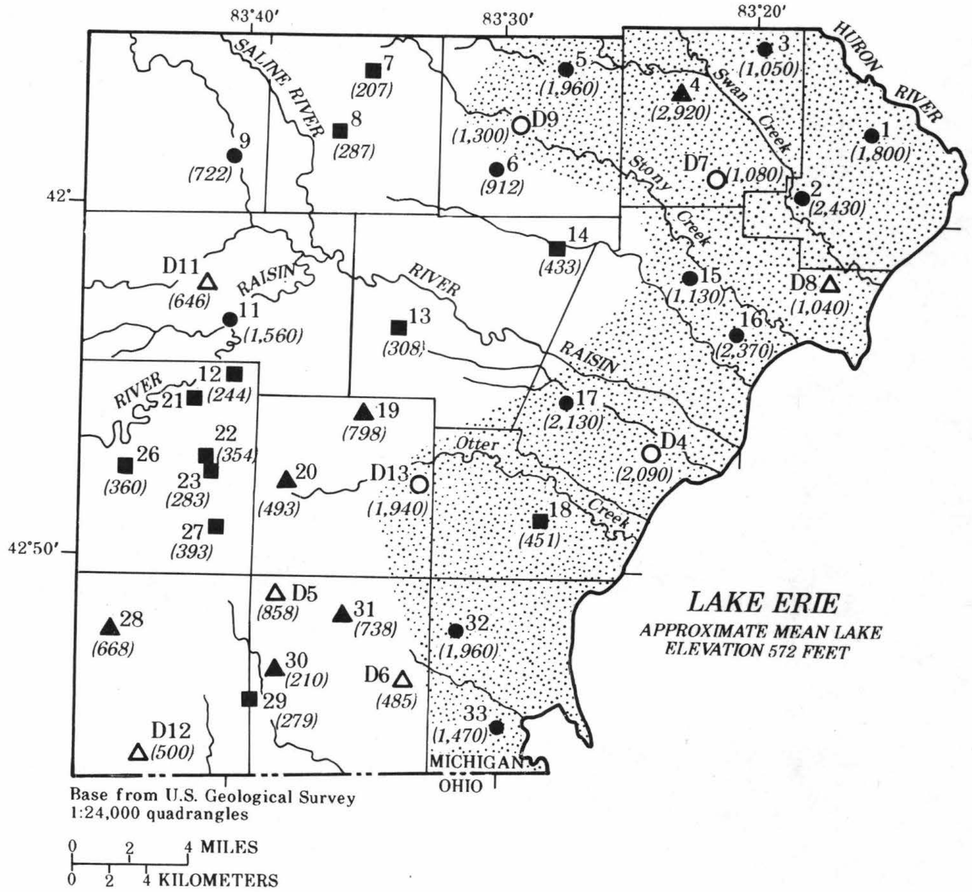


Figure 23. Water types for surface-water samples, Monroe County, Michigan, August,1990.



EXPLANATION

AREA WHERE DISSOLVED SOLIDS CONCENTRATION TYPICALLY EXCEEDS 1,000 MILLIGRAMS PER LITER

(738) DISSOLVED-SOLIDS CONCENTRATION--In milligrams per liter

D12 WELL IDENTIFIER--D prefix indicates domestic well

WATER TYPE IN WELL--Filled symbol indicates U.S. Geological Survey well. Unfilled symbol indicates domestic well

● Sulfate water

■ Bicarbonate water

▲ Mixed water

Figure 24. Dissolved-solids concentration in the Silurian-Devonian aquifer, Monroe County, Michigan, 1991-92.

In addition to varying areally, dissolved solids concentrations also vary vertically. Geophysical logs from well G27 (Appendix 1) are illustrative. The well is open to three rock units—water from the Sylvania Sandstone had a higher specific conductance (higher dissolved solids) than (water from the underlying Bass Islands Dolomite or overlying Detroit River Dolomite. Water from the Detroit River Dolomite had the lowest specific conductance of the three rock units at well G27.

Waters that have high sulfate and dissolved-solids concentrations are also very hard. Hardness traditionally refers to a water's tendency to form insoluble compounds with soap solutions and is caused by high concentrations of the alkaline earth elements calcium, magnesium, and strontium. High hardness can cause mineral deposition in pipes, plumbing fixtures, and boilers. According to Durfor and Becker (1964), waters are "very hard" at concentrations exceeding 180 mg/L $CaCO_3$. Hardness in 30 samples was in the very hard range, and several samples had hardness concentrations in excess of 1,000 mg/L $CaCO_3$. The hardness calculated by subtracting alkalinity from the total reported hardness is called noncarbonate hardness (Hem, 1989). More than 80 percent of the ground-water samples contained significant quantities of noncarbonate hardness.

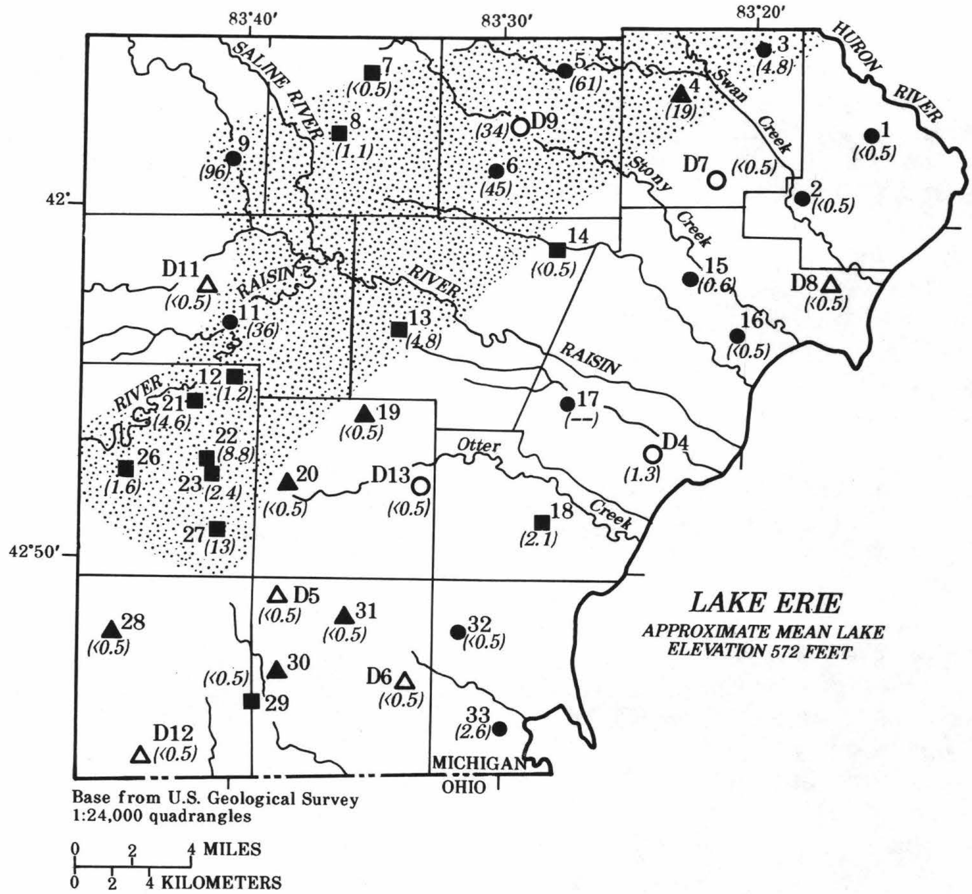
Hydrogen sulfide (H_2S) is a gas that imparts an objectionable odor to ground water and can corrode metal pipes and plumbing fixtures. The smell of H_2S is commonly described as that of rotten eggs, and the odor can be detected by most individuals at concentrations less than a part per billion (1 µg/L). No limits have been set for H_2S; and tolerance to H_2S varies from individual to individual. Nevertheless, municipal water suppliers usually aerate ground water that has significant H_2S concentrations to degas and oxidize the H_2S before distribution. When exposed to air, hydrogen sulfide in H_2S is quickly oxidized to native sulfur, giving the water a milky white color. In wells where iron- and H_2S-bearing waters mix, iron sulfide precipitates may form, giving the water an inky black color. Both types of waters have been observed historically in Monroe County (Leverett and others, 1906).

Fifty percent of the ground-water samples collected from the Silurian-Devonian aquifer had measurable concentrations of H_2S (total sulfide, in milligrams per liter as sulfur, in table 4 and table 3, at back of report, p. 83). Concentrations ranged from below the reporting limit (0.5 mg/L) to 96 mg/L. The composition of the H_2S-bearing waters was approximately equally distributed between bicarbonate and sulfate waters; only one mixed water sample contained a measurable concentration of H_2S. Wells with water having H_2S concentrations greater than 0.5 mg/L were along a northeast-southwest trend that largely corresponds to the subsurface outcrop area of the Dundee Formation and Detroit River Dolomite (fig. 25). In the carbonate aquifer system of northwestern Ohio, H_2S concentrations greater than 3.0 mg/L generally are found in Devonian rocks, the bulk of which were rocks of the Detroit River Dolomite (Ohio Department of Natural Resources, 1970). A similar, if less well defined, relation between measurable H_2S concentrations and wells completed in the Silurian-Devonian aquifer is evident in the data reported by Breen and Dumouchelle (1991) for the Silurian-Devonian carbonate aquifer of Wood, Lucas, and Sandusky Counties, northwestern Ohio.

A common water-quality problem for ground water containing little or no dissolved oxygen and H_2S is the occurrence of dissolved iron and manganese. At concentrations exceeding their respective SMCL's (300 µg/L and 50 µg/L), both elements can cause staining of clothing and porcelain surfaces. In Monroe County, more than 90 percent of the ground-water samples collected had detectable concentrations of both iron and manganese, but median concentrations for both elements were well below SMCL's. Only 20 percent of the ground-water samples collected from the Silurian-Devonian aquifer had dissolved-iron concentrations above the SMCL; less than 8 percent had manganese concentrations above the SMCL (tables 3 and 4). The distribution of ground water that had dissolved-iron concentrations greater than the SMCL is shown on figure 26. An irregular band of high dissolved-iron concentrations trends northeast-southwest across the county. The highest iron and manganese concentrations were found in ground-water samples collected from wells completed in the Sylvania Sandstone and Bass Islands Dolomite.

Although fluoride is an essential element that is incorporated into bones and teeth, it can lead to discoloration of teeth and excessive brittleness in bones if ingested at high concentrations over a period of years. Hence, the amount of fluoride present or added to municipal water supplies is regulated, and the SMCL is 2.0 mg/L. Fluoride concentrations in Monroe County ranged from 0.1 to 2.7 mg/L, and the median was 1.0 mg/L. In 75 percent of the wells sampled, fluoride concentrations were less than or equal to 1.3 mg/L; water from only one well had a fluoride concentration that exceeded the SMCL (G33, 2.7 mg/L). These results are comparable to results reported by Breen and Dumouchelle (1991) for ground water collected from the Silurian-Devonian aquifer of Wood, Lucas, and Sandusky Counties in northwestern Ohio. There, 90 percent of the samples had fluoride concentration less than or equal to the SMCL; the median fluoride concentration was 1.4 mg/L.

Chloride, which can be derived from natural or artificial salts, imparts a saline taste to water when concentrations exceed the SMCL of 250 mg/L. Chloride concentrations in Monroe County ranged from 1.1 to 600 mg/L. A chloride concern-



EXPLANATION

AREA WHERE HYDROGEN SULFIDE CONCENTRATION EXCEEDS THE REPORTING LIMIT OF 0.5 MILLIGRAM PER LITER

(45) HYDROGEN SULFIDE CONCENTRATION, IN MILLIGRAMS PER LITER--Dashed line indicates no data

D12 WELL IDENTIFIER--D prefix indicates domestic well

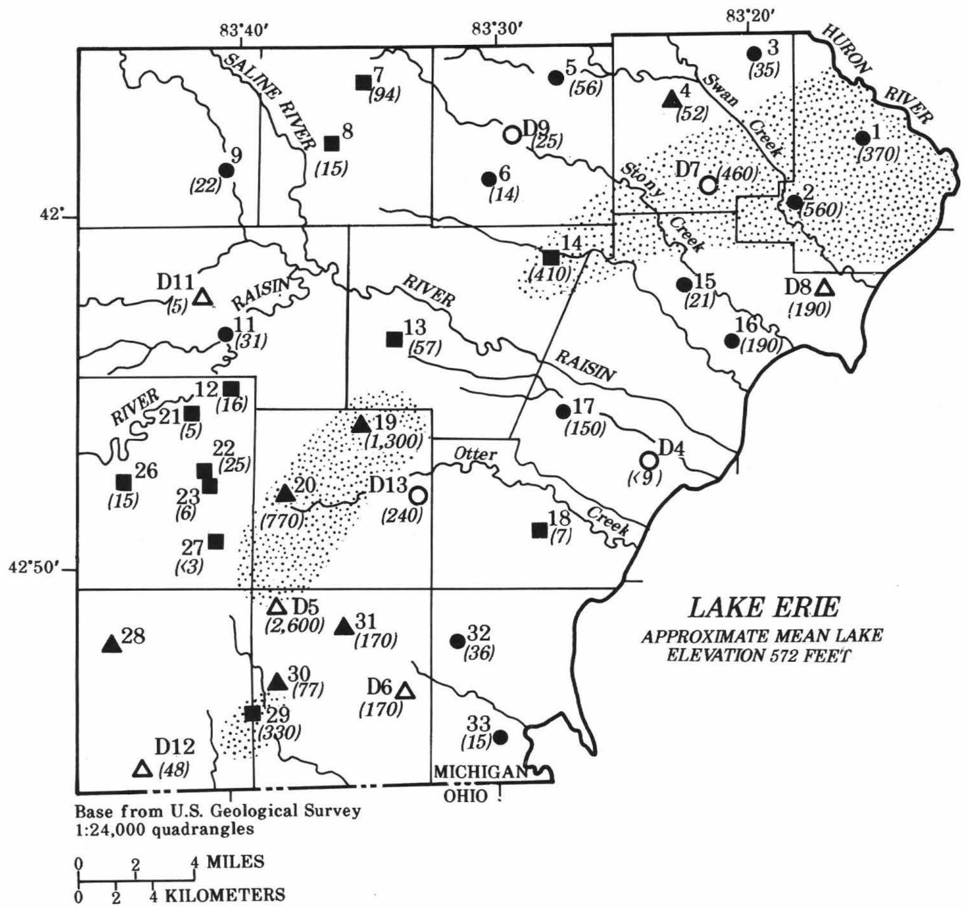
WATER TYPE IN WELL--Filled symbol indicates U.S. Geological Survey well. Unfilled symbol indicates domestic well

- ● Sulfate water
- ■ Bicarbonate water
- ▲ Mixed water

Figure 25. Areal distribution of dissolved hydrogen sulfide in the Silurian-Devonian aquifer, Monroe County, Michigan, 1991-92.

tration greater than the SMCL was found at only one well (G4, 600 mg/L) and is likely a result of human activities. The absence of chloride-rich waters in Monroe County is consistent with the lithology of the Silurian rocks in Monroe County. Although these rocks are mined for salt in other areas of the Michigan Basin, salt beds are nearly absent in the rocks in Monroe County (Mozola, 1970). The absence of elevated chloride concentrations also indicates that, at this time, the water quality of wells sampled in this study is not being adversely affected by road deicing.

The suitability of ground water for irrigation was evaluated by use of a method developed by the U.S. Salinity Laboratory (1954). The method evaluates the overall suitability of a water for irrigation on the basis of two hazard classes: the



EXPLANATION

[stippled pattern]	AREA WHERE DISSOLVED-IRON CONCENTRATION EXCEEDS THE SECONDARY MAXIMUM CONTAMINANT LEVEL OF 300 MILLIGRAMS PER LITER
(240)	DISSOLVED-IRON CONCENTRATION--In milligrams per liter
D12	WELL IDENTIFIER--D prefix indicates domestic well
	WATER TYPE IN WELL--Filled symbol indicates U.S. Geological Survey well. Unfilled symbol indicates domestic well
●	Sulfate water
■	Bicarbonate water
▲	Mixed water

Figure 26. Areal distribution of dissolved iron in the Silurian-Devonian aquifer, Monroe County, Michigan, 1991-92.

salinity hazard is based on fixed ranges of specific conductance, and the sodium hazard is a function of specific conductance based on relative concentrations of the cations most important to cation-exchange reactions in soil (calcium, magnesium, and sodium). The method was developed for irrigation waters in arid parts of the western United States and can be applied only in a general way to non-arid areas.

Fifty percent of the ground-water samples had a specific conductance between 750 and 2,250 µs/cm and are classified as high-salinity waters (table 6). Several of the samples with high sulfate concentration are classified as very high

Table 6.--Hazard classification of irrigation water

[µS/cm, microsiemens per centimeter at 25 degrees Celsius]

Salinity hazard classification	Description
C1	Low-salinity water that can be used on most crops and soils. Some leaching is necessary, thus soils with low permeability may be affected (specific conductance range = 100-250 µS/cm)
C2	Medium-salinity water that can be used if soil permeability and drainage are sufficiently high (specific conductance range = 250-750 µS/cm)
C3	High-salinity water that should not be used on soils of low permeability. Crops with low salt tolerance, even with adequate drainage, may be affected (specific conductance range = 750-2,250 µS/cm)
C4	Very high-salinity water is not suitable for irrigation under most conditions (specific conductance range = 2,250-5,000 µS/cm).
S1	Low-sodium water that can be used with most soils with little danger of developing hazardous levels of exchangeable sodium.
S2	Medium-sodium water that may pose problems in fine-textured soils that have a high cation-exchange capacity.
S3	High-sodium water that may produce harmful levels of sodium in most soils.
S4	Very high sodium water that is generally unsatisfactory for irrigation purposes.

salinity waters. However, because the high salinity classification is caused by high concentrations of dissolved calcium and sulfate, not by sodium, these waters can be considered suitable for irrigation. The median sodium adsorption ratio (SAR) value for samples from the Silurian-Devonian aquifer is 0.37 (table 6). Thus, most ground water in the Silurian-Devonian aquifer has a very low sodium hazard. Ground water from well G4, which has a sodium concentration of 250 mg/L, is the only water whose SAR approaches the moderate sodium hazard category.

Surface Water

Data collected during this study indicate that most surface water in Monroe County would be suitable for use as drinking water with only minimal treatment to remove bacteria (tables 3 and 5). However, some samples had high hardness and high dissolved-solids and sulfate concentrations, and some had pH's greater than the SMCL of 8.5. Surface waters having high dissolved-solids and sulfate concentrations generally are found downstream from sites where quarry-dewatering operations discharge. The chemistry of the quarry-discharge waters is similar to that of local ground water in the part of the Silurian-Devonian rock being quarried. At times, the quality of water being discharged into the streams may be modified by other human activities, as indicated by the potassium concentration found in samples collected at site S8 on Macon Creek during 1990-91.

Throughout the midwestern United States, fertilizers are typically applied in spring. Concentrations of nitrates in surface water commonly peak during spring and winter (when plant uptake of nitrogen is low), whereas lowest concentrations are in summer and fall (Battaglin and others, 1993). The highest dissolved-nitrate concentrations in Monroe County were in samples collected in late June and early July 1990. At several sites, nitrate concentrations were between 3 and 8 mg/L NO_3^- as N (fig. 27), and the median nitrite plus nitrate concentration was 1.8 mg/L (as N), significantly higher than the median nitrite plus nitrate concentration in August 1990. No samples collected in 1990 or 1991 exceeded the MCL's for dissolved nitrite (1.0 mg/L as N) or nitrate (10.0 mg/L as N). The sampling during this study, designed to characterize low-flow quality, may have missed the time of maximum nitrite plus nitrate concentrations in surface water in Monroe County.

Adequate amounts of DO in surface water are particularly important because, even if streamflow is being derived from anoxic ground water, concentrations of constituents that limit use of ground water (dissolved iron, manganese, or hydrogen sulfide) will quickly be reduced to nondetectable levels in the stream by chemical reactions that

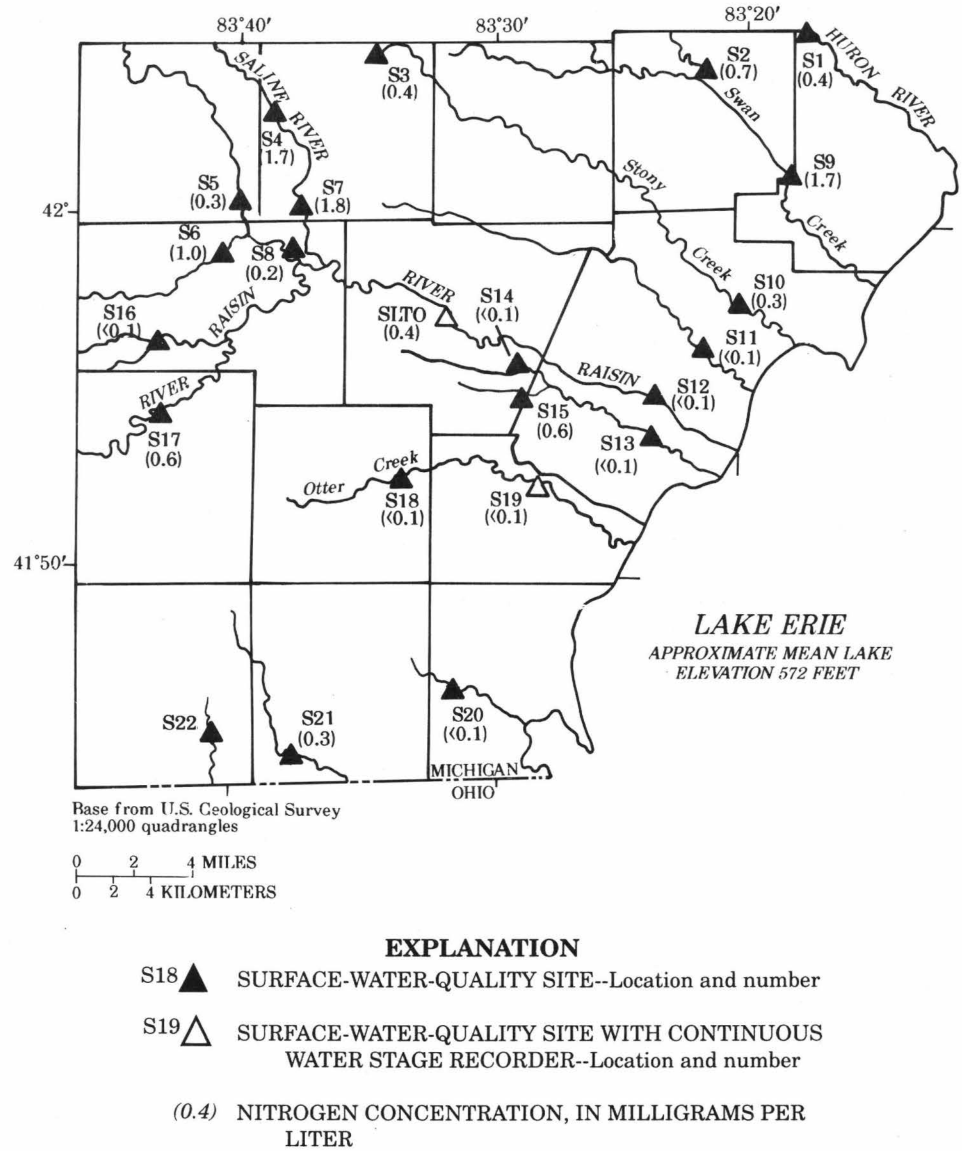


Figure 27. Concentration of nitrate-nitrogen in surface-water samples, Monroe County, Michigan, August, 1990.

convert these species to forms that do not impair water for most uses (iron manganese hydroxide precipitates, sulfate). Most surface waters were nearly saturated with respect to DO (tables 2 and 5). Samples from two sites (S9 and S11) had DO concentrations that approached minimum Michigan water-quality standard of 3.0 mg/L (Michigan Department of Natural Resources, 1990a). The data indicate that streams in Monroe County are not being loaded with significant quantities of oxygen-consuming organic substances. Such substances are typically derived from sewage or from agricultural or industrial wastes.

Fecal coliform bacteria in surface water are used as indicators of effluent from sewage-treatment plants and runoff from urban areas, feedlots, and pastures. Such sources often contain other disease-causing pathogens; hence, fecal coliform bacteria are used as indicator organisms to set health-based water-use standards. The Federal drinking-water regulation is 0 col./100 mL (U.S. Environmental Protection Agency, 1992). In Michigan, recreational water-use standards are 400, 2,000 and 5,000 col./100 mL for bathing waters, primary-contact waters, and secondary-contact waters (Michigan Department of Natural Resources, 1990a).

The fecal coliform data indicate that surface water in Monroe County is generally suitable for most recreational uses. Recreational water-use standards for bathing waters and primary-contact waters were exceeded at only a few surface-water sites (S16 and S21 in July, 1990; S13 and S14 in October 1991; table 7). The secondary-contact standard was exceeded at sites S13 and S14, in October 1991. The data indicate a strong seasonal dependence on fecal coliform bacteria populations: high concentrations in the summer and low concentrations in the winter. Fecal coliform bacteria live in the intestines of warm-blooded animals and are therefore acclimated to warm temperatures. During the winter, fecal coliform bacteria die quickly in waters at near-freezing temperatures.

Geochemistry of the Silurian-Devonian Aquifer

Mineral Equilibria

The chemistry of ground water is partly controlled by reactions between ground water and reactive minerals in the aquifer. Mineralogic controls on water composition and quality in Monroe County were investigated with the equilibrium thermodynamic model WATEQ4F (Ball and Nordstrom, 1991). The model calculates the aqueous speciation of a given water analysis and the saturation index (SI) of minerals that may be precipitating or dissolving in the system. The SI of a mineral is defined as

$$SI = \text{Log } IAP/K_T, \qquad (1)$$

where IAP is the ion activity product of the mineral and K_T is the thermodynamic equilibrium constant, evaluated at the temperature of the water sample. If the SI of a mineral is greater than zero, then the water is supersaturated with respect to that mineral, and precipitation of the mineral in the aquifer is possible. If the SI of a mineral is less than zero, then the water is undersaturated with respect to that mineral and dissolution of the mineral is possible. SI's equal to zero indicate equilibrium between ground water and the mineral; thus, neither precipitation nor dissolution of the mineral should occur.

SI's were calculated for minerals that may have a role in regulating the concentration of major and minor elements found in ground water from the Silurian-Devonian aquifer: the carbonate minerals calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), and strontianite ($SrCO_3$); the sulfate minerals gypsum ($CaSO_4 \cdot 2H_2O$), celestite ($SrSO_4$), and barite ($BaSO_4$); the iron minerals mackinawite (FeS), amorphous iron monosulfide (FeS), and siderite ($FeCO_3$); and quartz (SiO_2), chalcedony (SiO_2), and fluorite (CaF_2). The SI of pyrite (FeS_2) could not be evaluated because WATEQ4F requires an estimate of the oxidation-reduction potential (Eh) to calculate the IAP of pyrite. Instead, the SI's of amorphous iron monosulfide (FeS) and mackinawite (FeS) were evaluated. Although not found in rock samples collected during this study, these minerals can be used to estimate maximum dissolved-iron concentrations in H_2S-bearing ground water. In calculating the SI for siderite, amorphous FeS, and mackinawite, all dissolved iron in anaerobic ground water was assumed to be present as ferrous (Fe^{2+}) iron. Details and results of the speciation and SI calculations made with WATEQ4F are given in table 8.

Results of the WATEQ4F calculations indicate that nearly all ground-water samples were saturated with respect to calcite, and most were saturated with respect to dolomite (fig. 28). Equilibrium or near equilibrium with these minerals is expected because they are fairly soluble and are the dominant minerals in the Silurian-

Table 7.--Fecal coliform data for surface-water samples collected and analyzed by Monroe County Health Department, Monroe County, Michigan, 1990-91.

[Units are number of bacteria colonies per 100 milliliters of sample; --, data not collected.]

Site number	Date of collection					
	7-3-90	8-8-90	9-11-90	12-4-90	4-12-91	10-3-91
S1	60	100	40	0	195	250
S2	71	940	200	0	104	40
S3	370	380	100	5	412	640
S4	290	130	320	3	254	210
S5	370	160	0	7	73	1540
S6	480	380	160	19	167	520
S7	210	340	290	0	243	420
S8	220	30	0	4	124	530
S9	248	630	300	31	509	100
S10	690	20	120	0	358	400
S11	246	290	0	0	729	640
S12	190	200	70	0	396	620
S13	440	40	720	128	1,406	7,800
S14	790	300	30	1	130	20,000
S15	1,080	450	80	0	441	112
S16	2,180	190	0	3	562	260
S17	250	60	120	0	602	90
S18	490	260	190	6	146	--
S19	900	860	120	6	803	52
S20	1,260	450	160	3	164	80
S21	4,470	720	160	2	1050	1030
S22	870	--	0	0	89	--
SLTO	890	170	30	1	145	290

Table 8.--Log partial pressure of carbon dioxide (pCO_2) and saturation indices for selected minerals in ground-water samples, Monroe County, Michigan

[S, sulfate water; M, mixed water, B, bicarbonate water, SI, saturation index, --, no data]

Well	Water	Log	Saturation indices												
Number	Type	pCO_2	Barite	Calcite	Celestite	Chalcedony	Dolomite	FeS	Fluorite	Gypsum	Illite	Mackinawite	Quartz	Siderite	Strontianite
G1	S	-1.74	-0.10	0.21	-0.09	-0.17	0.14	--	0.31	-0.36	2.14	--	0.30	-0.59	-0.70
G2	S	-1.81	.05	.19	-.25	.09	.06	--	.46	-.15	3.18	--	.56	-.52	-.86
G3	S	-2.00	-.02	.17	-.08	.12	-.07	-.11	-.01	-.22	2.62	.63	.59	-2.07	-.87
G4	M	-2.08	-.09	.14	-.08	.15	-.05	-.32	-.56	-.26	2.64	.41	.62	-2.95	-.84
G5	S	-2.15	.03	-.05	.02	.09	-.48	-.82	-.44	-.30	--	-.08	.56	-4.03	-.90
G6	S	-2.08	.47	-.04	-.04	.19	-.25	-1.22	-.73	-.90	3.24	-.50	.67	-4.18	-.35
G7	B	-2.62	-1.68	.10	-4.07	-.05	-.12	--	-.98	-4.54	2.25	--	.52	-.29	-.60
G8	B	-1.95	-.73	.00	-3.07	-.09	-.25	-.36	-.60	-3.28	2.18	.38	.39	-1.52	-.96
G9	S	-2.10	1.01	-.38	-.03	-.13	-.91	-1.46	-.84	-1.07	--	-.73	.34	-4.82	-.51
G10	B	-2.24	--	.10	--	.11	.07	--	-1.16	--	2.12	--	.59	.29	-.70
G11	S	-1.49	.24	.34	.09	.37	.55	-.88	-.93	-.51	--	-.15	.85	-3.26	-.24
G12	B	-2.34	-.09	.23	-2.30	.11	.18	.07	-.84	-3.16	2.65	.81	.59	-1.32	-.07
G13	B	-2.27	.47	.19	-.74	.10	-.02	.49	-.50	-1.92	--	1.23	.48	-1.48	.20
G14	B	-1.78	.05	-.04	-2.33	-.15	-.58	--	-2.77	-1.76	--	--	.32	-.26	-1.79
G15	S	-1.89	.18	.12	-.01	-.06	-.17	-.81	-1.18	-.58	3.06	-.08	.41	-1.76	-.49
G16	S	-1.90	1.25	.24	.02	.06	.24	--	-.61	-.19	3.06	--	.53	-.89	-.72
G17	S	-2.12	-.01	.22	.23	.06	.10	--	-.50	-.24	--	--	.53	-.98	-.48
G18	B	-1.88	.77	.24	-.43	.02	.09	-.57	-.80	-1.88	--	.16	.49	-1.94	.52
G19	M	-1.55	.45	.19	-.41	.05	-1.31	--	-1.21	-1.00	2.96	--	.53	.18	-.40
G20	M	-2.07	1.02	.18	-.78	.19	.19	--	-1.10	-1.39	--	--	.66	.13	-.38
G21	B	-2.63	.47	.21	-1.09	.11	.22	-.29	-.83	-2.45	1.97	.45	.59	-2.35	.40
G22	B	-2.20	.71	-.14	-.24	.09	-.47	-.14	-.80	-1.90	--	.59	.56	-2.39	.35
G23	B	-2.35	.58	.04	-.60	.12	-.08	-.29	-1.01	-2.29	1.94	.44	.59	-1.97	.56
G26	B	-2.42	.86	.21	-.37	.06	.26	1.16	-.97	-1.91	--	1.89	.53	-.32	.59
G27	B	-2.27	.63	.11	-.12	.07	-.08	--	-.66	-1.72	2.82	--	.55	--	.55
G28	M	-1.71	.89	-.07	-.56	-.26	-.57	--	-1.30	-1.44	1.98		.21	-2.06	-.36
G29	B	-2.31	.47	.11	-1.12	-.06	-.13	--	-.96	-1.98	1.98	--	.41	-.04	-.21
G30	M	-3.00	.66	.18	-2.63	.07	-.42	--	-2.90	-1.83	2.22	--	.55	-.51	-1.79
G31	M	-1.89	.50	.16	-.80	-.02	-.15	--	-1.13	-1.23	2.71	--	.45	-.59	-.58
G32	S	-1.86	.74	.10	-.06	.03	-.20	--	-.06	-.25	--	--	.50	-1.74	-.88
G33	S	-2.44	.43	.12	-.06	-.02	.01	-.14	.22	-.53	--	.59	.45	-2.09	-.58
D4	S	-1.95	-.14	.24	-.05	.06	.06	--	-.38	-.20	3.63	--	.53	--	-.78
D5	M	-1.50	.50	.14	-.58	.02	-.39	--	-.83	-.81	2.62	--	.49	.34	-.80
D6	M	-1.79	.00	.14	-.03	.05	.01	--	-.58	-.80	3.36	--	.53	-.69	-.26
D7	S	-2.14	.31	.13	-.08	-.02	-.08	--	-.56	-1.43	1.75	--	.45	-.41	.31
D8	M	-2.08	-.06	.25	-.09	.05	.33	--	-.77	-.69	3.77	--	.53	-.20	-.32
D9	S	-2.02	.05	.13	-.11	.24	.03	-.84	.42	-.61	3.56	-.11	.71	-3.62	-.31
D11	M	-2.82	.12	.01	-.05	.25	.16	--	-.96	-1.40	2.02	--	.73	-1.94	.19
D12	M	-1.80	.99	.05	-1.79	-.02	-.30	--	-1.80	-1.41	--	--	.45	-1.21	-1.50
D13	S	-1.94	-.08	.19	.14	.02	-.19	--	-.56	-.30	--	--	.49	-.78	-.54

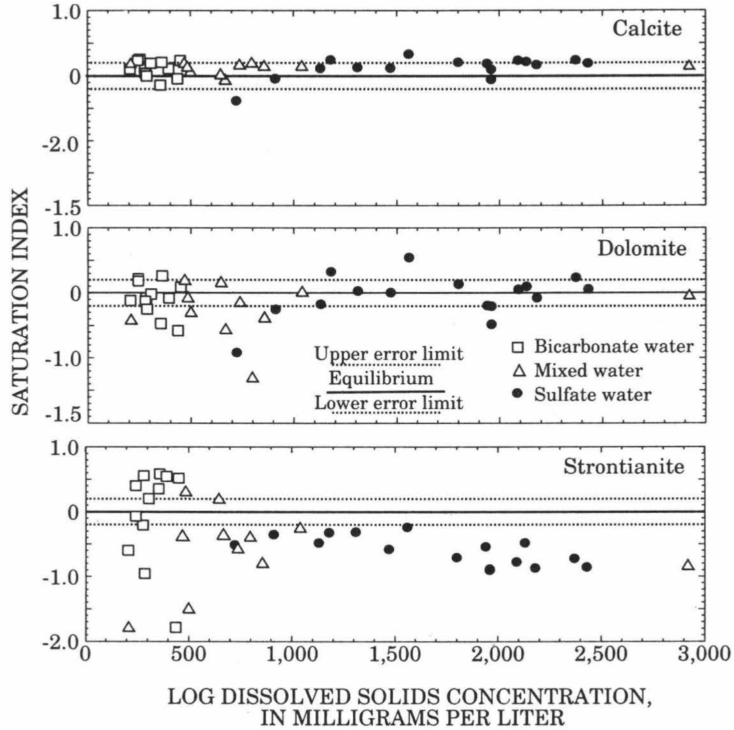


Figure 28. Saturation index as a function of dissolved-solids concentration for calcite, dolomite, and strontianite in the Silurian-Devonian aquifer, Monroe County, Michigan.

Devonian aquifer. Several bicarbonate- and mixed-water samples, however, were distinctly undersaturated with respect to dolomite. Undersaturation with respect to dolomite is a key component of the dedolomitization process discussed in subsequent sections. Most of the dilute bicarbonate waters were saturated or supersaturated with respect to strontianite, although a few bicarbonate waters were highly undersaturated. With increasing dissolved-solids concentrations, a clear trend toward strontianite undersaturation is evident. The wide range of values for the SI of strontianite suggests that this mineral is not controlling strontium concentrations in the bicarbonate waters. Strontianite was not observed in drilling chips from USGS wells.

A clear trend toward saturation of gypsum with increasing dissolved-solids concentration is evident (fig. 29); however, equilibrium with gypsum is never quite reached, because even the most concentrated sulfate and mixed waters are slightly undersaturated with respect to gypsum (table 8). Thus, continued dissolution of gypsum can be expected, and waters having even higher dissolved-solids concentrations may be present in the aquifer. In contrast with gypsum, waters with dissolved-solids concentrations less than 1,000 mg/L are generally undersaturated with respect to celestite (fig. 29). Strontium concentrations appear to be regulated by equilibrium with celestite in sulfate and mixed waters with dissolved-solids concentrations exceeding 1,000 mg/L. Celestite is a common secondary mineral in vugs and fractures in rock of the Silurian-Devonian aquifer. Comparing figure 28 to figure 29, waters become and remain undersaturated with respect to strontianite as dissolved-solids concentration increases, whereas waters remain at or near equilibrium with celestite as dissolved-solids concentration increases. These trends indicate that celestite, not strontitianite, controls the amount of strontium in ground water. Barite is highly insoluble, and most ground-water samples collected during this study are saturated to supersaturated with respect to barite (fig. 29). Precipitation of small quantities of barite in vugs and fractures is possible; barite was not observed, however, in drilling chips from USGS wells. Because

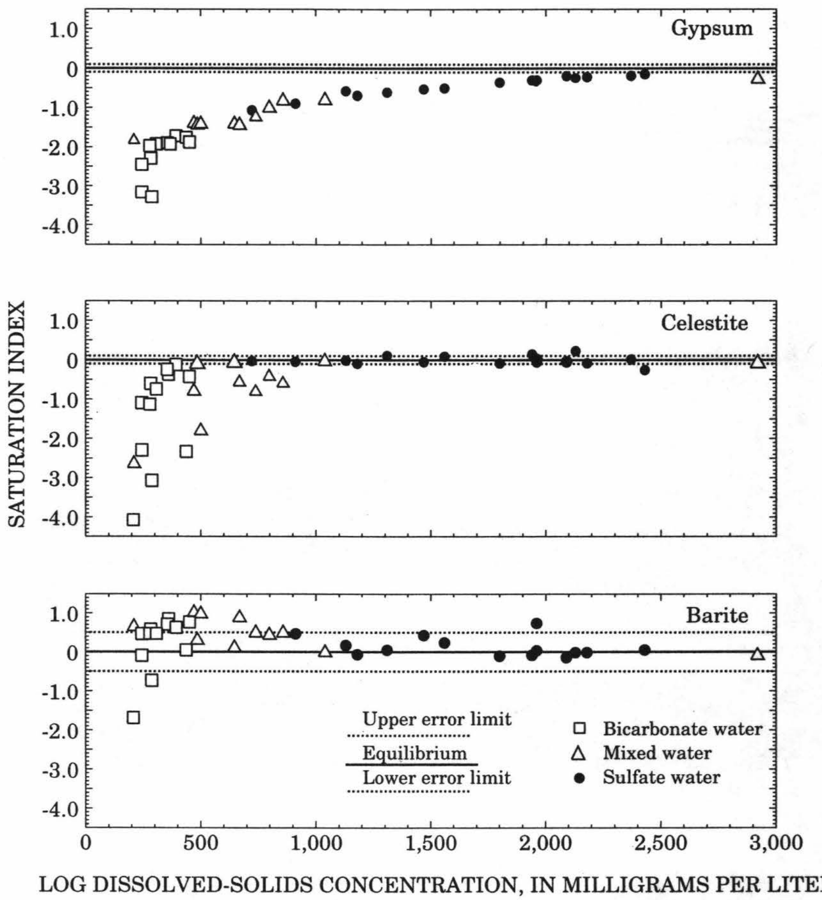


Figure 29. Saturation index as a function of dissolved-solids concentration for gypsum, celestite, and barite in the Silurian-Devonian aquifer, Monroe County, Michigan.

dissolved-barium concentrations are inversely related to dissolved-sulfate concentrations, dissolved-barium concentrations in bicarbonate waters will be high, whereas dissolved-barium concentrations in sulfate waters will be low.

The stability of minerals that can affect dissolved-iron concentrations in ground water of the Silurian-Devonian aquifer is controlled by the pH and oxidation-reduction potential of ground water. Under oxidizing conditions (measurable DO present), ferrous iron (Fe^{2+}) in neutral-pH ground water is rapidly oxidized to ferric iron (Fe^{3+}). Dissolved ferric iron is then precipitated as ferric hydroxide, the compound responsible for reddish-brown stains on clothing and plumbing fixtures. Under reducing conditions (measurable DO not present), iron will be present as ferrous iron, and dissolved-iron concentrations may be controlled by the precipitation of either ferrous carbonate (siderite) or ferrous sulfide. In waters lacking measurable H_2S, precipitation of siderite may regulate dissolved iron concentrations; however, results of the WATEQ4F calculations show considerable scatter in the SI's for siderite (fig. 30). Thus, precipitation of siderite is probably not regulating dissolved-iron concentrations in ground water having no measurable H_2S. In waters that do have measurable concentrations of H_2S, siderite is undersaturated by two to four orders of magnitude (fig. 30; table 8). H_2S-bearing ground water generally has SI's that are bracketed by the SI's of amorphous FeS and mackinawite (fig. 30). Dissolved-iron concentrations will be very low if any

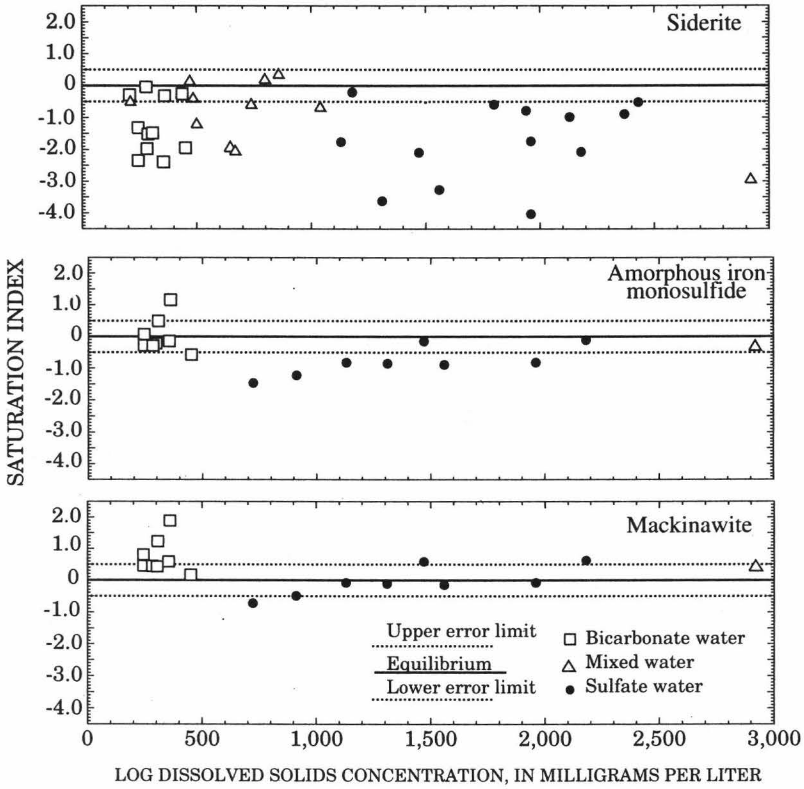


Figure 30. Saturation index as a function of dissolved-solids concentration for siderite, amorphous iron monosulfide, and mackinawite in the Silurian-Devonian aquifer, Monroe County, Michigan.

H_2S is present, because solubilities of the ferrous sulfide phases (amorphous FeS, mackinawite, and pyrite) are extremely low.

Water-Gas-Rock Reactions

In this section, the major water-gas-rock reactions in the Silurian-Devonian aquifer are discussed and related to the formation of the two end-member water types, bicarbonate and sulfate. A brief discussion of the sulfate-reduction reaction involved in the formation of H_2S also is given. The trend from bicarbonate-type water having low dissolved-solids concentrations to sulfate-type waters having high dissolved-solids concentrations is caused by reactions that occur naturally as ground water flows through carbonate rocks of the aquifer.

At the most basic level, the reactions that determine the compositional characteristics of ground water in Monroe County are simple dissolution reactions. For example, the dissolution of dolomitic carbonate rock by CO_2-rich ground water can be written as

$$CaMg(CO_3)_{2(s)} + 2H_2O + 2CO_2 \leftrightarrow Ca^{2+} + Mg^{2+} + 4HCO_3^-. \quad (2)$$

This reaction yields a calcium magnesium bicarbonate water. If dissolved calcium, magnesium, and bicarbonate are added to the ground water solely through this dissolution reaction, then a plot of the molar concentrations [Ca+Mg] against [HCO_3] will yield a linear trend with a slope of 0.5. Most bicarbonate waters with low dissolved-solids concentrations plot near the line predicted by the carbonate-dissolution reaction (fig. 31).

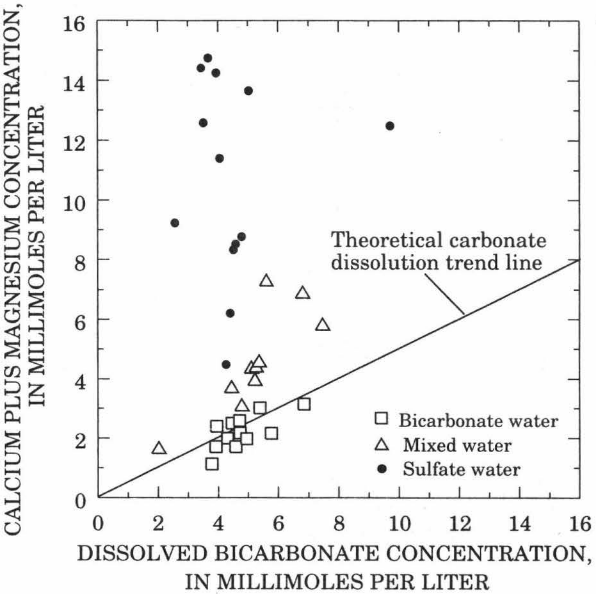


Figure 31. Concentration of calcium plus magnesium as a function of concentration of dissolved bicarbonate in the Silurian-Devonian aquifer, Monroe County, Michigan.

Most mixed waters and sulfate waters do not plot near the line and are highly enriched in calcium and magnesium relative to the concentrations predicted by the dolomite-dissolution reaction (fig. 31). The formation of a calcium sulfate water is better represented by the dissolution of gypsum:

$$CaSO_4 \cdot 2H_2O_{(s)} \leftrightarrow Ca^{2+} + SO_4^{2-} + 2H_2O. \qquad (3)$$

If this is the only reaction responsible for the formation of the calcium sulfate waters, then a plot of the molar concentrations of [Ca] against [SO_4] should be linear, and the slope should be 1. Most ground-water samples, however, do not plot along the line predicted by the gypsum-dissolution model (fig. 32). Instead, most plot along a line whose slope, as estimated by least-squares regression, is significantly less than 1 (slope = 0.70, r = 0.97).

The lack of agreement with trends predicted by the simple dissolution models indicates that other reactions are controlling the major-ion chemistry of the Silurian-Devonian aquifer. Geochemical studies of other carbonate aquifers indicate that a combined dissolution-precipitation reaction called dedolomitization may be important (Back and others, 1983; Busby and others, 1991). Dedolomitization occurs when gypsum or anhydrite dissolve after equilibrium with calcite and dolomite has been reached. Dissolution of gypsum or anhydrite releases calcium and sulfate; the calcium then reacts with the dolomite and causes precipitation of calcite. The dedolomitization reaction can be written as

$$CaMg(CO_3)_{2(s)} + CaSO_4\ 2H_2O_{(s)} + H_2CO_3 \leftrightarrow$$
$$CaCO_{3(s)} + Ca^{2+} + Mg^{2+} + SO_4^{2-} + 2HCO_3^{-} + 2H_2O. \qquad (4)$$

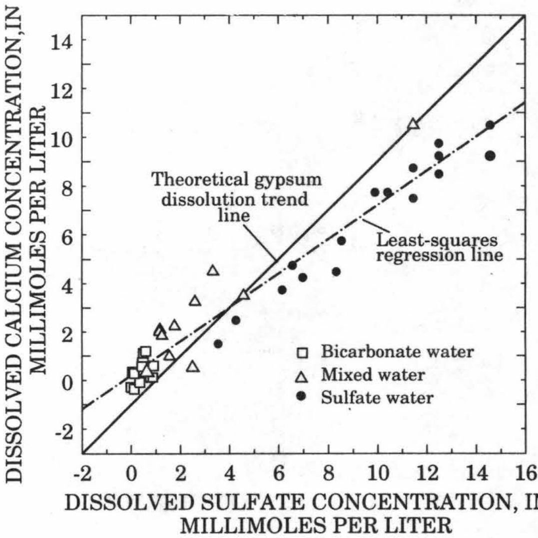


Figure 32. Concentration of dissolved calcium as a function of concentration of dissolved sulfate in the Silurian-Devonian aquifer, Monroe County, Michigan.

As dedolomitization proceeds, Ca:Mg ratios in the solution decrease, and the sulfate concentration of the ground water increases. On a plot of the molar sums of [Ca+Mg] against [SO4 + 0.5HCO3] the dedolomitization reaction will yield a line with a slope of 1. The data show good agreement with the dedolomitization reaction (fig. 33). Least-squares regression analysis shows that the data follow a linear trend whose slope is 1.08 and whose correlation coefficient (r-value) is 0.98.

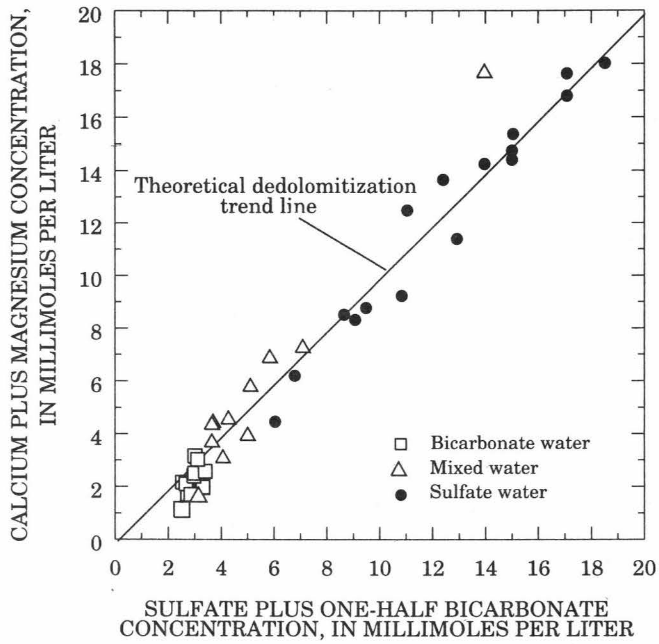


Figure 33. Concentration of calcium plus magnesium as a function of concentration of sulfate plus one-half bicarbonate in the Silurian-Devonian aquifer, Monroe County, Michigan.

An alternative to the dedolomitization reaction involves dissolution of dolomitic carbonates by sulfuric acid (H_2SO_4) produced by the oxidation of pyrite (FeS_2):

$$FeS_2 + (15/4)O_2 + (7/2)\,H_2O \leftrightarrow Fe(OH)_{3(s)} + 2H_2SO_4 \quad (5)$$

(Nordstrom and others, 1979). The sulfuric acid then reacts with dolomite yielding

$$CaMg(CO_3)_{2(s)} + H_2SO_4 \leftrightarrow Ca^{2+} + Mg^{2+} + SO_4^{2-} + 2HCO_3^{-}. (6)$$

These reactions yield products whose stoichiometry is identical to that of the dedolomitization reaction. The reactions will occur in shallow, oxygenated zones of the aquifer where sufficient dissolved oxygen is available. Pyrite (FeS_2) was noted in drill chips from well G4 completed in the Sylvania Sandstone; pyrite is reportedly present as a minor constituent (< 0.5 weight percent) in most rocks of the Silurian-Devonian carbonate sequence (Stout, 1941). Alternatively, experimental work by Moses and others (1987) has shown that small amounts of pyrite can be oxidized by ferric iron under the anoxic, near-neutral-pH conditions that characterize deeper parts of the Silurian-Devonian aquifer.

The presence of H_2S in the Silurian-Devonian aquifer is a common impediment to use of ground water in Monroe County. The geochemical process responsible for the presence of H_2S in the Silurian-Devonian aquifer is sulfate reduction. Sulfate reduction involves the conversion of dissolved sulfate to H_2S. The reaction is bacterially mediated, and it requires the presence of oxidizable organic carbon in the aquifer. Organic carbon can take the form of solid carbonaceous material such as lignite, or can be present as liquid petroleum. Liquid petroleum is more easily used by the sulfate-reducing bacteria; hence, H_2S is a common constituent of the natural gas produced by wells tapping hydrocarbon-bearing rocks.

The sulfate-reduction reaction can be written as

$$SO_4^{2-} + 2C_{organic} + 2H_2O \leftrightarrow H_2S + 2HCO_3^{-}. \quad (7)$$

This reaction produces dissolved H_2S and dissolved bisulfide ion, HS^-. At pH greater than 7, the bisulfide ion is the dominant form of sulfide in natural waters (Hem, 1989). Interaction of bisulfide ions with metal pipes is responsible for the corrosion associated with sulfide-rich waters. Degassing of molecular H_2S at the wellbore or in pressure tanks gives rise to the noxious rotten-egg odor given off by such waters. The stoichiometry of equation 7 indicates that if sulfate reduction is the dominant process responsible for production of H_2S in the aquifer, then the molar ratio of total hydrogen sulfide to bicarbonate will increase. A maximum value of 0.5 will be observed if all bicarbonate in the ground water is derived from sulfate reduction. The H_2S: HCO_3 molar ratios of H_2S-bearing ground water in the Silurian-Devonian aquifer increase with increasing H_2S concentration (fig. 34). This relation is consistent with the stoichiometry of equation 7 and indicates that sulfate reduction is the process responsible for the formation of H_2S in the Silurian-Devonian aquifer.

As noted previously, the presence of H_2S seems to be restricted to the Dundee Formation and Detroit River Dolomite (fig. 25). Petroliferous odors were noted from drill chips from USGS wells completed in these formations. Petroleum compounds and reactive carbonaceous material may contribute to the abundance of H_2S in these two units. However, hydrocarbons and petroliferous residues were also noted in drill chips from USGS wells in Silurian rocks. Detailed data on the type and abundance of organic carbon in each formation are unavailable, and statistically valid correlations between formation lithology and H_2S occurrence cannot be made. In general, H_2S concentrations in the Silurian-Devonian aquifer seem to be independent of depth in Monroe County, although most H_2S-bearing ground water is found from 50 to 100 ft below land surface (table 3, at back of report, p. 83). Data reported by the Ohio Department of Natural Resources (1970) indicate that H_2S concentrations in Silurian-Devonian carbonates of northwestern Ohio increase with depth.

In well G23, an increase in the specific-conductance log at a depth of 71 feet (Appendix 1) corresponds to native sulfur found in drill chips from that depth (Appendix 2). This finding indicates that native sulfur may mark a change in water chemistry. The native sulfur may be precipitating by the oxidation of H_2S at the interface between water types (Nielson, 1978). The inferred vertical change in water types may be common in most of Monroe County and illustrates the difficulty in identifying and interpreting areal trends in water chemistry.

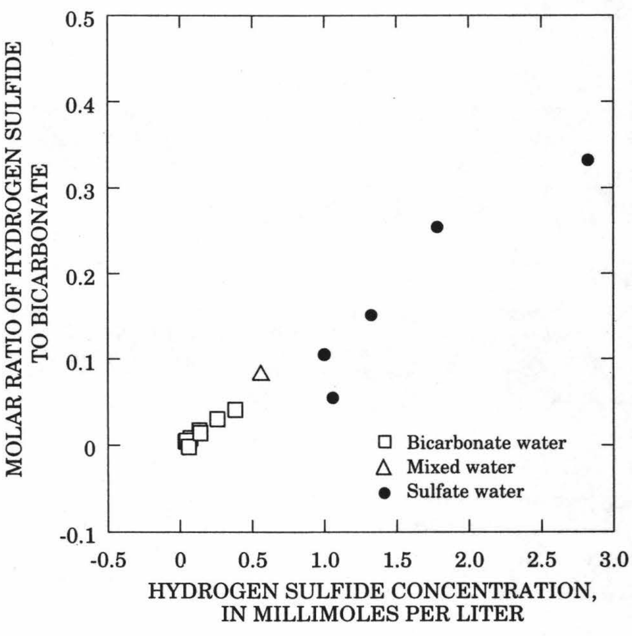


Figure 34. Molar ratio of hydrogen sulfide to bicarbonate as a function of hydrogen sulfide concentration for hydrogen sulfide-bearing water in the Silurian-Devonian aquifer, Monroe County, Michigan.

To summarize, the end-member water types are controlled by lithology and geochemistry. Ground water circulating through carbonate rocks devoid of gypsum and celestite will be hard to very hard, will have dissolved-solids concentrations of only a few hundred milligrams per liter, and will have calcium (magnesium) bicarbonate compositions consistent with the carbonate-dissolution model (eq. 2). As the bicarbonate water enters gypsum- or celestite-bearing rocks, irreversible dissolution of sulfate minerals will cause dedolomitization, and water compositions will evolve through the mixed bicarbonate sulfate composition to waters having high dissolved-solids concentrations and calcium (magnesium) sulfate compositions (eq. 4) Water that recharges directly into gypsum-bearing rocks, such as the Bass Islands Dolomite and Salina Group, will also have sulfate-rich compositions characterized by extreme hardness and high dissolved-solids concentrations (eq. 3). Under anaerobic conditions, sulfate reduction (eq. 7) will occur if oxidizable organic matter is present. The distribution of H_2S observed in Monroe County indicates that reactive organic material that is easily used by sulfate-reducing bacteria is most abundant in rocks of the Dundee Formation and Detroit River Dolomite.

Isotope Geochemistry

Stable isotopes of oxygen ($^{18}O/^{16}O$) and hydrogen (D/H) in water were analyzed to provide an independent means of distinguishing water types and sources in the aquifer. Stable isotopes of dissolved sulfate ($^{34}S/^{32}S$) and dissolved inorganic carbon ($^{13}C/^{12}C$) were used to determine sources of these elements and identify geochemical reactions occurring in the aquifer. Tritium (^{3}H) concentrations and carbon-14 (^{14}C) activities were used to estimate the relative ages of ground water in selected parts of the aquifer, providing further information on the hydraulic properties of the Silurian-Devonian aquifer in Monroe County.

Deuterium and Oxygen-18

Water samples were collected for determination of $^{18}O/^{16}O$ and D/H ratios from 24 USGS wells and three domestic wells. The isotope data (table 9) are reported in delta (δ) notation relative to the international water standard VSMOW (Vienna Standard Mean Ocean Water) in units of parts per thousand (per mil). The analytical precision of the δD and $\delta^{18}O$ values reported in table 9 are $\pm$ 1.5 and $\pm$ 0.1 per mil.

Stable isotope analyses were done to determine if ground water from different parts of the Silurian-Devonian aquifer could be distinguished by their oxygen and hydrogen isotope ratios (fig. 35). The data plot on or just above the global meteoric water line defined by Craig (1961) and are derived from infiltration of precipitation. Except for the sample from G33, δD values for these waters range from -49 to -69 per mil, and $\delta^{18}O$ values range from -7.6 to -10.2 per mil. These values are similar to isotopic compositions of surface-water samples collected at five USGS benchmark stations in the Lower Peninsula of Michigan (Tyler Coplen, U.S. Geological Survey, written commun., 1991).

The isotopic composition of water from well G33 is highly depleted relative to all other waters; water produced from this well is on a flow path that extends eastward from southwestern Monroe County toward Lake Erie, contains no measurable tritium, and has an estimated ^{14}C age of at least 15,000 years (as discussed later in this report). Thus, the isotopic composition of this water may reflect recharge of the Silurian-Devonian aquifer by isotopically depleted glacial meltwaters in the late Pleistocene.

Tritium

Tritium is a radioactive isotope of hydrogen that is widely used as an indicator of post-1953 recharge. Sharp increases in the tritium concentration of rain followed the period of atomic bomb testing in the 1950's and early 1960's. Tritium concentrations in rainwater peaked at several thousand tritium units during 1963-64 (Michel, 1989). The time-dependent nature of the tritium input function, combined with the short half-life of tritium (12.43 years), makes tritium an excellent hydrologic tracer for use in ground-water systems in which ground water is less than 40 years old. However, unless water associated with the 1963-64 bomb peak is sampled, tritium can be used only to obtain qualitative estimates of the age of the water. If detectable quantities of tritium ($\geq$ 1.5 TU) are measured in the water, some fraction of that water must have entered the aquifer after 1953.

To derive constraints on the recharge age of the ground water, one must know or estimate the tritium concentration of precipitation falling on southeastern Michigan. Tritium data come from several locations across North America. The most complete data set is for Ottawa, Canada, and

Table 9.--Isotope data for ground water, Monroe County, Michigan, September 1991

[B, bicarbonate water; S, sulfate water; M, mixed water; NC, not classified; TU, tritium units; pmc, percent modern carbon; --, no data collected]

Well number	Water type	δD (per mil)	$\delta^{18}O$ (per mil)	^{3}H[1] (TU)	$\delta^{13}C$ (per mil)	^{14}C (pmc)	$\delta^{34}S$ (per mil)
G1	S	-55.0	-8.35	4.3±0.6	--	--	--
G2	S	-52.5	-8.00	2.5±.8	--	--	--
G3	S	-60.5	-9.20	7.4±1.2	--	--	--
G6	S	-56.5	-8.90	2.6±.6	-17.0	15.2	21.9
G7	B	-60.0	-8.50	<.8	--	--	--
G8	B	-54.5	-8.40	<.8	--	--	--
G9	S	-68.0	-10.15	1.5±.8	-12.5	4.7	29.0
G10	B	-60.0	-8.95	<.8	--	--	--
G11	S	-56.0	-8.65	1.1±.8	--	--	--
G13	B	-59.5	-9.00	6.8±1.0	--	--	--
G14	B	-57.5	-9.10	20.4±1.8	-13.8	--	--
G15	S	-52.0	-7.95	<.8	--	--	--
G17	S	-51.5	-8.00	.9±.8	--	--	--
G18	B	-51.5	-7.90	.9±.8	--	--	--
G19	M	-63.0	-9.50	34.0±2.6	--	--	--
G22	B	-53.5	-8.15	<.8	--	--	--
G23	B	-53.0	-8.10	<.8	-14.1	35.9	44.1
G25	NC	-53.0	-8.10	1.9±.6	--	--	--
G26	B	-49.0	-7.60	3.7±.6	--	--	--
G27	B	--	--	<.8	--	--	--
G28	M	-56.5	-8.80	23.1±1.6	--	--	--
G29	B	-57.5	-9.00	27.8±2.4	--	--	--
G30	M	-57.5	-8.95	26.2±1.0	-11.7	38.3	5.5
G31	M	-55.0	-8.60	18.8±1.4	--	--	--
G32	S	--	--	1.0±.8	--	--	--
G33	S	-96.0	-13.70	<.8	-7.6	5.8	--
D1	NC	-52.0	-8.00	12.0±1.0	--	--	--
D2	NC	-51.0	-7.80	7.1±.8	--	--	--
D3	NC	-55.0	-8.55	21.9±1.8	--	--	--

1 For concentrations above the reporting limit (0.8 TU), the number given is the tritium concentration plus the 2-sigma uncertainty reported by the lab.

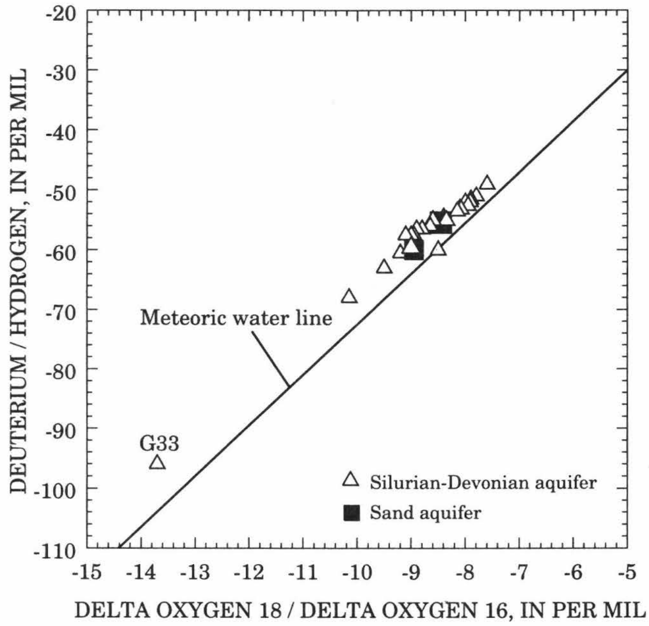


Figure 35. Relation between stable isotope ratios of deuterim/hydrogen and oxygen-18/oxygen-16 in ground water, Monroe County, Michigan, September, 1991.

contains data from 1953 to the mid-1980's (International Atomic Energy Agency, 1981). The USGS began measuring tritium concentrations at several locations in the United States in 1960. Data from these stations were combined with the Ottawa data set to estimate the annual precipitation-weighted tritium deposition across the continental United States for 1953-83 (Michel, 1989). During 1984-92, available data indicate that rain falling in southeastern Michigan had tritium concentrations ranging from 7 to 15 TU (R. L. Michel, U.S. Geological Survey, written commun. 1993). The tritium curve (fig. 36) is corrected for radioactive decay such that the tritium concentrations reflect 1992, the year samples were collected for this study. In addition, the curve in figure 36 does not account for seasonal variations in tritium concentrations—concentrations in rain are usually lowest in winter and early spring. Because most recharge in the northern United States occurs during the winter and early spring, the curve in figure 36 may slightly overestimate the tritium concentration of rain recharging the Silurian-Devonian aquifer in recent years.

Tritium data typically are used to estimate a range of recharge dates, not a precise date. For example, the maximum tritium concentration in water from the Silurian-Devonian aquifer was at well G19 (34.0±2.5 TU). This water did not recharge the aquifer after 1974, because recharge after 1974 had tritium concentrations less than 30 TU (fig. 36), and the water did not recharge the aquifer before 1954. Thus, the tritium curve indicates that water in well G19 recharged the aquifer between 1954 and 1974. Similarly, ground water that has tritium concentrations in the range of 20 to 34 TU recharged the aquifer between 1954 and the early 1980's. Ground water that has a tritium concentration less than or equal to 1.5 TU is pre-bomb-water that entered the aquifer before 1953. Water from 13 USGS wells was pre-bomb (table 9). The remaining wells—13 in the Silurian-Devonian aquifer and 3 in the sand aquifer—yielded water with a discernible post-bomb tritium concentration indicating that some fraction of the water in the sample entered the Silurian-Devonian aquifer after 1953.

Sulfur Isotopes

Stable isotope ratios for dissolved sulfate were determined for ground-water samples collected from four wells (G6, G9, G23, and G30). The $^{34}S/^{32}S$ ratios are reported in standard delta notation ($\delta^{34}S$) and have an analytical precision of

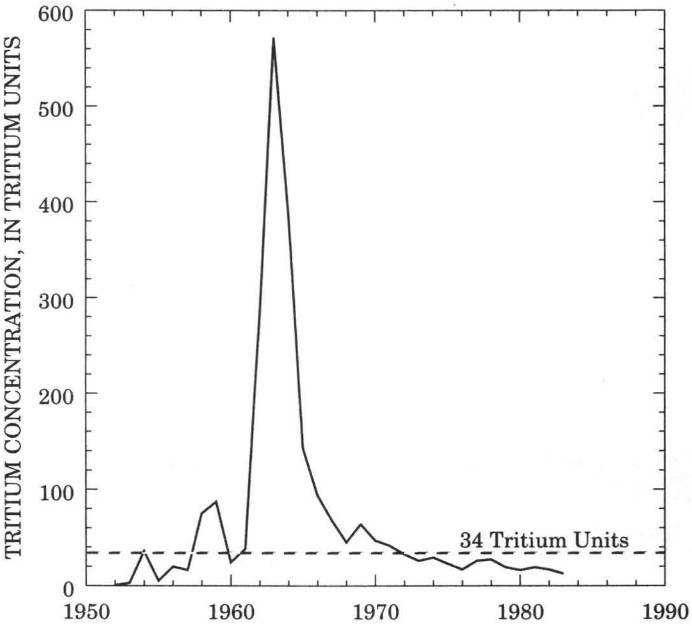


Figure 36. Decay-corrected concentration of tritium in rainwater, southeastern Michigan, 1953-83 (Tritium concentrations are corrected for radioactive decay up to January 1992 and are based on tritium-deposition estimates from Michel, 1989).

+ 0.1 per mil (table 9). These samples were collected to determine the origin of dissolved sulfate in the Silurian-Devonian aquifer.

Variations in the $\delta^{34}S$ value of dissolved sulfate in ground water can be caused by differences in the isotopic composition of the source of the dissolved sulfate (for example, variations in the $\delta^{34}S$ values of sulfur-bearing minerals such as pyrite or gypsum), or they may reflect changes caused by biogeochemical reactions such as sulfate reduction (eq. 7). Sulfate reduction is particularly important because microbial reduction of sulfate to H_2S preferentially incorporates light ^{32}S into the product H_2S. Residual sulfate is then enriched in the heavier sulfur isotope. Because sulfate reduction is common in most shallow marine sediments, the $\delta^{34}S$ value of dissolved sulfate in modern seawater is about +20 per mil (Thode and others, 1961). Through geologic time, the isotopic composition of sulfate in seawater has ranged from about approximately +10 to +30 per mil. Gypsum derived from Silurian-Devonian evaporites has $\delta^{34}S$ values ranging from between +17 to +27 per mil, although a more restricted range, +18 to +20 per mil, is typical of Middle Devonian evaporites (Krouse, 1980). $\delta^{34}S$ values for sulfate in gypsum and anhydrite samples collected from Silurian carbonates in northwestern Ohio range from +24.7 to +28.7 (Botoman and Faure, 1976; L.L. Lesney, U.S. Geological Survey, written commun., 1993).

In contrast, because ^{32}S is preferentially incorporated into H_2S, sulfide minerals formed in sediments where sulfate reduction is occurring will have $\delta^{34}S$ values that are highly depleted relative to dissolving sulfate minerals. $\delta^{34}S$ values of sulfide minerals (pyrite, marcasite, galena, and sphalerite) collected from Silurian-Devonian rocks in northwestern Ohio range from -21.9 to +7.0 per mil (Botoman and Faure, 1976). $\delta^{34}S$ values of sulfidic sulfur extracted from whole rock samples of Devonian and Silurian core samples from northwestern Ohio range from -24.9 to +3.9 per mil (L.L. Lesney, U.S. Geological Survey, written commun., 1993). As more and more sulfate is removed from solution by sulfate reduction, the $\delta^{34}S$ values of the remaining dissolved sulfate become further enriched in ^{34}S. In aquifers where extensive sulfate reduction has occurred, enrichments of 10 to 30 per mil relative to the original source sulfate are not uncommon (Krouse, 1980).

$\delta^{34}S$ values for dissolved sulfate vary systematically with water type and lithology and provide information for distinguishing whether dedolomitization (eq. 4) or oxidation of sulfide minerals (eqs. 5 and 6) is the dominant geochemical process at particular places in the aquifer. The $\delta^{34}S$ value of +21.9 per mil in the calcium sulfate water from well G6 is similar to that reported for Middle Devonian gypsum, indicating that the origin of dissolved sulfate is dissolution of gypsum, an origin consistent with the dedolomitization model. The $\delta^{34}S$ value in water from G6 is slightly enriched (by a few per mil) relative to the $\delta^{34}S$ values expected for sulfate derived by dissolution of Middle Devonian gypsum. This enrichment could be caused by sulfate reduction, as indicated by an H_2S concentration of 45 mg/L in the same sample. Although gypsum was not noted in drill chips obtained during drilling of this well, lenses and thin layers of gypsum have been found in Detroit River Dolomite rocks underlying Monroe County (Mozola, 1970).

The origin of dissolved sulfate in the calcium sulfate water of G9 is less clear. The $\delta^{34}S$ value of +29.1 per mil is enriched relative to that reported for sulfate derived from evaporitic gypsum of Middle Devonian age, yet the well is completed in the limestone-dominated Dundee Formation. Enrichment of residual marine sulfate by way of sulfate reduction could explain the enrichment of $\delta^{34}S$ relative to marine sulfate. Sulfate reduction is occurring in the Dundee Formation, as evidenced by the 96 mg/L of H_2S in water from G9. However, gypsum was not observed in drill chips from the Dundee Formation or younger formations that are subcrops upgradient from well G9. Secondary celestite and native sulfur were noted in drill chips obtained from wells completed in the Dundee Formation. $\delta^{34}S$ values of these minerals were not determined, but both may contribute some sulfur to the aquifer in this part of Monroe County.

Dissolved sulfate in the relatively dilute bicarbonate water from well G23 has the most isotopically enriched $\delta^{34}S$ value (+44.1 per mil) of the four samples collected during this study. Well G23 is completed in rocks of the Detroit River Dolomite, and the water sample had an H_2S concentration of 2.4 mg/L. Its enriched $\delta^{34}S$ value likely reflects sulfate reduction of marine sulfate derived from gypsum in rocks of the Detroit River Dolomite. In contrast, the isotopically light $\delta^{34}S$ value of dissolved sulfate in the mixed water obtained from well G30 (+5.5 per mil) probably reflects the oxidation of sulfide minerals. Well G30 is in a recharge area, has water with a measurable concentration of DO (3.3 mg/L), and is completed in non-gypsum-bearing limestones of the Bass Islands Dolomite. Oxidation of the sulfide minerals may have occurred in glacial sediments that overlie the Silurian-Devonian aquifer or in the aquifer itself.

In summary, dedolomitization and sulfate reduction occur in the Silurian-Devonian aquifer and are the main reactions affecting the isotopic composition of dissolved sulfate in the four ground-water samples analyzed for $\delta^{34}S$. In particular, sulfate reduction causes $\delta^{34}S$ enrichment of 2 to 24 per mil in dissolved sulfate derived from the dissolution of gypsum in the Silurian-Devonian aquifer. At well G30, however, oxidation of sulfide minerals, and perhaps native sulfur, is also occurring and may be the main source of dissolved sulfate in dilute, oxygenated bicarbonate waters that are found in parts of the Silurian-Devonian aquifer where gypsum is absent.

Carbon Isotopes

Ground-water samples collected from five wells (G6, G9, G23, G30, and G33) were used to determine stable isotope ratios for dissolved inorganic carbon ($^{13}C/^{12}C$) and to determine carbon-14 activities (^{14}C) (table 9). The $^{13}C/^{12}C$ ratios are reported in standard delta notation ($\delta^{13}C$) and have an analytical precision of $\pm$ 0.1 per mil; the ^{14}C values are reported in percent modern carbon (pmc). The $\delta^{13}C$ data provide information regarding sources of dissolved inorganic carbon in ground water and are also used to correct the ^{14}C activities for dilutional effects caused by dissolution of carbonates in the Silurian-Devonian aquifer.

Radioactive ^{14}C, produced in the upper atmosphere by cosmic-ray reactions, is oxidized to carbon dioxide and incorporated into plant and animal tissue. Measurement of the ^{14}C activity of a carbon-bearing sample allows use of the radioactive-decay equation calculate the age since death of the plant or animal:

$$t = - 8{,}270 \ln (R), \qquad (8)$$

where t is time, in years, and R is the measured ^{14}C activity of the sample, expressed as the ratio of ^{14}C activity in the sample to the ^{14}C activity of modern carbon (Mook, 1980). Analytical determinations of R are multiplied by 100. The range that can be reliably determined is approximately 500 to 45,000 years before present.

Radiocarbon dating of dissolved inorganic carbon samples in ground water is complicated by the fact that inorganic carbon can be derived from several sources, including dissolution of carbonate minerals and oxidation of old organic matter. Both of these sources have ^{14}C activities of zero because they were formed hundreds of thousands of years ago. These processes add "dead" carbon to the ground water, diluting the amount of ^{14}C originally present in the water and, if uncorrected, yield apparent ages that are hundreds or thousands of years older than the actual age of the sample. To correct for these effects, an adjustment factor (Q) is added to the decay equation (Freeze and Cherry, 1979; Mook, 1980)

$$t = -8{,}270 \ln (R) + 8{,}270 \ln (Q). \qquad (9)$$

The value of Q is 1.0 for bicarbonate waters in which all of the bicarbonate is produced by dissolution of carbonate minerals in the unsaturated soil zone by way of reaction C, because elevated concentrations of soil CO_2 are sufficient to maintain isotopic equilibrium between soil-gas CO_2 and dissolved bicarbonate. The CO_2 is produced by the decay of plant matter of recent origin (tens or hundreds of years old), and its ^{14}C activity is functionally equivalent to that of modern atmospheric ^{14}C. The value of Q will be less than 1.0 if further dissolution occurs in the aquifer under conditions where exchange with soil-gas CO_2 cannot occur. Minimum Q values will not be less than 0.5 for aquifers in which no postrecharge CO_2 is produced (Wigley, 1975). Q values may approach 0.3 for aquifers in which additional CO_2 is being produced under closed-system conditions (for example, by oxidation of old organic matter during sulfate reduction).

Limits on the ^{14}C ages of ground water from wells G6, G9, G23, G30, and G33 were estimated by use of Q values of 1.0, 0.5, and 0.3 (table 10). A Q value of 1.0 results in the maximum estimated age of water. Also shown in table 10 are ^{14}C age estimates based on the isotopic dilution technique of Pearson and White (1967). This method corrects the reported ^{14}C activity by use of $\delta^{13}C$ data according to the following equation:

$$^{14}C\,(adjusted) = {}^{14}C\,(lab) \times \left[\frac{\delta^{13}C_{soil} - \delta^{13}C_{carbonate}}{\delta^{13}C_{water} - \delta^{13}C_{carbonate}}\right], \qquad (10)$$

where ^{14}C (adjusted) is the ^{14}C activity adjusted for dissolution of carbonate rocks with a known $\delta^{13}C$ value, ^{14}C (lab) is the ^{14}C activity reported by the laboratory, $\delta^{13}C_{soil}$ is the isotopic composition of soil-gas CO_2, $\delta^{13}C_{carbonate}$ is the isotopic composition of marine carbonate rocks in the study area, and $\delta^{13}C_{water}$ is the isotopic composition of dissolved inorganic carbon in the water sample. $\delta^{13}C_{soil}$ values in temperate climates typically range from -18 to -25 per mil (Back and others, 1983; Busby and others, 1991). On the basis of results reported by Busby and others (1991), a $\delta^{13}C_{soil}$ value of -20 per mil was used in equation 10. In northwestern Ohio, $\delta^{13}C_{carbonate}$ values in Silurian-Devonian carbonate rocks ranged from between -3 to +1.5 per mil (L.L. Lesney, U.S. Geological Survey, written commun., 1993). Therefore, an intermediate value of 0 per mil was used for Monroe County.

The accuracy of estimated ^{14}C ages in Monroe County is dependent on the accuracy of the Q values. The Q values used to correct the raw-age estimates (Q=1.0) for geochemical reactions in the Silurian-Devonian aquifer were selected arbitrarily. A Q value of 0.5 is expected for closed-system dissolution of carbonate minerals where no additional sources of carbon are present and no precipitation of secondary carbonate minerals occurs. Thus, this Q value may overestimate the age of ground water subject to dedolomitization. Q values near 0.3 represent situations where dead carbon was added to the system through the oxidation of old organic carbon (for example, by sulfate reduction). Ground water from wells G6 and G9 contains high H_2S concentrations and is likely to have undergone significant sulfate reduction. To produce accurate estimates of the Q value of each ground-water sample, one must use geochemical models that account for precipitation-dissolution reactions, sulfate reduction, and isotopic exchange along the flow path. Computer programs to do this type of geochemical modeling, such as NETPATH (Plummer and others, 1991), are available. However, these programs require additional isotopic and geochemical data.

Table 10. Estimated carbon-14 age for ground water, Monroe County, Michigan, September 1991

[B, bicarbonate water; S, sulfate water; M, mixed water. Well locations are shown on plate 1]

Well number	Water type	Age, in years, from corrected radioactive decay equation			Age, in years, and Q value from Pearson-White equation		Dissolved-sulfate concentration, in milligrams per liter
		Q= 1.0	Q= 0.5	Q= 0.3	Age	Q	
G6	S	15,600	9.800	5,600	14,200	0.85	410
G9	S	25,300	19,600	15,300	21,400	.63	340
G23	B	8,500	2,700	-1,500	5,500	.71	34
G30	M	8,000	2,200	-2,000	3,500	.59	61
G33	S	23,500	17,800	13,600	15,500	.38	800

Keeping the above cautions in mind, one can conservatively state that water from wells G9 and G33 is very old and is likely greater than 15,000 years old. The water from G33 is probably older than that from G9, because the water from G33 contains no measurable tritium, has undergone a minimal amount of sulfate reduction (2.6 mg/L H_2S), and was collected from a well that has a short open interval (21 ft). Water from well G9 contains the largest concentration of H_2S found in this study (96 mg/L), contains a detectable concentration of tritium (1.5 TU), and was collected from a deep well that has an open interval of 110 ft. Thus, water from well G9 is likely a mixture of a large proportion of very old water and a small proportion of tritiated post-bomb water. Similarly, water from well G6 also is a mixture of young and old water. Although the Pearson-White age approaches 15,000 years, a minor post-bomb component (2.6 TU) is clearly discenable. The isotopically light $\delta^{13}C$ value of this sample water (-17.0) is indicative of water only slightly affected by carbonate dissolutions; however, the high H_2S concentration (45 mg/L) indicates addition of isotopically depleted dead organic carbon via sulfate reduction (eq. 7). Thus, the absolute age of the old component of this water is uncertain and may be only a few thousand years.

Dilute bicarbonate waters from wells G23 and G30 contain little or no H_2S and low sulfate concentrations. Thus, these waters are unlikely to have been significantly affected by sulfate reduction or dedolomitization and therefore are likely to have Q values greater than 0.5. Indeed, for Q values near 0.3, these waters would have negative ages (table 10). Thus, these waters are likely to be no more than a few thousand years old. Water from well G23, which is not tritiated, may be several hundred or a few thousand years old; water from well G30, which contains 26 TU, has a large component of post-1953 recharge. G30 is a deep well (155 ft) and has an open interval of nearly 120 ft. Although water produced by the deep part of the well may be old, the younger, post-1953 component is dominant, as evidenced by its high tritium concentration. The resulting mixture of young and old water cannot be reliably dated by the ^{14}C technique.

Relation Between Ground-Water Quality and Hydrogeology

Our understanding of hydrogeology can be extended and clarified through interpretations of ground-water-quality data. For example, the presence or absence of certain constituents (tritium, dissolved oxygen, nitrates, hydrogen sulfide) can be used to determine where the aquifer is vulnerable to contamination from human activities, to estimate relative rates of recharge, and to infer where the aquifer is confined or unconfined. Along flow paths, water-rock reactions should produce general trends in ground-water quality such that certain water types in the Silurian-Devonian aquifer can be considered characteristic of young and old waters. Finally, age estimates deduced from tritium and ^{14}C dating can be used to estimate various hydrogeologic properties within selected parts of the Silurian-Devonian aquifer.

The presence or absence of tritium provides insight into the susceptibility of the Silurian-Devonian aquifer to contamination from sources at the land surface. For example, detectable concentrations of recently manufactured pesticides would not be expected in nontritiated (pre-1953) waters. In contrast, evidence of chemical infiltration from surface activities might be more likely in parts of the aquifer where ground water is young. Tritiated, young ground water (water with concentrations of tritium >1.5 TU) is present in a southwest-northeast-trending area that underlies most of Whiteford, Ida, Raisinville, Ash, and Berlin Townships (fig. 37). Tritiated ground water is typically found in areas where the Silurian-Devonian aquifer is overlain by unconsolidated deposits less than 50 ft thick. As noted by Breen and Dumouchelle (1991), some degree of correlation between thickness of unconsolidated deposits and tritium concentration is expected; ground water with detectable tritium concentrations in the carbonate aquifer should generally be found in areas covered by thin or permeable unconsolidated deposits. Ground water whose tritium concentration is indicative of a dominant post-bomb recharge component (> 20 TU) is generally found in areas where unconsolidated deposits are less than 30 ft thick (fig. 38); however, scatter in the data preclude correlation of thickness and tritium concentration.

The data in figures 37 and 38 also indicate a general relation between ground-water age, water type, and the location of recharge and discharge areas for the Silurian-Devonian aquifer. The concentration of tritium in sulfate waters is either nondetectable or less than 8.0 TU, an indication that these waters are either very old or are dominated by a pre-1953 component of recharge. Sulfate waters are present on the eastern border of Monroe County along the shore of Lake Erie in discharge areas for ground water flowing from southwestern Monroe County. According to the potentiometric surface given in figures 10 and 14, the southwestern part of Monroe County is a regional ground-water high. This area, which comprises parts of Whiteford, Bedford, Summerfield, and Ida Townships, is generally covered by thin unconsolidated deposits and represents a significant recharge area for the Silurian-Devonian aquifer. Ground water in the recharge area is characterized by bicarbonate or mixed-composition waters that have tritium concentrations greater than 20 TU. The observed evolution from young, tritiated bicarbonate and mixed waters to nontritiated sulfate waters is consistent with the trends in water composition and relative age reported for other carbonate aquifers (Back and others, 1983; Busby and others, 1991).

The presence or absence of DO in ground water can also be used as a qualitative indicator of recharge-discharge areas and as an indicator of whether or not the aquifer is confined or unconfined. If an aquifer is unconfined, it will be in contact with soil gas that is usually saturated with atmospheric oxygen. Thus, ground water near the water table should have measurable concentrations of DO. The DO concentration of ground water, however, also depends on the amount of oxidizable organic matter in the aquifer (Hem, 1989). In confined aquifers, oxidation of organic matter in aquifer materials can quickly reduce DO concentrations to nondetectable levels; however, in confined aquifers that do not contain significant amounts of reactive organic matter, measurable concentrations of DO may be present in waters that are hundreds or even thousands of years old at locations far removed from the original recharge area.

Concentrations of DO greater than 1.0 mg/L in the Silurian-Devonian aquifer tend to correlate with areas of the aquifer that are unconfined (fig. 37). Examination of data for the ground-water samples that have measurable concentrations of DO and tritium (table 2, at back of report, p. 78, and table 9) indicates a moderate correlation between DO and tritium concentrations. Of the 14 samples that had a detectable component of post-1953 recharge (tritium concentrations > 1.5 TU), 9 had DO concentrations greater than 1.0 mg/L. Thus, the presence of DO is a fairly reliable indicator of recent recharge and unconfined conditions in the Silurian-Devonian aquifer. Unconfined parts of the carbonate aquifer that have received recent recharge are potentially vulnerable to point and nonpoint sources of contaminants.

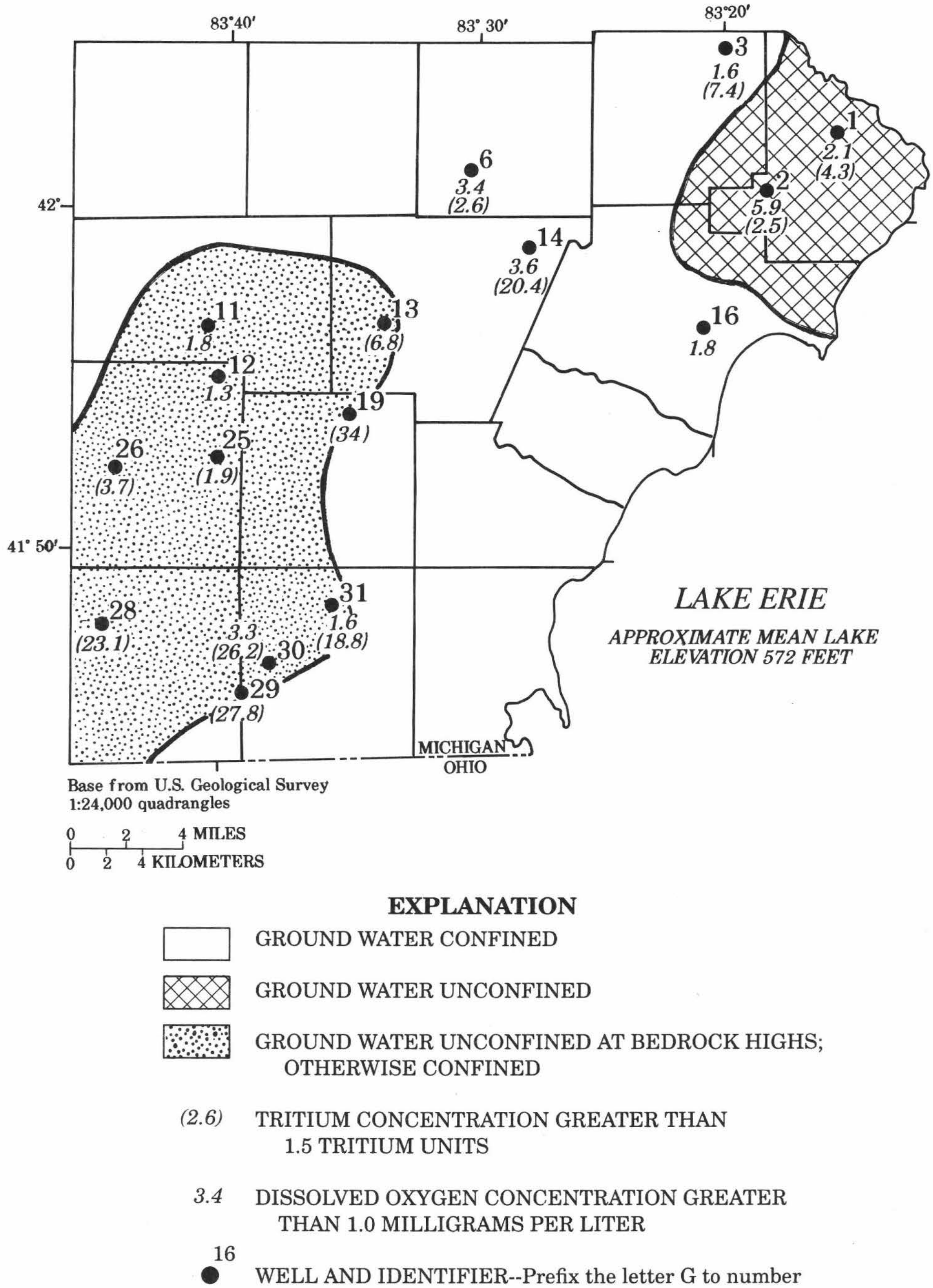


Figure 37. Areal distribution of water with tritium concentrations greater than 1.5 tritium units and dissolved-oxygen concentrations greater than 1.0 milligram per liter in the Silurian-Devonian aquifer, Monroe County, Michigan, 1991-92.

Recharge-age estimates derived from tritium and ^{14}C data can also be used to roughly estimate average ground-water velocities along assumed flow paths in the Silurian-Devonian aquifer. The ground-water velocity can then be substituted into a modified version of the equation describing ground-water flow to estimate the average hydraulic conductivity along the flow path. This technique was first used by Hanshaw and others (1965) to obtain ground-water-velocity estimates for the carbonate-rock aquifer of central Florida and was later used Back and others (1983) and Busby and others (1991) to estimate rates of ground-water flow in parts of the Madison aquifer and its equivalents in Montana, South Dakota, and Wyoming.

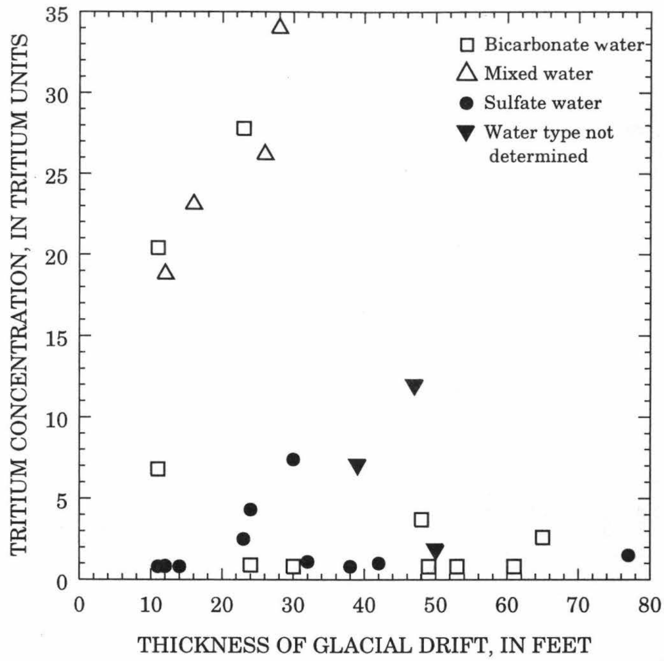


Figure 38. Relation of tritium concentration in the Silurian-Devonian aquifer to thickness of unconsolidated deposits, Monroe County, Michigan, September, 1991.

Ground-water velocity is computed by dividing the flow-path length by the estimated flow time. Data collected for this study allows for calculation of average ground-water velocity along the flow path from southwestern Monroe County to near Lake Erie in southeastern Monroe County. Recharge waters for this flow path were assumed to have entered the aquifer near well G30 and to have discharged near well G33. Tritium and ^{14}C data indicate that ground water at well G30 is of recent origin and that water at well G33 is at least 15,000 years old. The distance between the two wells is approximately 40,000 ft. Dividing the flow-path length (40,000 ft) by the estimated flowtime (15,000 years) yields an average ground-water velocity of 2.7 ft/yr (0.0073 ft/d). The average hydraulic conductivity along this flow path can be computed by use of a modified form of Darcy's law

$$K = \frac{v\theta\Delta L}{\Delta H}, \qquad (11)$$

where K is the hydraulic conductivity, in feet per day; v is the ground-water velocity, 0.0073 ft/d; θ is the effective porosity of the carbonate aquifer, 1 to 10 percent based on values reported for other carbonate aquifers by Back and others (1983) and Busby and others (1991); ΔL is the length of the flow path 40,000 ft; and ΔH is the total head loss from the recharge area to well G33, about 80 ft. Substitution of these values into equation 11 yields average hydraulic conductivities ranging from 0.036 to 0.36 ft/d. This range of hydraulic conductivities is comparable to that reported for other nonkarst carbonate aquifers (Freeze and Cherry, 1979; Back and others, 1983). If a saturated aquifer thickness of 200 feet is assumed, then the hydraulic conductivities calculated above yield transmissivities ranging from 7.2 to 72 ft^2/d. These transmissivities are near the low end of the range of transmissivities estimated from slug tests (table 1). The transmissivities estimated from the ^{14}C date may be low because the flow path is along a direction of lower transmissivity or because the assumed porosities are too high. In addition, the hydraulic gradient has varied significantly over the last 15,000 years because of glaciation and climatic changes.

EFFECTS OF DROUGHT

Droughts in Monroe County affect most aspects of the water resources. Drought lowers ground-water levels and limits the amount of ground water available. Significant reductions in streamflow limit the amount of surface water available for use. The quality of surface water during droughts is similar to the quality of shallow ground water.

Mild droughts are common in Michigan, but severe droughts are infrequent and generally of short duration (Nurnberger, 1980). Precipitation normally is evenly distributed, but periods of dry weather can last as long as several weeks (Blumer and others, 1991). During such extended dry periods, occasional precipitation may ease a meteorological drought, but may not be sufficient to ease a hydrological drought; that is, to return streamflow or ground-water levels to normal.

Droughts have been recorded in Michigan during every decade from the 1930's through the 1980's (Blumer and others, 1991). The two most severe droughts were statewide and occurred during 1930-37 and during 1960-67. These droughts had recurrence intervals of 50 to 70 years and 40 to 65 years, respectively.

The most recent statewide drought occurred in 1988 (Blumer and others, 1991). During 1987 and 1988, temperatures were above normal and precipitation was unevenly distributed. Precipitation was below normal in spring—a critical period for ground-water recharge. Minimum streamflows were recorded at many sites in 1988, and water use was affected throughout the State.

The monthly Palmer Drought Severity Index (PDSI) (Palmer, 1965) for southeastern Michigan from 1920 through 1992 was calculated by the National Climatic Data Center in Asheville, N.C. (written commun., 1993). The PDSI is derived from antecedent precipitation during the period being evaluated and from the duration and magnitude of the moisture deficiency. Negative values of the PDSI are indicative of drought. During the drought of 1988, the lowest monthly index reached the severe range in June (fig. 39). Although the 1988 drought was severe, it was of short duration.

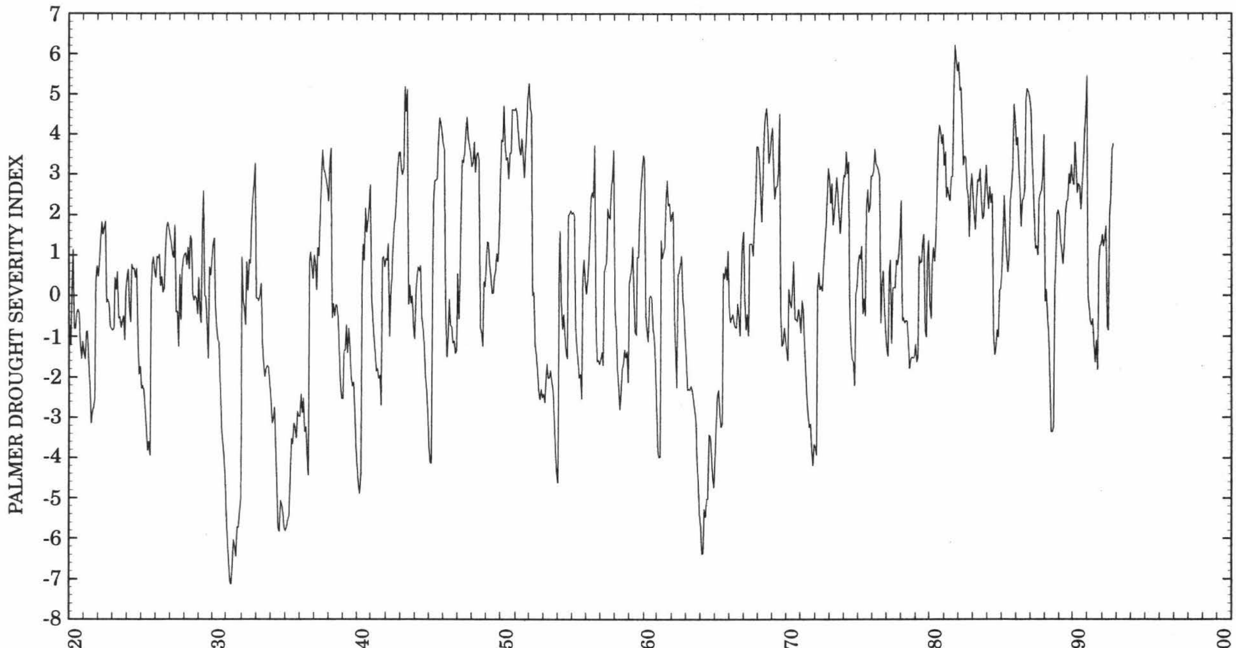


Figure 39. Palmer Drought Severity Index for southeastern Michigan, 1920-92.

Droughts during previous decades were of greater severity and duration. The perceived severity of the 1988 drought in Monroe County may have resulted not so much from the meteorological severity of the drought but more from the hydrological severity of the drought and the long period of time since the previous drought (16 years). Increased water use since previous droughts probably contributed to an increase in the hydrological severity of the 1988 drought.

Ground Water

In summer 1988, ground-water levels dropped sharply in well GLTO (fig. 13), the only observation well in Monroe County in 1988. Similar declines in the Silurian-Devonian aquifer probably occurred throughout the county, because water-levels fluctuations in other USGS observation wells were similar to those in well GLTO during the period of this study (fig. 8). Water-level declines were likely greatest in the southwestern part of the county where water-level fluctuations are greatest (fig. 15).

Despite the probable countywide decline in water levels during the drought of 1988, the only wells in which water levels declined below pump intakes were reported in Summerfield and Bedford Townships (Monroe County Health Department, written commun., 1989). About 12 owners of domestic wells in Summerfield Township claimed that drought and irrigation pumpage had made their wells unusable. In areas where ground water is used for irrigation, the summer decline in ground-water levels is exacerbated, because generally crops are only irrigated during periods when precipitation—and therefore recharge—is below normal. About 200 owners of domestic wells in Bedford Township requested conversion to the Toledo, Ohio, water-distribution system, and township officials believed that some of the requests may have been prompted by the drought.

Historically, reports of reduced or zero discharge from wells in the Silurian-Devonian aquifer are not uncommon. Such reports have been linked not only to droughts but also to interference from nearby uses such as irrigation, quarry dewatering, and increased domestic or municipal pumpage. Sherzer (1900) stated that a continued drought in Monroe County significantly reduced discharge from some flowing wells, meaning that water levels in the aquifer declined significantly. He also reported that the opening of a new quarry in Exeter Township had a "noticeable effect" on water levels in wells northeast of the quarry. As mentioned previously, the strike of the bedrock in Monroe County is southwest to northeast, and, in fractured carbonate aquifers, transmissivity is typically greatest along strike. Sherzer noted that a deep well in the city of Monroe had to be plugged because it "so seriously interfered with the action of the wells of that region." In summer 1977, water levels in some shallow wells near Grape declined below pumps when a nearby quarry was deepened (inactive quarry near well G13, pl. 1) (Monroe County Health Department, written commun., 1977). In summer 1993, owners of some wells near the London quarry (active quarry near well G7, pl. 1) attributed lower water levels to the deepening of the quarry and increased dewatering. Because of the similar effects of drought and large withdrawals, and because the combination of the two exacerbate drawdown in wells, the relations among withdrawals, drawdown, and well construction are discussed in the remainder of this section.

Quarry dewatering at the six active quarries is the largest use of ground water in Monroe County, accounting for about 70 percent of ground-water use. Daily pumpage in 1993 ranged from 0.14 Mgal/d at the Maybee quarry to 4.2 Mgal/d at the Rockwood quarry (Monroe County Health Department, written commun., 1993). Monthly discharges for five quarries during 1990-93 are shown in figure 40. (Monthly data are not available for the Rockwood quarry.) Also shown in figure 40 are water-level hydrographs for the USGS observation wells closest to the quarries. Most of the graphs show that water levels in wells increase when quarry discharge increases and that water levels decrease when quarry discharge decreases. The implication of similar increases and decreases is that quarry discharges and ground-water levels both respond to seasonal recharge. When ground-water levels rise, quarry discharges increase to keep the quarry dewatered. Therefore, figure 40 does not indicate that quarry discharge is affecting ground-water levels in wells G8, G9, G11, and G29. In summer 1992, water levels in wells G6 and G17 declined when discharge from the Maybee and Monroe quarries increased, indicating that quarry discharge may have caused water-level decline. However, the water-level declines are not different from those in other wells for the same period (fig. 8), so the declines may not be related to quarry discharge. Data are insufficient for evaluating the relation between discharge from the London quarry and water levels in well G7.

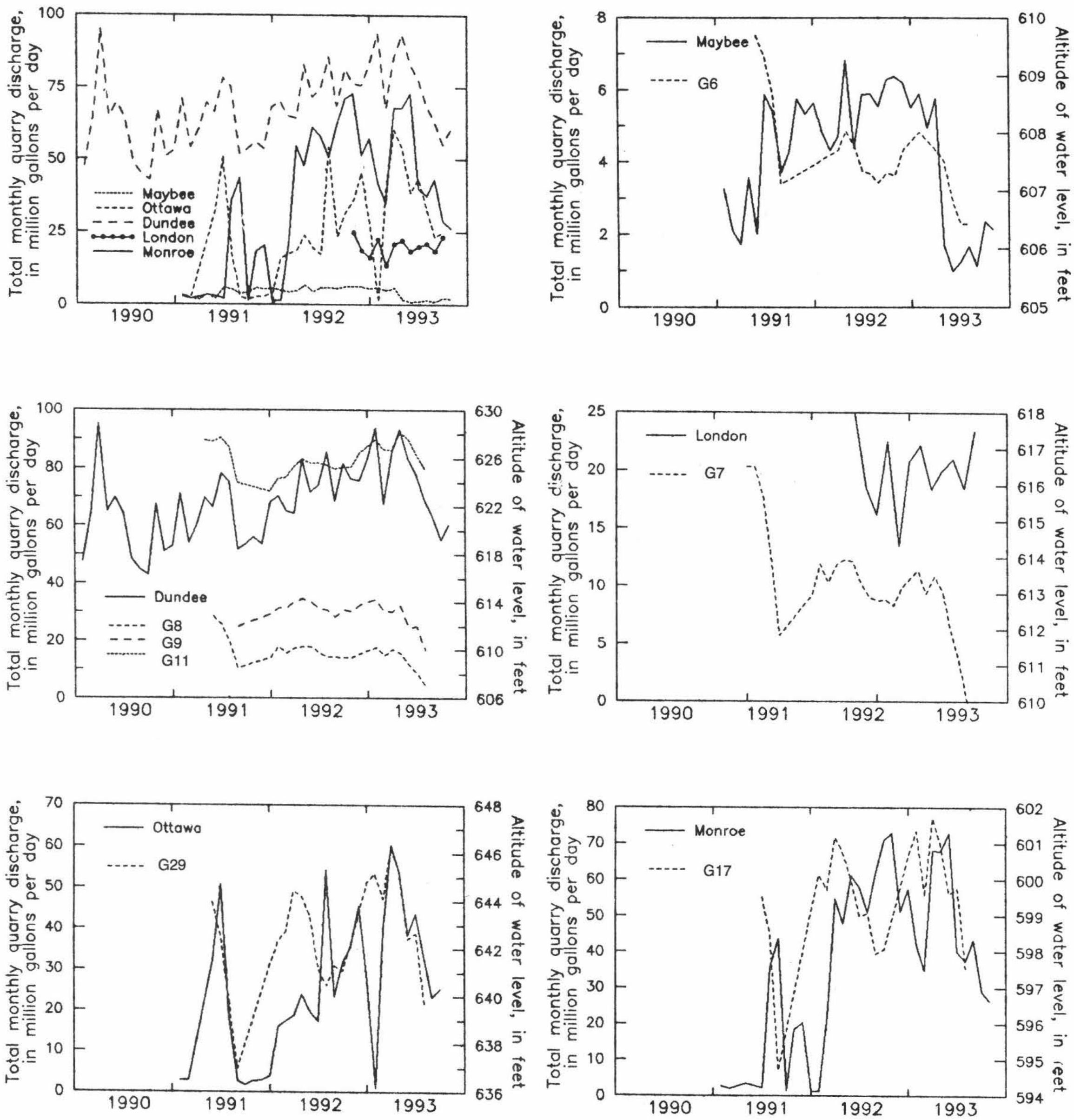


Figure 40. Total monthly quarry discharge compared with water levels in nearby observation wells, Monroe County, Michigan, 1990-93.

The potential drawdown resulting from irrigation and quarry dewatering was estimated analytically by use of the Theis (1935) solution. Drawdown at several distances was estimated for typical withdrawal rates, two transmissivities, and two values of storage coefficient (table 11). The values of transmissivity and storage coefficient used to estimate drawdowns shown in the top two sections in table 11 are those from the multiple-well aquifer test at the Petersburg State Game Area. In the third section, a higher transmissivity was used, similar to the highest reported in table 1. In the fourth section, a higher storage coefficient, typical of a sparsely fractured unconfined aquifer, was used. The estimated drawdowns in table 11 illustrate how different aquifer properties and withdrawal rates can affect nearby wells. In using the Theis solution, one assumes that all wells fully penetrate the aquifer and that the aquifer is homogeneous, isotropic, and confined by an impermeable confining unit. The assumption that the aquifer is fully confined near pumped irrigation wells and quarries is probably not met in Monroe County. Drawdown may be less than that shown in table 11 because of

Table 11.--Estimated drawdown resulting from typical withdrawals from irrigation wells and quarries.

[Estimates based on assumption that (1) withdrawal is from a fully pernetrating well in an infinite, homogeneous, isotropic, confined aquifer, and (2) drawdown is measured in a fully penetrating well in the same aquifer. ft^2/d, feet squared per day; gal/min, gallons per minute.]

Irrigation well: 1 day continuous pumping; transmissivity = 1,300ft^2/d; storage coefficinet = 0.00012

Distance from well (mi)	Drawdown (ft) for given rate of withdrawal (gal/min)		
	80	160	320
1/8	3.0	6.0	12
1/4	2.0	4.0	8.0
1	.3	.6	1.2

Quarry: 100 days continuous pumping; transmissivity = 1,300 ft^2/d; storage coefficient = 0.00012

Distance from quarry (mi)	Drawdown (ft) for given rate of withdrawal (gal/min)		
	100	1,000	3,000
1/2	5.5	55	165
1	4.1	41	123
5	1.3	13	39

Quarry: 100 days continuous pumping; transmissivity = 6,000 ft^2/d; storage coefficient = 0.00012

Distance from quarry (mi)	Drawdown (ft) for given rate of withdrawal (gal/min)		
	100	1,000	3,000
1/2	1.2	12	36
1	.9	9.0	27
5	.3	3.0	9.0

Quarry: 100 days continuous pumping; transmissivity = 1,300 ft^2/d; storage coefficient = 0.01

Distance form quarry (mi)	Drawdown (ft) for given rate of withdrawal (gal/min)		
	100	1,00	3,000
1/2	1.6	16	48
1	.5	5.0	15

leakage from overlying unconsolidated deposits, drainage of pores where the aquifer is unconfined, or a higher storage coefficient for an unconfined aquifer. On the other hand, stresses on an aquifer are additive. Thus, a domestic well pumping near a large irrigation well during a drought will have a drawdown that is the sum of drawdowns due to domestic pumpage, irrigation pumpage, and drought.

Wells in Monroe County are of several types, and the choice of type depends on the intended use and the source of the water (fig. 41). The type of well construction, the depth of the well, and the source of water all have implications with respect to effects of drought and nearby pumpage.

Drive-point wells, which are no longer approved by the Monroe County Health Department, are shallow, small-diameter wells completed in surficial saturated sand deposits. Drive-point wells are susceptible to drought, quarry dewatering, and artificial surface drainage. Drought may lower water levels below the well screen or deplete a perched aquifer. Water from surficial deposits may drain to adjacent quarries drain tiles or ditches, causing drive-point wells to stop producing.

Shallow bedrock wells, usually 4 to 5 in. in diameter, are used to obtain domestic supplies from the weathered zone and fractures near the bedrock surface. These wells are cased through overlying unconsolidated material and then left open to a few feet below the weathered zone. Shallow bedrock wells are typically only 45 to 60 ft deep, so as to avoid mineralized water that may be deeper in the bedrock. However, these wells are susceptible to drought or nearby pumping, especially in areas where seasonal water-level fluctuations are large (such as southwestern Monroe County). A drought, combined with increased water use, may temporarily lower the potentiometric surface below the weathered zone, causing shallow bedrock wells to stop producing for the duration of the drought. The 12 wells that stopped producing in Summerfield Township in 1988 were shallow bedrock wells (Larry Pickens, Monroe County Health Department, oral commun., 1993).

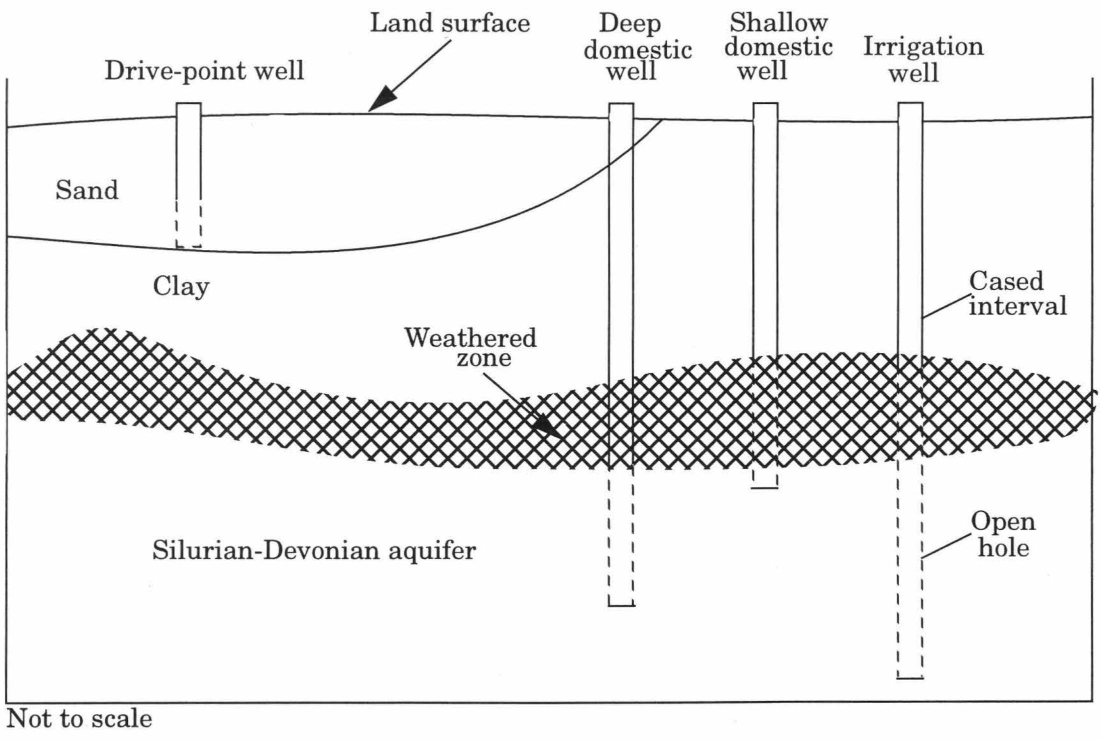


Figure 41. Common types of well construction, Monroe County, Michigan.

Deep bedrock wells, usually 4 to 10 in. in diameter, are used to obtain domestic and municipal supplies. The larger diameter wells are used for municipal supply. These wells are left open to depths greater than 50 ft and obtain water from fractures below the weathered zone. Deep bedrock wells are the least susceptible to the effects of drought and nearby pumpage because (1) the source of water is usually several fractures, (2) water levels are less likely to fall below the deep fractures, and (3) more water is available from wellbore storage above the pump than in shallow wells. In areas of Monroe County most susceptible to the effects of drought or heavy pumpage, deep bedrock wells are the most likely to continue to produce needed quantities of water.

Irrigation wells, usually 5 to 12 in. in diameter, are used to obtain supplies at rates much greater than those needed for domestic purposes, typically 250 to 350 gal/min rather than 10 gal/min. In the past, irrigation wells were usually cased to the top of the bedrock and obtained water from the weathered zone and deeper fractures. When these irrigation wells are being pumped, water levels typically fall below the weathered zone. However, water continues to drain or cascade within the well bore from the weathered zone to the pumping water level. Consequently, nearby shallow bedrock wells—open only to the weathered zone—could potentially stop producing. Nearby deep bedrock wells would continue to produce. Currently, Monroe County requires new irrigation wells to be drilled, cased, and grouted through the weathered zone to minimize their effect on nearby shallow bedrock wells (Larry Pickens, Monroe County Health Department, oral commun., 1994).

Surface Water

Droughts cause reduced streamflow in Monroe County. During low-flow conditions, ground-water discharge (base flow) is the only natural component of streamflow; during droughts, base flow is reduced because of a lowered water table. The streamflow measurements made in 1990 during low flow (table 3, at back of report, p. 83) are indicative of streamflow during drought.

The consumptive uses of surface water are likely to be greatest when streamflows are low during droughts. According to Fulcher and others (1986, p. iii), "... consumptive uses cause significant reductions in streamflow in the River Raisin, with most severe impacts expected during drought conditions." Fulcher and others (1986, p. 29) concluded that streamflows used for establishing allowable artificial discharges to the River Raisin should be lowered to reflect consumptive water uses during drought.

Streamflow data from the gaging stations on the River Raisin near Monroe and Otter Creek near LaSalle are a measure of the hydrologic severity of the 1988 drought. Mean discharge at the River Raisin gaging station during water year 1988 was 687 ft^3/s. The magnitude of this discharge ranked 24th among the 52 years of record at the station. In comparison, the lowest ranked water year was 1964, when mean discharge was 172 ft^3/s; the highest ranked water year was 1982, when a mean discharge was 1,379 ft^3/s. Thus, on an annual basis, streamflow was near normal in 1988.

Flow-duration analysis indicates periods of low flow in 1988.The 1-, 3-, 7-, 14-, and 30-day low flows for 1988 were the fifth lowest for the period of record.Similarly, the 60-, 90-, and 120-day low flows ranked seventh, eight, and ninth respectively. Thus, although the annual discharge was near normal, flow was unusually low at times.

A summary of mean monthly streamflow data for River Raisin near Monroe, Michigan for 1937-92 (fig. 42) shows that streamflow in River Raisin was below the monthly median from March through August 1988. Record lows were set for monthly mean streamflow during June and July 1988. Streamflow discharge was above average in January, February, October, and November of 1988.

The relation between streamflow on Otter Creek and precipitation data and ground-water-level data from nearby stations is shown in figure 43. As with streamflow in River Raisin, streamflow in Otter Creek during the latter part of water year 1988 was unusually low. A 26-day period of no flow began on June 21, 1988. The 4-month period of low flows in 1988 was the most extreme during the 5-year period of record on Otter Creek.

A series of negative departures from normal precipitation beginning in 1988 (upper box, fig. 43) precedes the low-flows in Otter Creek. Positive precipitation departures during the remaining part of the year returned streamflow conditions to near average by the end of the calendar year. Ground-water levels in well GLTO (lower box, fig. 43) also followed changes in precipitation and streamflow but lagged changes in streamflow by about 1 month.

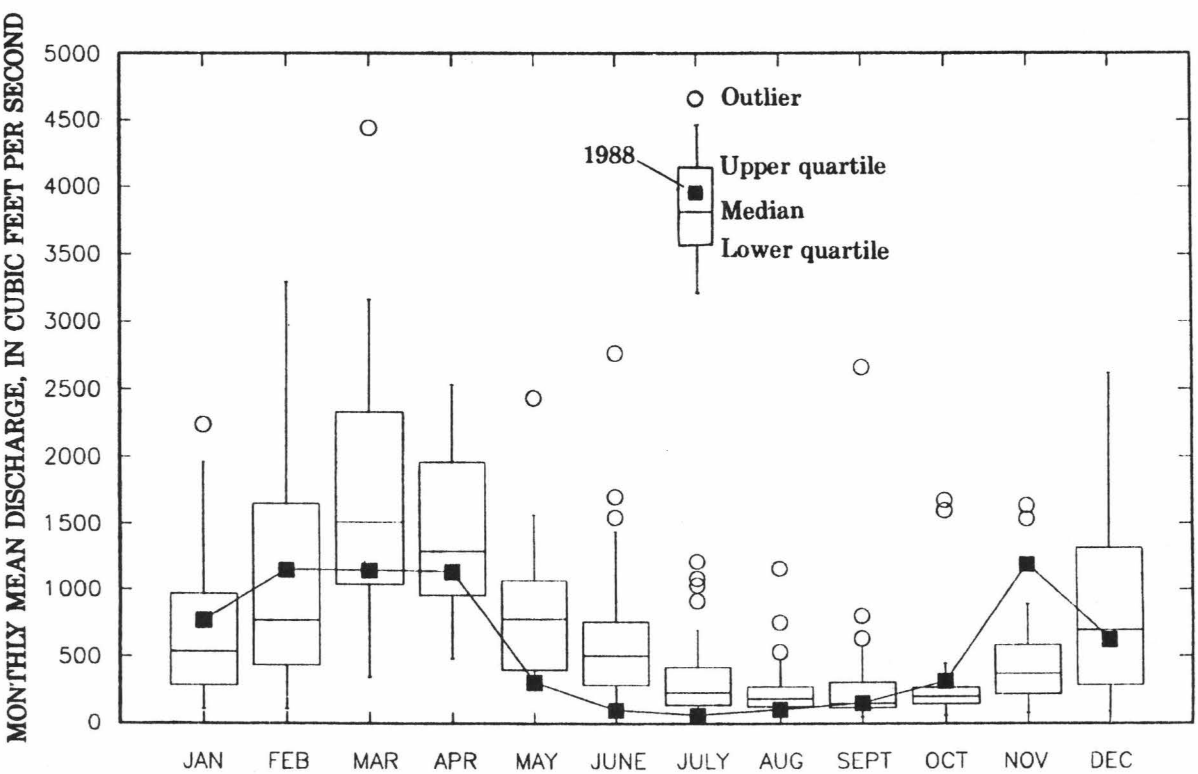


Figure 42. Relation of discharge in 1988 to monthly mean discharge during 1937-92 at the River Raisin near Monroe, Michigan.

The quality of surface water during droughts is similar to that during other low flows. Long-term water-quality records (1978-92) from the River Raisin near Monroe were examined to determine what relations, if any, could be found between constituent concentrations and streamflow. During low flow, concentrations of some naturally occurring constituents are greater than during higher flow (fig. 44). Precipitation typically has lower constituent concentrations than does ground water; consequently low flows (mostly ground water) have higher concentrations of constituents than high flows do (mostly precipitation runoff). In contrast, concentrations of nitrogen (an indicator of human activities) tend to be highest during high flows (fig. 45), when runoff from fields and lawns is a greater proportion of the streamflow.

SUMMARY

Monroe County, in southeastern Michigan, relies heavily on its aquifers and streams for drinking water, irrigation, and water for other uses. In parts of the county, however, ground water at moderate depths can contain objectionable

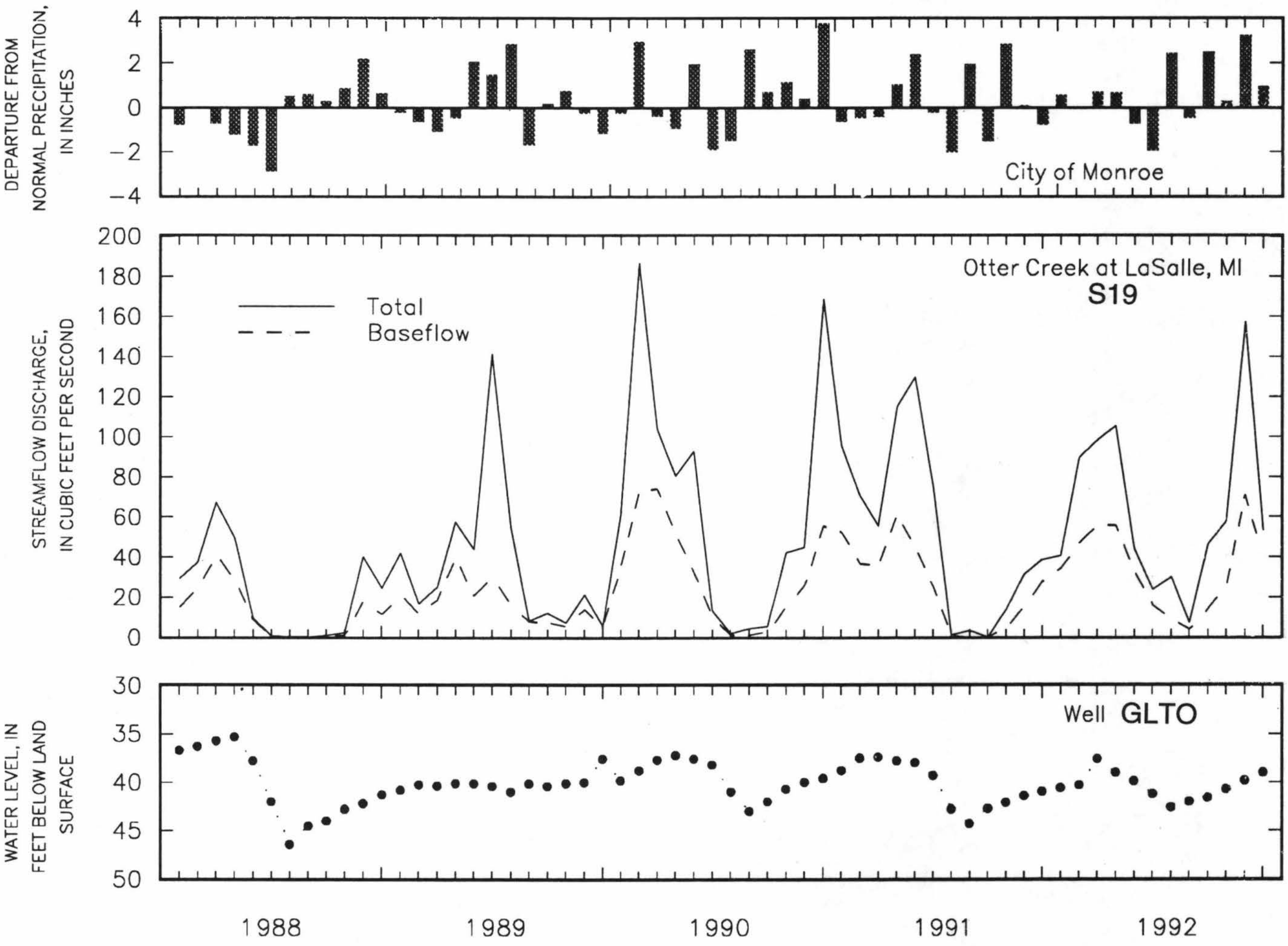


Figure 43. Relations among precipitation, streamflow, and ground-water levels, Monroe County, Michigan, 1988-92.

amounts of hydrogen sulfide or can be highly mineralized, and aquifers that yield water of suitable quality for most uses are heavily stressed. Historically, droughts in Monroe County have limited the availability of ground water. Although surface-water resources are usually sufficient in the county and of suitable quality for most uses, these resources also are susceptible to the effects of drought.

Most of Monroe County is a plain with low relief that slopes southeastward toward Lake Erie. The county encompasses about 562 mi^2, of which three-quarters is agricultural land. About 134,000 people live in the county, more than half of them residing in Bedford, Frenchtown, and Monroe Townships.

Residents in the most densely populated parts of Monroe County depend on surface water from the city of Monroe, the city of Toledo (Ohio), and Detroit. Residents in the remainder of the county depend on municipal ground-water or surface-

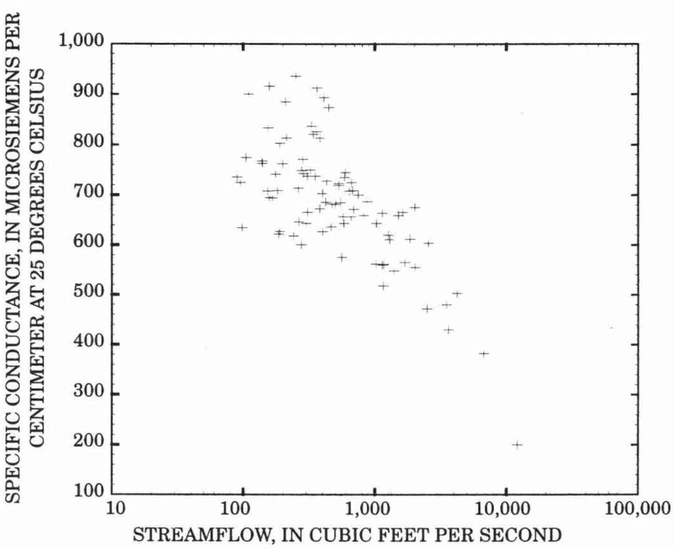


Figure 44. Relation between specific conductance and streamflow at River Raisin near Monroe, Michigan, 1978-92

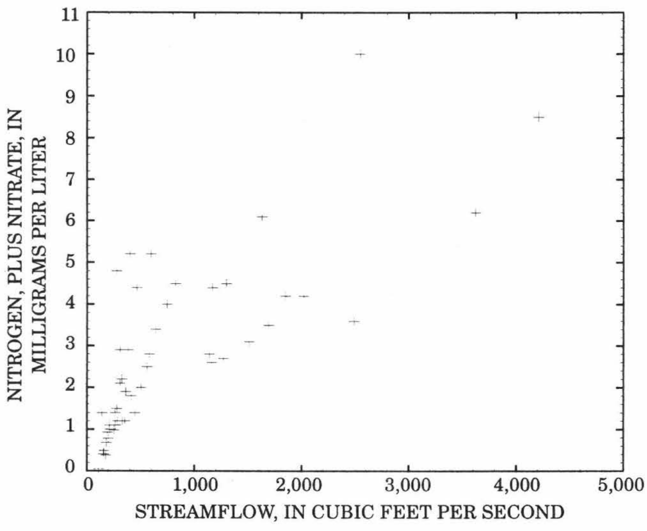


Figure 45. Relation between total nitrogen and streamflow at River Raisin near Monroe, Michigan 1978-92.

water supplies or on individual wells. Farming is an important part of the county's economy, and most crops can be raised satisfactorily if rainfall is normal; however, ground water and surface water are used to irrigate during dry periods. Although quarries are not a major land use (0.4 percent), large amounts of ground water are pumped from them (about 70 percent of the ground-water use in the county).

Monroe County is underlain by sedimentary rock of Silurian and Devonian ages, mostly carbonate rock and sandstone. All of the bedrock units are fractured, and sinkholes are present in the southwestern part of Monroe County.

Unconsolidated deposits composed of clay, silt, and sand—till, glaciofluvial deposits, alluvium, and glaciolacustrine deposits—overlie the bedrock throughout most of the county. Clay is the surficial deposit throughout much of the county. However, sand is the surficial deposit in a 2- to 8-mile wide, north-to-south-trending band across west-central Monroe County. In parts of Bedford and Whiteford Townships, sand is at the land surface and directly overlies the bedrock. The thickness of unconsolidated deposits in the county is varied; however, throughout most of the county, unconsolidated deposits are less than 50 ft thick.

The sand aquifer and Silurian-Devonian aquifer are the principal sources of ground water in Monroe County. The sand aquifer, which consists of discontinuous saturated sand deposits, can yield small quantities of water for domestic uses. Where bedrock valleys are filled with sand and gravel, more sustainable yields may be obtained. Perched ground water is common in Monroe County and is occasionally used for domestic purposes; however, because wells in perched aquifers are susceptible to drought, interference from nearby pumpage, and contamination they are generally an unreliable source of water.

Water withdrawn from the Silurian-Devonian aquifer comes primarily from fractures and bedding plane partings. Analyses of two aquifer tests at wells open to the aquifer indicated transmissivities of 1,300 and 3,800 ft^2/d and storage coefficients of 0.00012 and 0.0001. Estimates of transmissivity from slug-test data for 24 wells ranged from 10 to 6,600 ft^2/d.

The major recharge area for the Silurian-Devonian aquifer in Monroe County is in the southwest, where unconsolidated deposits are relatively thin and sandy. Ground water flows from the major recharge area toward Lake Erie or Ohio. Ground-water levels in the eastern parts of the county are below the mean altitude of Lake Erie; consequently, water could potentially move into the Silurian-Devonian aquifer from Lake Erie in these areas. Large hydraulic gradients in east Monroe County are associated with cones of depression on the potentiometric surface that result from pumpage near the Wayne-Monroe County border and in the Toledo, Ohio, area. Hydraulic gradients in the recharge area are small.

Most of the Silurian-Devonian aquifer in Monroe County is confined. However, the aquifer is unconfined at bedrock highs, principally in the recharge area, and in the northeast where ground-water levels have been lowered by pumping. At locations where ground water in the weathered zone is unconfined, ground water in deeper fractures probably is confined.

Water levels in wells change continuously in response to changes in recharge to or discharge from the Silurian-Devonian aquifer. When recharge exceeds discharge, usually in spring, water levels rise; when discharge exceeds recharge, usually in summer, water levels fall. Water levels tend to fluctuate the most in the recharge areas in the southwestern part of the county. Discharge occurs naturally and as a result of pumpage. The long-term effect of pumpage has been to lower water levels regionally. Local, short-term declines in water level generally result from pumpage.

Streams in Monroe County are either directly tributary to Lake Erie or are in the Huron River Basin, the River Raisin Basin, or the Ottawa River Basin. Because of the low slope of the land and the large amount of agricultural land use, Monroe County has a dense network of artificial drains. Most basins are underlain by fine-grained unconsolidated deposits, but bedrock crops out in parts of some streambeds.

Daily discharge record has been collected by the USGS at River Raisin near Monroe since 1937 and at Otter Creek near LaSalle since 1987. Seasonal fluctuations in streamflow are similar to seasonal fluctuations in ground-water levels—typically streamflow is highest in the spring and lowest in the summer.

Stream discharge was measured at 24 sites in Monroe County during low flow in summer 1990, when streamflow was all or mostly ground-water discharge. The lower reaches of River Raisin (S12) and Plum Creek (S13) were losing, indicating flow from the stream to the Silurian-

Devonian aquifer. Normalized discharge at the other sites ranged from 0.22 in/yr in Macon Creek (S8) to 14.7 in/yr in Little Lake Creek (S20).

The water-quality sampling program in Monroe County was designed to provide a general assessment of current water quality in Monroe County and to evaluate natural and artificial processes that affect water quality. Ground-water samples were collected from 31 USGS observation wells and 10 domestic wells completed in the Silurian-Devonian aquifer. Surface-water samples were collected from streams at 24 sites during low flow.

In general, ground-water quality is suitable for domestic use and irrigation, although concentrations of some constituents are objectionable for domestic use. The most common ground-water-quality problem in Monroe County is high dissolved-solids concentration, which is correlated with elevated hardness and sulfate concentration. Hydrogen sulfide gas, a by-product of sulfate reduction, also is a water-quality problem in parts of Monroe County. Fifty percent of the ground-water samples collected from the Silurian-Devonian aquifer had measurable concentrations of hydrogen sulfide. These samples were from wells that lie along a southwest-northeast trend that largely corresponds to the Dundee Formation and the Detroit River Dolomite subcrops.

The dominant geochemical trend observed in the Silurian-Devonian aquifer is a transition from bicarbonate-dominated waters with relatively low dissolved-solids concentrations to sulfate-dominated waters with high dissolved-solids concentrations. Sulfate waters are the dominant water type in eastern Monroe County, whereas bicarbonate waters are the dominant water type in the north-central and northwestern parts of the county. Mixed water types are scattered throughout the southwestern part of the county.

Isotope data from the Silurian-Devonian aquifer support conclusions from the hydrogeologic part of the study. Tritiated ground water, indicative of recent recharge, is found in a southwest-to-northeast-trending band through most of Whiteford, Ida, Raisinville, Ash, and Berlin Townships. The lack of tritium in areas where drift thickness exceeds 30 ft indicates that recharge to the Silurian-Devonian aquifer in those areas takes more than 40 years. Estimates of ground-water age from carbon isotope data indicate that sulfate-rich waters are the oldest, with estimated ages at some wells exceeding 15,000 years.

In general, surface-water quality during low flow is suitable for most uses and is similar to that of water from the Silurian-Devonian aquifer. Minimal treatment to remove bacteria is necessary in summer months. During the rest of the year, bacteria are absent. None of the samples collected in 1990 or 1991 had nitrite or nitrate concentrations that exceeded the MCL's of 1.0 and 10.0 mg/L. Most surface waters were nearly saturated with respect to dissolved oxygen; thus, streams in Monroe County are probably not being loaded with oxygen-consuming substances derived from sources such as sewage, agricultural wastes or industrial wastes.

Mild droughts are common in Michigan, but severe droughts are infrequent and generally of short duration. The two most severe droughts were statewide and occurred during 1930-37 and during 1960-67. The most recent statewide drought occurred in 1988. Although the 1988 drought was severe, it was relatively short in duration.

In summer 1988, water levels declined in the Silurian-Devonian aquifer throughout Monroe County. Declines were probably greatest in the recharge area in the southwestern part of the county where seasonal fluctuations are typically greatest.

Reports of decreased or zero discharge from wells in the Silurian-Devonian aquifer are not uncommon historically in Monroe County. Typically, the reports have been linked not only to droughts, but also to interference from nearby uses such as irrigation, quarry dewatering, and increased domestic or municipal pumpage. Shallow bedrock wells—completed to just below the weathered zone—are most affected by drought and by interference from nearby uses. The wells that went dry in Summerfield Township in 1988 were shallow bedrock wells. Deep bedrock wells did not go dry. Deep bedrock wells derive water from deeper fractures and will continue to produce if the weathered zone is dewatered.

Droughts cause reduced streamflow in Monroe County. During low-flow conditions, most streamflow is base flow (ground-water discharge to streams). During droughts, base flow is reduced because of a lowered water table. The consumptive uses of surface water tend to be greater during droughts and exacerbate the effects of drought on streamflow. The quality of surface water during droughts is similar to that during normal low-flow conditions.

REFERENCES CITED

Back, W., Hanshaw, B.B., Plummer, L.N., Rahn, P.H., Rightmire, C.T., and Rubin, M., 1983, Process and rate of dedolomitization-mass transfer and ^{14}C dating in a regional carbonate aquifer: Geological Society of America Bulletin, v. 94, p. 1415-1429.

Ball, J.W., and Nordstrom, D. K., 1991, User's manual for WATEQ4F, with revised thermodynamic data base and test cases for calculating speciation of major, trace, and redox elements in natural waters: U.S. Geological Survey Open-File Report 91-183, 189 p.

Battaglin, W.A., Goolsby, D.A. and Coupe, R.H., 1993 Annual use and transport of agricultural chemicals in the Mississippi River, 1991-92, *in* Goolsby, D.A., Blair, C., and Ballard, G.E., eds., Selected papers on agricultural chemicals in water resources of the midcontinental United States: U.S. Geological Survey Open File Report 93-418, p. 26-40.

Bedell, D.J., and Van Til, R. L., 1979, Irrigation in Michigan: Michigan water Resources Commission, 44 p.

Blumer, S.P., Nurnberger, F.V., Hamilton, D.A., and Sorrell, R.C., 1991, Michigan floods and droughts, in National Water Summary 1988-89: U. S. Geological Survey Water-Supply Paper 2375, p. 335-344.

Botoman, G., and Faure, G., 1976, Sulfur isotope composition of some sulfide and sulfate minerals in Ohio: Ohio Journal of Science, v. 76, p. 66-71.

Bowman, W.L., 1981, Soil survey of Monroe County, Michigan: U.S. Soil Conservation Service, 136p.

Breen, K.J., and Dumouchelle, D.H., 1991, Geohydrology and quality of water in aquifers in Lucas, Sandusky, and Wood Counties, northwestern Ohio: U.S. Geological Survey Water-Resources Investigations Report 91-4024, 234 p.

Britton, L.J., and Greeson, P.E., eds., 1987, Methods for collection and analysis of aquatic biological and microbiological samples: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A4, 363 p.

Busby, J.F., Plummer, L.N., Lee, R.W., and Hanshaw, B.B., 1991, Geochemical evolution of water in the Madison aquifer in parts of Montana, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1273-F, 89 p.

Cooper, H.H., Jr., Bredehoeft, J.D., and Papadopulos, S.I., (1967) Response of a finite-diameter well to an instantaneous charge of water: Water Resources Research, v. 3, p. 263-269.

Craig, H., 1961, Isotopic variations in meteoric waters: Science, v. 133, p. 1702-1703.

Dorr, J.A., and Eschman, D.F., 1970, Geology of Michigan: Ann Arbor, Mich., University of Michigan Press, 476 p.

Dufor, C.N., and Becker, Edith, 1964, Public water supplies of the 100 largest cities in the United States: U.S. Geological Survey Water-Supply Paper 1812, 364 p.

Fishman, M.J., and Friedman, L.C., eds., 1989, Methods for determination of inorganic substances in water and fluvial sediments:U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A1, 545 p.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, N.J., Prentice-Hall, 604 p.

Friedmann, L.C., and Erdmann, D.E., 1982, Quality assurance practices for the chemical and biological analyses of water and fluvial sediments: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A6, 181 p.

Fulcher, G.W., Miller, S.A., and Van Til, R., 1986, Effects of consumptive water uses on drought flows in the River Raisin: Michigan Department of Natural Resources, Engineering-Water Management Division, 32 p.

Gillespie, J.L., and Dumouchelle, D.H., 1989, Ground-water flow and quality near the upper great lakes connecting channels, Michigan: U.S. Geological Survey Water - Resources Investigation Report, 88-4232, 82p.

Hanshaw, B.B., Back, W., and Rubin, M., 1965, Radiocarbon determinations for estimating groundwater flow velocities in Central Florida: Science, v. 148, p. 494-495.

Helsel, D.R., and Gilliom, R.J., 1986, Estimation of descriptive statistics for multiply censored water quality data: Water Resources Research, v. 24, p. 1997-2004.

Hem, J.D., 1989, Study and interpretation of the chemical characteristics of natural waters (3d ed.), U.S. Geological Survey Water-Supply Paper 2254, 263 p.

Hydrolab Corporation, 1979, System 4000 water quality instrumentation: Bulletin 8000-1/79, 29 p.

Johnson, R.H., 1962, Water-bearing characteristics of the Lockport Dolomite near Niagara Falls, New York: U. S. Geological Survey Professional Paper 450-C, p. C123-C125.

Knutilla, R.L., and Allen, W.B., 1975, Water resources of the River Raisin Basin southeastern Michigan: U.S. Geological Survey Hydrologic Investigations Atlas HA-520, 2 sheets, scale 1:250,000.

Krouse, H.R., 1980, Sulphur isotopes in our environment, *in* Fritz, P., and Fontes, J.Ch., eds., Handbook of environmental isotope geochemistry, volume 1, the terrestrial environment, A: New York, Elsevier, p. 435-472.

Larson, R.W., Allen, W.B., and Hanson, S.D., 1975, Water Resources of the Huron River Basin, southeastern Michigan: U. S. Geological Survey Hydrologic Investigations Atlas HA-514, 2 sheets, scale 1:250,000.

Leverett, Frank, and others, 1906, Water Supplies of Monroe County, *in* Flowing wells, southern portion, southern peninsula of Michigan: U. S. Geological Survey Water-Supply and Irrigation Paper 182, _p.

Michel, R.L., 1989, Tritium deposition in the continental United States, 1953-1983: U.S. Geological Survey Water-Resources Investigations Report 89-4072, 46 p.

Michigan Department of Natural Resources 1990, Winds of change - a special report: Michigan Natural Resources Magazine, v. 59, no. 4, p. 19-34.

Monroe County Planning Department, 1985, Monroe County comprehensive plan update: - Public Utilities Component: 37 p.

Mook, W.G., 1980, Carbon-14 in hydrogeological studies *in* Fritz, P., and Fontes, J.Ch., eds., Handbook of environmental isotope geochemistry, volume 1- the terrestrial environment, A: New York, Elsevier, p. 49-74.

Moses, C.O., Nordstrom, D.K., Herman, J.S., and Mills, A.L., 1987. Aqueous pyrite oxidation by dissolved oxygen and ferric iron: Geochimica et Cosmochimica Acta, v. 51, p. 1561-1571.

Mozola, A.J., 1970, Geology for environmental planning in Monroe County, Michigan: Michigan Department of Natural Resources, Report of Investigation 13, 34 p.

National Oceanic and Atmospheric Administration 1970- 90, Climatological data, annual summary - Michigan: Asheville, N.C., National Climatic Data Center [published annually].

Nielsen, H., 1978, Isotopes in nature, *in* Wedepohl, K.H., and others, eds., Handbook of geochemistry: New York, Springer-Verlag, v. II, pt. 2, chap 16B, p. 16-B-22 to 16-B-23.

Nordstrom, D.K., Jenne, E.A., and Ball, J.W., 1979, Redox equilibria of iron in acid mine waters, *in* Jenne, E.A., ed., Chemical modeling of aqueous systems—speciation, sorption, solubility, and kinetics: American Chemical Society Symposium Series 93, p. 51-79.

Nurnburger, F.V., 1980, Meteorological drought in Michigan - A review of the past 50 years, *in* Michigan State University Institute of Water Research, Conference on Supplemental Irrigation - Advantages and disadvantages: Lansing, Michigan, March 18, 1980, 21 p.

Olcott, P.G. 1992, Ground water atlas of the United States, segment 9, Iowa, Michigan, Minnesota, Wisconsin: U.S. Geological Survey Hydrologic Investigations Atlas HA-730-J, p. J18-J20.

Ohio Department of Natural Resources, 1970, Ground water for planning in northwest Ohio--a study of the carbonate rock aquifers: Ohio Department of Natural Resources, Ohio Water Plan Inventory Report 22, 63 p.

Palmer, W.C.,1965, Meteorlogical drought: U.S. Weather Bureau Research Paper 45, p. 1-58.

Pearson, F.J., and White, D.E., 1967, Carbon-14 ages and flow rates of water in Carrizon sand, Atascosa County, Texas: Water Resources Research, v. 3, 251 p.

Plummer, L.N., Prestemon, E.C., and Parkhurst, D.L., 1991, An interactive code (NETPATH) for modeling net geochemical reactions along a flow path: U.S. Geological Survey Water-Resources Investigations Report 91-4078, 227 p.

Sherrill, M.G., 1978, Geology and ground water in Door County, Wisconsin, with emphasis on contamination potential in the Silurian dolomite: U. S. Geological Survey Water-Supply Paper 2047, 38 p.

Sherzer, W.H., 1900, Geological report on Monroe County: Geological Survey of Michigan, v. 7, part 1.

Stout, Wilber, 1941, Dolomites and limestones of western Ohio: Ohio Geological Survey Bulletin 42, 468 p.

Theis, C.V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: Transactions of the American Geophysical Union, v. 16, p. 519 - 524.

Thode, H.G., Monster, J., and Dunford, H.B., 1961, Sulphur isotope geochemistry: Geochim et Cosmochim Acta, v. 25, p. 159.

Twenter, F.R., Knutilla, R.L., and Cummings,T.R., 1975, Water resources of basins for minor streams draining into St. Clair River, Lake St. Clair, Detroit River, and Lake Erie, southeastern Michigan: U.S. Geological Survey Hydrologic Investigations Atlas HA-546, 3 sheets, scale 1:250,000.

U.S. Bureau of the Census, 1991, 1990 Census of population and housing, summary population and housing characteristics- Michigan: U. S. Bureau of Census.

U.S. Environmental Protection Agency, 1992, Drinking water regulations and health advisories: Washington D.C., Office of Water, 13 p.

______ 1993, Drinking water- inside EPA's water policy report, U.S. Environmental Protection Agency, v. 2, no. 23, p. T-4.

U.S. Salinity Laboratory, 1954, Diagnosis and improvement of saline and alkali soils: U.S. Department of Agriculture Handbook 60, 160 p.

Ward, J.R., and Harr, C.A., 1990, Methods for collection and processing of surface-water and bed-material samples for physical and chemical analyses: U.S. Geological Survey Open File Report 90-140, 71 p.

Westjohn, D.B., 1989, Applications of geophysics in the delineation of the freshwater/saline-water interface in the Michigan basin, *in* Swain, L.A., and Johnson, A.L., eds., Aquifers of the Midwest Area: American Water Resources Association Monograph Series, no. 13, p. 111-134.

Wigley, T.M., 1975, Carbon 14 dating of ground water from closed and open systems: Water Resources Research, v. 11, p. 324-328.

Wood, W.W., 1976, Guidelines for collection and field analysis of ground-water samples for selected unstable constituents: U.S. Geological Survey Techniques of Water-Resources Investigations, book 1, chap. D2, 24 p.

TABLES OF DATA

Table 2. Chemical and physical characteristics of ground water, Monroe County, Michigan, 1991-92

[Analyses by U.S. Geological Survey. Well locations shown on plate 1. µS/cm, microsiemens per centimeter at 25 degrees Celsius; ˚C, degrees Celsius; NTU, nephelometric turbidity units; mg/L, milligrams per liter; µg/L, micrograms per liter; <, less than; --, no analysis done.]

Well identifier	Date	Depth of well, total (feet)	Specific conductance, lab (µS/cm)	pH, lab (standard units)	Temperature, water (°C)	Turbidity (NTU)	Oxygen, dissolved (mg/L)	Hardness, total (mg/L as $CaCO_3$)	Alkalinity, lab (mg/L as $CaCO_3$)	Solids, residue at 180°C, disolved (mg/L)
G1	04-27-92	50	2,150	7.3	13.5	27	2.1	1,400	251	1,800
G2	04-27-92	60	2,530	7.3	11.5	120	5.9	1,800	226	2,430
G3	05-05-92	85	2,380	7.1	--	.40	1.6	1,500	184	2,180
G4	11-05-91	65	3,900	7.0	--	450	.5	1,800	172	2,920
G5	11-05-91	80	2,250	7.1	--	4.0	.2	1,300	176	1,960
G6	05-05-92	185	1,230	7.6	--	1.0	3.4	640	220	912
G7	11-04-91	95	344	7.7	--	2.7	.1	110	189	207
G8	11-04-91	110	523	7.4	--	12	.2	220	288	287
G9	04-28-92	200	1,100	7.5	12.0	4.3	.2	470	213	722
G10	10-30-91	111	589	7.7	--	2.6	.3	150	295	328
G11	01-23-92	110	1,990	7.1	--	1.2	1.8	1,300	486	1,560
G12	01-23-92	100	462	7.6	--	620	1.3	230	236	244
G13	04-28-92	110	508	7.4	12.0	1.0	1.0	270	223	307
G14	04-28-92	65	766	7.3	11.5	26	3.6	300	269	437
G15	11-05-91	50	1,460	7.2	--	230	--	850	225	1,130
G16	04-28-92	90	2,550	7.1	11.5	96	1.8	1,700	226	2,370
G17	05-20-92	95	2,310	7.3	--	.90	--	1,500	172	2,130
G18	01-23-92	50	694	7.4	--	.60	.1	370	342	451
G19	10-30-91	80	1,170	7.1	--	10	.8	590	373	798
G20	01-23-92	70	783	7.4	--	4.6	.4	380	222	470
G21	01-23-92	75	406	7.6	--	.90	.2	190	196	244
G22	04-29-92	87	538	7.7	11.0	.60	.3	250	215	354
G23	04-29-92	90	486	7.7	11.0	.60	.2	210	229	283
G26	04-29-92	80	606	7.6	11.0	.70	.4	230	247	360
G27	04-29-92	208	625	7.3	1.0	.70	.5	320	235	393
G28	10-29-91	75	1,140	7.2	--	1.1	.8	450	255	668
G29	10-29-91	71	519	7.6	--	3.3	.3	250	197	279
G30	04-28-92	155	341	7.9	12.0	4.7	3.3	160	101	210
G31	10-29-91	80	1,160	7.3	--	2.8	1.6	460	268	738
G32	04-28-92	75	2,200	7.2	11.0	110	.3	1,400	197	1,960
G33	04-28-92	85	1,730	7.4	11.5	.50	.2	940	128	1,470
D4	05-06-92	100	2,220	7.1	--	.50	.3	1,500	203	2,090
D5	05-19-92	57	1,180	7.1	--	34	.2	690	340	858
D6	05-06-92	72	713	7.5	--	17	.4	340	239	485
D7	05-06-92	59	1,490	7.3	--	5.0	5.9	870	229	1,180
D8	05-06-92	61	1,430	7.2	--	.40	.4	750	280	1,040
D9	05-20-92	38	1,610	7.3	--	8.4	.2	900	239	1,310
D10	05-07-92	--	2,100	7.2	--	4.9	.4	470	168	2,010
D11	05-19-92	65	957	8.2	--	.30	.4	420	261	646
D12	05-19-92	110	785	7.5	--	.30	.4	440	263	500
D13	05-19-92	--	2,090	7.2	--	1.1	.4	1,200	203	1,940

Table 2. Chemical and physical characteristics of ground water, Monroe County, Michigan, 1991-92--Continued

Well identifier	Solids, sum of constituents dissolved (mg/L)	Calcium dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/l as Na)	Potassium, dissolved (mg/L as K)	Sulfate, dissolved (mg/L as SO_4)	Sulfide, total (mg/L as S)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Nitrogen, nitrite dissolved (mg/L as N)
G1	1,710	350	120	33	5.3	950	<0.5	80	1.3	8.2	<0.010
G2	2,220	460	150	19	4.0	1,400	<.5	23	1.0	14	<.010
G3	1,950	410	110	46	5.3	1,200	4.8	43	1.7	15	<.010
G4	2,700	460	150	250	9.8	1,100	19	600	.90	16	<.010
G5	1,800	340	100	67	3.1	1,100	61	54	1.1	14	<.010
G6	835	140	66	17	3.1	410	45	8.6	1.0	18	<.010
G7	203	29	9.8	31	1.0	.20	<.5	2.6	1.2	13	<.010
G8	300	52	21	34	1.7	2.5	1.1	3.6	1.5	9.5	<.010
G9	704	100	48	41	3.7	340	96	12	1.0	8.7	<.010
G10	--	32	17	74	3.3	<.10	<.5	21	1.0	15	<.010
G11	1,610	270	140	26	5.2	820	36	8.7	.70	27	<.010
G12	269	54	20	12	1.1	3.1	1.3	13	1.1	15	<.010
G13	308	69	19	3.0	1.0	46	4.8	1.1	1.5	12	<.010
G14	433	88	20	37	1.4	58	<.5	58	.10	8.1	<.010
G15	1,120	230	63	7.4	2.7	630	.6	22	.50	10	<.010
G16	2,180	410	160	18	4.6	1,400	<.5	22	.90	13	<.010
G17	1,900	380	120	23	2.5	1,200	--	36	1.0	13	<.010
G18	439	85	25	8.6	2.2	48	2.1	3.9	1.0	12	<.010
G19	761	170	37	20	1.9	250	<.5	29	.50	13	<.010
G20	493	120	16	22	1.1	110	<.5	62	.60	18	<.010
G21	253	39	18	17	1.2	21	4.6	4.6	1.3	15	<.010
G22	356	45	21	23	1.5	74	8.8	6.4	1.3	14	<.010
G23	307	37	19	22	1.2	34	2.4	4.2	1.1	15	<.010
G26	371	43	22	--	1.4	76	1.6	6.5	1.1	13	<.010
G27	396	64	24	13	1.7	86	13	1.5	1.3	13	<.010
G28	647	120	32	52	3.2	110	<.5	150	.50	6.3	<.010
G29	282	63	20	4.9	.90	43	<.5	12	.90	10	<.010
G30	213	54	6.1	4.2	.50	61	<.5	12	.10	14	<.010
G31	692	130	31	59	2.8	170	<.5	120	.60	11	<.010
G32	1,760	390	110	6.0	2.4	1,100	<.5	11	1.6	12	<.010
G33	1,270	220	91	--	2.7	800	2.6	36	2.7	11	<.010
D4	1,900	430	110	4.9	2.4	1200	1.3	6.8	1.1	13	<.010
D5	824	220	33	5.5	1.4	320	<.5	17	.70	12	<.010
D6	467	79	26	36	2.3	150	<.5	1.7	1.4	11	<.010
D7	1,080	190	92	29	3.8	590	<.5	8.2	.90	13	<.010
D8	981	180	67	23	3.7	440	<.5	64	1.1	13	<.010
D9	1,200	210	86	41	2.9	670	34	6.6	1.3	20	<.010
D10	1,390	150	22	4.4	2.0	1,100	<.5	5.9	.80	3.1	<.010
D11	621	61	58	43	2.4	240	<.5	11	1.1	21	<.010
D12	476	120	33	3.3	1.6	110	<.5	38	.40	11	<.010
D13	1,590	350	65	8.7	3.4	1,000	<.5	9.7	.90	12	<.010

Table 2. Chemical and physical characteristics of ground water, Monroe County, Michigan, 1991-92--Continued

Well identifier	Nitrogen NO^2+NO^3 dissolved (mg/L as N)	Aluminum, dissolved (µg/L as Al	Arsenic dis-solved (µg/L as As)	Barium, dis-solved(µg/L as Ba)	Beryllium, dissolved (µg/L as Be)	Cadmium, dissolved (µg/L as Cd)	Chromium, dissolved (µg/L as Cr)	Cobalt, dis-solved (µg/L as Co)	Copper, dis-solved (µg/L as Cu)	Iron, dis-solved (µg/L as Fe)
G1	<0.050	20	<1	8	<1	<2.0	2	<6	1	370
G2	<.050	20	<1	9	<1	<2.0	2	<6	<1	560
G3	<.050	20	<1	8	<2	<3.0	<1	<9	<1	35
G4	<.050	10	<1	8	<2	3.0	5	<9	<1	52
G5	<.050	<10	<1	9	<2	<3.0	2	<9	<1	56
G6	<.050	20	<1	35	<.5	<1.0	<1	<3	<1	14
G7	<.050	20	1	170	<.5	<1.0	1	<3	<1	94
G8	<.050	20	<1	150	<.5	<1.0	<1	<3	<1	15
G9	<.050	<10	<1	130	.8	<1.0	<1	<3	<1	22
G10	<.050	10	<1	190	<.5	<1.0	<1	<3	<1	430
G11	<.050	<10	<1	17	<2	<3.0	<1	<9	<1	31
G12	<.050	20	<1	520	<.5	<1.0	<1	<3	<1	16
G13	<.050	<10	<1	150	<2	<3.0	<1	<9	<1	57
G14	.060	<10	1	49	.7	<1.0	<1	<3	<1	410
G15	<.050	30	<1	15	<.5	<1.0	2	<3	<1	21
G16	<.050	20	<1	14	2	<3.0	<1	<9	<1	190
G17	<.050	<10	<1	8	<2	<3.0	<1	<9	<1	150
G18	<.050	<10	<1	320	<.5	<1.0	<1	<3	<1	7
G19	.280	20	<1	46	<.5	<1.0	<1	<3	<1	1,300
G20	<.050	<10	<1	280	<.5	<1.0	<1	<3	<1	770
G21	<.050	10	<1	270	<.5	<1.0	<1	<3	<1	5
G22	<.050	<10	<1	160	<3	<5.0	<1	<20	<1	25
G23	<.050	10	<1	230	<.5	<1.0	<1	<3	<1	6
G26	<.050	<10	<1	220	<.5	<1.0	<1	<3	<1	15
G27	<.050	20	<1	120	<.5	<1.0	<1	<3	<1	<3
G28	.310	20	<1	230	<.5	<1.0	1	<3	2	9
G29	<.050	20	1	150	<.5	<1.0	1	<3	<1	330
G30	<.050	30	<1	150	<.5	<1.0	<1	<3	<1	77
G31	<.050	20	<1	66	<.5	<1.0	2	<3	<1	170
G32	<.050	20	<1	46	2	<3.0	1	<9	<1	36
G33	<.050	20	<1	24	.5	<1.0	<1	<3	<1	15
D4	<.050	50	<1	6	<2	<3.0	2	<9	2	<9
D5	<.050	20	<1	46	<.5	<1.0	<1	<3	<1	2,600
D6	<.050	10	<1	41	<.5	<1.0	<1	<3	<1	170
D7	.058	40	<1	9	<.5	<1.0	<1	<3	<1	460
D8	<.050	30	<1	12	<.5	<1.0	<1	<3	1	190
D9	<.050	20	<1	11	<2	<3.0	<1	<9	<1	25
D10	<.050	30	<1	3	<2	<3.0	<1	<9	<1	340
D11	<.050	10	<1	20	<.5	<1.0	<1	<3	<1	5
D12	<.050	<10	<1	270	.7	<1.0	<1	<3	<1	48
D13	<.050	<10	<1	7	<2	<3.0	<1	<9	<1	240

Table 2. Chemical and physical characteristics of ground water, Monroe County, Michigan, 1991-92--Continued

Well identifier	Lead, dissolved (µg/L as Pb)	Lithium, dissolved (µg/L as Li)	Manganese, dissolved (µg/L as Mn)	Molybdenum, dissolved (µg/L as Mo)	Nickel, dissolved (µg/L as Ni)	Silver, dissolved (µg/L as Ag)	Strontium, dissolved (µ/L as Sr)	Vanadium, dissolved (µ/L as V)	Zinc, dissolved (µg/L as Zn)	Carbon, organic, dissolved (mg/L as C)
G1	<1	75	10	<20	1	<1.0	13,000	<12	54	5.1
G2	<1	96	8	<20	1	<1.0	12,000	<12	13	2.2
G3	<1	35	7	<30	<1	<1.0	11,000	<18	<9	1.8
G4	<1	200	34	<30	<1	<1.0	14,000	<18	25	3.0
G5	<1	53	10	<30	<1	<1.0	14,000	<18	<9	2.4
G6	<1	33	5	<10	<1	<1.0	20,000	<6	<3	2.7
G7	<1	7	6	10	<1	<1.0	1,700	<6	<3	1.1
G8	<1	7	3	<10	<1	<1.0	1,700	<6	8	2.3
G9	<1	23	3	<10	<1	<1.0	22,000	<6	16	2.2
G10	<1	27	18	<10	<1	<1.0	1,500	<6	3	1.4
G11	<1	140	100	<30	<1	<1.0	21,000	<18	15	1.9
G12	<1	13	11	<10	<1	<1.0	7,900	<6	4	1.8
G13	<1	14	<3	<30	<1	<1.0	21,000	<18	15	1.6
G14	<1	<4	170	20	5	<1.0	470	<6	19	5.4
G15	<1	38	6	<10	1	<1.0	17,000	<6	14	2.5
G16	<1	79	18	<30	<1	<1.0	13,000	<18	21	2.0
G17	<1	51	6	<30	<1	<1.0	22,000	<18	31	7.1
G18	<1	23	3	<10	<1	<1.0	48,000	<6	4	10
G19	<1	16	30	<10	<1	<1.0	13,000	<6	9	2.0
G20	<1	12	26	<10	<1	<1.0	9,600	<6	<3	3.5
G21	<1	11	<1	<10	<1	<1.0	18,000	<6	8	2.0
G22	<1	<20	<5	<50	<1	<1.0	41,000	<30	<15	4.3
G23	<1	10	4	<10	<1	<1.0	36,000	<6	17	4.6
G26	<1	11	3	<10	<1	<1.0	30,000	<6	<3	4.2
G27	<1	12	3	<10	<1	<1.0	50,000	<6	<3	2.7
G28	7	10	12	10	7	<1.0	18,000	<6	14	1.9
G29	<1	7	10	<10	<1	<1.0	8,900	<6	5	1.2
G30	<1	<4	8	<10	<1	<1.0	170	<6	6	1.6
G31	<1	18	8	20	<1	<1.0	7,000	<6	23	2.8
G32	<1	44	3	<30	<1	<1.0	12,000	<18	<9	1.8
G33	<1	55	4	<10	<1	<1.0	13,000	<6	<3	.8
D4	<1	33	7	<30	1	<1.0	12,000	<18	<9	2.2
D5	<1	28	99	<10	2	<1.0	7,400	<6	23	1.2
D6	<1	14	5	<10	<1	<1.0	35,000	<6	120	3.5
D7	<1	38	9	<10	<1	<1.0	15,000	<6	23	1.4
D8	<1	27	7	<10	2	<1.0	21,000	<6	49	2.9
D9	<1	35	5	<30	<1	<1.0	22,000	<18	17	2.2
D10	<1	7	2	<30	<1	<1.0	5,000	<18	12	2.4
D11	<1	39	7	<10	<1	<1.0	27,000	<6	11	1.1
D12	<1	9	6	<10	<1	<1.0	980	<6	12	2.0
D13	<1	49	10	<30	<1	<1.0	19,000	<18	200	2.1

Table 2. Chemical and physical characteristics of ground water, Monroe County, Michigan, 1991-92--Continued

Well identifier	Sodium adsorption ratio	Analytical charge balance
G1	.4	7.5
G2	.2	6.1
G3	.5	6.3
G4	2.6	7.6
G5	.8	1.8
G6	.3	3.5
G7	1.3	-6.2
G8	1.0	-1.6
G9	.8	-3.5
G10	2.6	-2.7
G11	.3	-1.2
G12	.4	-2.2
G13	.1	2.5
G14	.9	-6.5
G15	.1	-4.5
G16	.2	1.4
G17	.3	3.0
G18	.2	-2.2
G19	.4	-5.4
G20	.5	.5
G21	.6	1.3
G22	.7	-2.2
G23	.7	-4.8
G26	.9	-12.0
G27	.4	4.7
G28	1.1	-2.3
G29	.1	.6
G30	.1	-6.4
G31	1.2	-3.9
G32	.1	6.7
G33	.3	-.3
D4	.1	5.8
D5	.1	1.8
D6	.9	6.0
D7	.4	9.1
D8	.4	-3.3
D9	.6	4.9
D10	.1	-93.0
D11	1.0	-2.0
D12	.1	3.1
D13	.1	-6.1

Table 3. Chemical and physical characteristics of surface water, Monroe County, Michigan, 1990-91

[Analyses by U.S. Geological Survey. Surface water sites shown on plate 1. mi², square miles; µS/cm, microsiemens per centimeter at 25 degrees Celsius; °C, degrees Celsius; mm of Hg, millimeters of mercury; NTU, nephelometric turbidity units; mg/L, milligrams per liter; --, no analyses done; <, less than; E, estimated.]

Site number	Station name	Drainage area (mi²)	Date	Discharge, cubic feet per second	Specific conductance (µS/cm)	pH field (standard units)	pH lab (standard units)	Temperature water (°C)	Barometric pressure (mm of Hg)	Turbidity (NTU)	Oxygen, dissolved (mg/L)
S1	Huron River at	866	07-02-90	437	690	8.4	--	25.0	--	--	8.5
	Flat Rock		08-08-90	102	664	8.6	7.9	24.0	751	11	9.2
S2	Swan Creek near	32	07-02-90	2.1	673	8.3	--	23.5	--	--	7.2
	Carleton		08-08-90	.14	770	8.2	7.8	20.5	751	20	7.0
S3	Stony Creek at	68	07-02-90	16	828	8.4	--	18.5	--	--	7.4
	Oakville		08-08-90	8.0	720	8.4	8.0	16.5	749	25	9.0
			07-24-91	7.8	708	8.3	8.2	20.0	746	4.0	7.8
S4	Saline River near	113	07-02-90	33	816	8.4	--	22.0	739	--	6.7
	Milan		08-08-90	22	809	8.2	7.9	19.5	748	43	7.1
S5	North Branch	44	07-02-90	2.5	735	8.3	--	18.0	747	--	8.4
	Macon Creek near		08-09-90	.19	592	8.3	8.0	18.0	--	4.4	8.1
	Azalia		09-10-91	E.05	--	7.7	7.7	23.0	747	3.3	5.6
S6	Macon Creek near	94	07-02-90	7.7	699	8.6	--	20.0	747	--	8.4
	Dundee at Ann		08-07-90	2.6	676	8.4	8.2	18.0	749	7.0	9.3
	Arbor Road		07-23-91	2.3	618	8.3	8.2	24.0	744	5.6	7.2
			09-10-91	3.9	--	7.4	7.9	22.0	746	9.0	7.0
			10-01-91	--	622	8.2	8.0	13.5	746	3.2	7.9
			10-01-91	--	--	--	8.0	--	--	2.8	--
S7	Saline River near	127	07-03-90	34	796	8.4	--	21.0	745	--	7.1
	Dundee		08-09-90	22	840	8.3	7.9	19.0	749	55	7.1
			07-24-91	22	901	8.2	8.2	21.0	746	45	7.0
			09-10-91	--	--	--	8.1	--	--	3.6	--
			09-10-91	24	794	8.2	8.0	21.5	745	34	6.5
			10-02-91	--	881	8.3	8.2	14.0	741	27	8.3
S8	Macon Creek near	144	07-02-90	16	705	8.4	--	22.5	746	--	8.9
	Dundee at Stowell		08-09-90	1.6	3,150	7.7	7.3	19.5	750	3.4	6.8
	Road		07-23-91	11	3,370	7.8	7.3	28.0	744	3.0	7.7
			09-10-91	3.1	1,610	8.0	7.6	22.0	747	4.5	7.0
			10-01-91	--	--	7.7	7.4	14.5	746	1.7	7.0

Table 3. Chemical and physical characteristics of surface water, Monroe County, Michigan, 1990-91--Continued

Site number	Station name	Drainage area (mi^2)	Date	Discharge, cubic feet per second	Specific conductance (µS/cm)	pH field (standard units)	pH lab (standard units)	Temperature water (°C)	Barometric pressure (mm of Hg)	Turbidity (NTU)	Oxygen, dissolved (mg/L)
S9	Swan Creek near Newport	81	07-02-90	4.0	765	7.8	--	24.0	--	--	4.3
			08-08-90	.41	1,230	7.9	7.7	23.5	751	12	6.8
			09-11-91	.71	1,040	7.8	7.7	19.0	752	17	3.3
S10	Stony Creek near Woodland Beach	121	06-27-90	25	644	8.3	--	20.0	745	--	7.0
			08-09-90	7.6	741	8.3	8.0	19.0	752	4.7	7.3
			07-23-91	4.8	697	8.2	8.2	26.5	746	3.5	8.7
			09-11-91	8.9	710	8.2	8.1	19.0	748	3.5	7.0
			10-01-91	--	695	9.1	8.2	18.0	748	2.2	10.0
			10-01-91	--	--	--	8.2	--		1.5	--
S11	Sandy Creek near Golfcrest	25	06-27-90	1.1	766	8.2	--	20.0	745	--	6.0
			08-08-90	--	1,290	7.9	7.7	22.0	--	3.5	10.2
			09-11-90	E.12	653	8.1	7.7	22.5	751	2.3	8.4
			09-11-91	.04	938	7.3	7.5	17.0	752	2.5	3.6
S12	River Raisin at Monroe	1,062	06-27-90	285	733	8.6	--	23.0	746	--	10.1
			08-08-90	141	657	8.6	7.9	23.0	751	11	11.0
S13	Plum Creek at Monroe	32	06-27-90	1.9	901	8.8	--	22.0	748	--	13.2
			08-07-90	.82	2,180	8.1	7.7	19.0	752	15	8.7
			07-23-91	3.3	2,190	8.0	7.8	24.0	746	1.1	9.7
			09-11-91	6.4	--	7.7	7.7	17.0	752	0.20	8.3
			10-02-91	--	2,080	8.5	7.7	15.5	744	1.3	8.3
S14	Plum Creek near Monroe	14	07-02-90	1.5	806	8.1	--	19.5	749	--	6.6
			08-07-90	.06	2,150	7.6	7.6	17.0	--	11	4.0
S15	Pitts Creek near Strasburg	11	07-02-90	1.9	855	8.0	--	19.0	749	--	7.1
			08-07-90	.28	2,730	7.9	7.7	18.5	--	5.1	5.0
S16	Little River Raisin near Dundee	42	07-03-90	9.2	674	8.5	--	28.0	743	--	15.6
			08-07-90	.77	545	8.6	8.0	27.0	748	10	11.0
			07-23-91	.44	504	8.8	8.5	33.5	743	9.3	11.0
			09-10-91	1.4	470	7.9	8.1	23.0	747	22	10.3
			09-10-91	--	--	--	8.1	--	--	27	--
			10-01-91	--	474	8.4	8.1	18.0	745	20	9.8
S17	River Raisin at Petersburg	701	07-03-90	321	614	8.3	--	22.5	745	--	7.0
			08-09-90	110	656	8.6	8.1	20.5	749	3.5	9.4
S18	Lockwood Drain near Ida Center	8	07-03-90	1.3	522	8.1	--	21.5	748	--	7.1
			08-08-90	.09	556	8.2	7.8	15.5	750	2.5	6.2

Table 3. Chemical and physical characteristics of surface water, Monroe County, Michigan, 1990-91--Continued

Site number	Station name	Drainage area (mi^2)	Date	Discharge, cubic feet per second	Specific conductance (µS/cm)	pH field (standard units)	pH lab (standard units)	Temperature water (°C)	Barometric pressure (mm of Hg)	Turbidity (NTU)	Oxygen, dissolved (mg/L)
S19	Otter Creek at Lasalle	51	06-27-90	4.3	560	8.8	--	25.0	748	--	10.6
			08-07-90	.34	651	8.2	7.8	22.5	--	3.5	10.0
			09-11-90	1.8	751	8.3	8.0	21.5	751	7.9	9.9
			07-24-91	.06	630	8.0	7.9	23.5	747	4.5	4.7
			09-11-91	.20	840	7.6	7.8	19.0	752	3.0	8.1
S20	Little Lake Creek near Erie	11	07-03-90	.18	673	8.0	--	19.0	748	--	5.9
			08-08-90	.02	661	7.9	7.6	19.0	--	10	10.8
			07-23-91	.01	--	8.1	7.9	27.5	745	13	8.3
			09-10-91	<.01	780	8.2	7.8	23.0	748	9.0	7.5
S21	Halfway Creek near Lambertville	34	07-02-90	.68	832	8.2	--	21.5	748	--	7.0
			08-08-90	1.0	845	8.3	8.1	17.0	--	2.4	8.8
			09-11-90	.84	899	8.1	8.0	19.5	752	4.5	7.0
			07-23-91	4.0	854	8.1	8.1	24.0	747	3.4	6.5
			09-10-91	.71	909	8.2	8.0	22.0	747	5.6	6.7
			10-01-91	--	924	8.2	8.0	13.0	749	2.5	8.0
S22	North Tenmile Creek near Whiteford Center	32	07-02-90	1.3	608	8.3	--	23.0	748	--	8.0
			09-10-91	.01	1,030	7.9	7.4	22.0	746	2.5	4.5
S23	Saline River near Saline	95	07-02-90	33	816	8.4	--	22.0	739	--	6.7
			07-03-90	28	821	8.3	--	19.5	743	--	7.6
			08-09-90	21	901	8.3	8.0	18.5	748	3.0	8.4
SLTO	River Raisin near Monroe	1,904	06-27-90	308	738	8.5	--	21.0	747	--	10.1
			08-08-90	153	708	8.6	7.8	25.0	749	15	10.7
			07-24-91	90	736	8.5	8.1	27.0	746	15	10.2
			10-02-91	95	725	--	8.0	17.0	742	5.5	9.0

Table 3. Chemical and physical characteristics of surface water, Monroe County, Michigan, 1990-91--Continued

Site number	Station name	Oxygen, dissolved (percent saturation)	Hardness total (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Alkalinity lab (mg/L as $CaCO_3$)	Sulfate, dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)
S1	Huron River at	--	--	--	--	--	--	--	46		--
	Flat Rock	111	230	61	20	39	3.6	179	48		.30
S2	Swan Creek near	--	--	--	--	--	--	--	61	60	--
	Carleton	79	290	88	18	35	7.6	192	67	80	<.10
S3	Stony Creek at	--	--	--	--	--	--	--	63	60	--
	Oakville	94	290	79	23	25	2.8	214	54	43	.30
		88	340	95	24	23	2.7	243	68	60	.10
S4	Saline River near	79	--	--	--	--	--	--	94	67	--
	Milan	79	330	90	26	40	3.8	222	85	74	.20
S5	North Branch	91	--	--	--	--	--	--	61	41	--
	Macon Creek near	--	270	68	24	19	7.5	195	69	44	.40
	Azalia	--	260	69	22	19	10	164	88	43	.20
S6	Macon Creek near	95	--	--	--	--	--	--	72	41	--
	Dundee at Ann	100	310	86	24	21	5.1	219	88	44	.20
	Arbor Road	88	280	74	24	15	4.2	191	92	36	.20
		--	280	74	23	16	5.3	188	83	33	.20
		78	290	77	24	14	5.1	206	95	35	.30
		--	290	78	24	15	5.1	206	96	36	.30
S7	Saline River near	82	--	--	--	--	--	--	95	68	--
	Dundee	78	330	91	26	44	4.0	225	86	81	.30
		81	370	100	30	47	4.4	261	100	87	.30
		--	330	89	26	46	4.8	236	93	78	.30
		76	340	90	27	44	4.9	223	91	76	.30
		83	370	100	28	41	4.6	227	100	83	.40
S8	Macon Creek near	105	--	--	--	--	--	--	68	37	--
	Dundee at Stowell	76	1300	440	37	59	5.6	59	--	95	.50
	Road	102	1200	440	25	56	460	43	1700	170	1.4
		82	600	200	25	34	170	110	670	75	.50
		--	1300	430	49	59	530	72	1600	190	1.4

Table 3. Chemical and physical characteristics of surface water, Monroe County, Michigan, 1990-91--Continued

Site number	Station name	Oxygen, dis-solved (percent satura-tion)	Hard-ness total (mg/L as $CaCO_3$)	Calcium, dis-solved (mg/L as Ca)	Magne-sium, dis-solved (mg/L as Mg)	Sodium, dis-solved (mg/L as Na)	Potas-ium, dis-solved (mg/L as K)	Alka-linity lab (mg/L as $CaCO_3$)	Sulfate, dis-solved (mg/L as SO_4)	Chloride, dis-solved (mg/L as Cl)	Fluoride, dis-solved (mg/L as F)
S9	Swan Creek near	--	--	--	--	--	--	--	85	75	--
	Newport, MI	82	480	130	38	61	8.2	183	300	110	.10
		36	380	100	31	59	8.6	182	210	100	.50
S10	Stony Creek near	79	--	--	--	--	--	--	64	47	--
	Woodland Beach	80	330	90	26	24	2.8	208	110	57	.40
		111	320	87	25	25	3.1	211	91	59	.20
		77	320	90	24	22	3.3	218	92	51	.20
		108	320	87	24	22	3.1	226	80	59	.20
		--	320	87	24	23	3.2	226	85	61	.20
S11	Sandy Creek near	68	--	--	--	--	--	--	110	70	--
	Golfcrest	--	540	150	41	65	4.3	149	380	120	.40
		99	280	79	19	33	4.5	144	110	59	.30
		38	430	120	31	46	3.9	154	260	71	.30
S12	River Raisin at	121	--	--	--	--	--	--	89	38	--
	Monroe	130	280	73	23	26	6.4	200	81	46	.30
S13	Plum Creek at	154	--	--	--	--	--	--	240	72	--
	Monroe	96	1,400	480	49	14	2.7	161	1,100	33	.80
		119	1,500	480	64	17	3.5	131	1,400	42	.80
		--	1,500	480	64	17	4.4	177	1,300	34	.90
		86	1,300	450	50	14	4.6	174	1,100	35	.90
S14	Plum Creek near	73	--	--	--	--	--	--	130	59	--
	Monroe	--	1400	390		49	4.5		1,000	92	.70
S15	Pitts Creek near	78	--	--	--	--	--	--	98	85	--
	Strasburg	--	1,800	510	120	49	5.1	204	1,500	100	.20
S16	Little River Raisin	205	--	--	--	--	--	--	62	43	--
	near Dundee	141	230	54	22	20	4.3	135	69	54	.20
		159	200	43	23	23	5.1	125	54	58	.20
		123	220	54	21	14	4.1	116	89	34	.20
		--	210	53	20	13	4.1	116	91	34	.20
		106	220	53	22	12	3.2	135	94	27	.20
S17	River Raisin at	83	--	--	--	--	--	--	46	30	--
	Petersburg	107	310	88	23	25	2.4	233	64	59	.10

Table 3. Chemical and physical characteristics of surface water, Monroe County, Michigan, 1990-91--Continued

Site number	Station name	Oxygen, dissolved (percent saturation)	Hardness total (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Alkalinity lab (mg/L as $CaCO_3$)	Sulfate, dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)
S18	Lockwood Drain	82	--	--	--	--	--	--	48	48	--
	near Ida Center	63	200	54	15	32	4.6	151	34	70	.10
S19	Otter Creek at	131	--	--	--	--	--	--	65	45	--
	Lasalle	--	270	71	22	25	3.8	123	130	59	.20
		114	290	82	20	34	6.2	164	93	84	.20
		57	260	68	22	23	4.7	114	140	52	.20
		89	360	98	28	39	6.9	144	190	87	.20
S20	Little Lake Creek	65	--	--	--	--	--	--	60	55	--
	near Erie	--	280	82	19	24	5.5	231	39	60	<.10
		--	300	85	22	24	7.5	238	38	58	.20
		89	370	89	36	18	3.2	195	150	56	.20
S21	Halfway Creek	81	--	--	--	--	--	--	180	47	--
	near Lambertville	--	400	110	30	14	2.5	226	200	34	.30
		77	440	120	35	16	3.4	230	230	35	.30
		79	480	130	37	15	3.2	224	240	38	.50
		78	440	120	35	18	3.4	213	240	35	.50
		77	470	130	36	12	4.0	234	250	33	.60
S22	North Tenmile	95	--	--	--	--	--	--	49	55	--
	Creek near Whiteford Center	53	420	140	18	34	4.9	98	340	79	.20
S23	Saline River near	79	--	--	--	--	--	--	94		--
	Saline	85	--	--	--	--	--	--	100		--
		92	370	100	28	36	3.5	262	83		.20
SLTO	River Raisin near	116	--	--	--	--	--	--	99	39	--
	Monroe	132	310	85	24	28	8.6	206	100	52	.20
		131	320	87	24	28	13	198	100	51	.30
		96	300	84	23	27	9.4	215	90	56	<.10

Table 3. Chemical and physical characteristics of surface water, Monroe County, Michigan, 1990-91--Continued

Site number	Station name	Silica, dissolved (mg/L as SiO_2)	Solids, residue at 180°C dissolved (mg/L)	Nitrogen, nitrite, dissolved (mg/L as N)	Nitrogen, NO_2+NO_3, dissolved (mg/L as N)
S1	Huron River at	--	--	.03	.6
	Flat Rock	6.0	387	.02	.4
S2	Swan Creek near	--	--	.020	1.30
	Carleton	6.1	479	.020	.700
S3	Stony Creek at	--	--	.010	.800
	Oakville	4.5	412	<.010	.400
		10	411	<.010	.510
S4	Saline River near	--	--	.020	1.90
	Milan	9.1	495	.020	1.70
S5	North Branch	--	--	.030	3.50
	Macon Creek near	0.80	355	<.010	.300
	Azalia	1.6	345	<.010	.120
S6	Macon Creek near	--	--	.010	3.60
	Dundee at Ann	3.4	377	.010	1.00
	Arbor Road	2.4	345	<.010	.240
		2.5	335	<.010	.160
		1.5	366	<.010	<.050
		1.6	378	<.010	<.050
S7	Saline River near	--	--	.010	1.90
	Dundee	9.3	515	<.010	1.80
		11	516	.020	4.70
		11	480	.010	1.60
		10	483	.010	1.60
		10	558	<.010	2.10
S8	Macon Creek near	--	--	.030	3.50
	Dundee at Stowell	4.0	2,820	<.010	.200
	Road	5.0	2,780	.010	.150
		6.3	1,240	.020	.570
		6.7	3,030	.020	.260

Table 3. Chemical and physical characteristics of surface water, Monroe County, Michigan, 1990-91--Continued

Site number	Station name	Silica, dissolved (mg/L as SiO_2)	Solids, residue at 180°C dissolved (mg/L)	Nitrogen, nitrite, dissolved (mg/L as N)	Nitrogen, NO_2+NO_3, dissolved (mg/L as N)
S9	Swan Creek near	--	--	.090	2.00
	Newport	5.2	782	.200	1.70
		1.9	638	.240	1.80
S10	Stony Creek near	--	--	.010	1.30
	Woodland Beach	5.7	445	<.010	.300
		6.5	411	<.010	.140
		7.6	415	<.010	.240
		5.8	403	<.010	<.050
		5.8	426	<.010	<.050
S11	Sandy Creek near	--	--	.030	2.50
	Golfcrest	4.9	906	<.010	<.010
		4.4	431	<.010	<.010
		5.4	631	.030	.280
S12	River Raisin at	--	--	.010	1.70
	Monroe	4.8	392	<.010	<.100
S13	Plum Creek at	--	--	.020	1.40
	Monroe	8.5	2,020	<.010	<.100
		9.1	2,050	.020	.430
		8.9	2,130	.110	1.40
		8.3	2,000	.070	1.00
S14	Plum Creek near	--	--	.030	4.10
	Monroe	11	1920	<.010	<.100
S15	Pitts Creek near	--	--	.070	6.10
	Strasburg	11	2,560	.030	.600
S16	Little River Raisin	--	--	.060	7.80
	near Dundee	2.0	380	.010	<.100
		6.7	276	<.010	<.050
		1.7	275	.010	.066
		1.7	280	<.010	<.059
		.30	272	<.010	<.050
S17	River Raisin at	--	--	.070	5.60
	Petersburg	8.8	426	<.010	.600

Table 3. Chemical and physical characteristics of surface water, Monroe County, Michigan, 1990-91--Continued

Site number	Station name	Silica, dissolved (mg/L as SiO_2)	Solids, residue at 180°C dissolved (mg/L)	Nitrogen, nitrite, dissolved (mg/L as N)	Nitrogen, NO_2+NO_3, dissolved (mg/L as N)
S18	Lockwood Drain	--	--	.010	1.00
	near Ida Center	2.6	334	<.010	<.100
S19	Otter Creek at	--	--	.020	1.60
	Lasalle	2.8	424	<.010	<.100
		4.6	447	<.010	.400
		5.4	376	<.010	.170
		2.6	552	<.010	.082
S20	Little Lake Creek	--	--	.030	1.10
	near Erie	7.9	386	.010	<.100
		3.7	375	<.010	<.050
		5.3	479	.030	.030
S21	Halfway Creek	--	--	.030	.800
	near Lambertville	9.3	592	<.010	.300
		9.2	612	<.010	.300
		9.2	593	.010	.580
		9.4	590	.020	.380
		8.1	611	.010	.190
S22	North Tenmile	--	--	.030	2.60
	Creek near White-	3.5	692	.030	.230
	ford Center				
S23	Saline River near	--	--		
	Saline	--	--	.02	1.7
		11	544	.02	1.9
SLTO	River Raisin near	--	--	.020	1.70
	Monroe	5.3	442	<.010	.400
		8.1	424	.010	.260
		6.6	423	<.010	.820

GLOSSARY

Absorption. The entrance of water into the soil or rocks by all natural processes. It includes infiltration of precipitation or snowmelt, gravity flow of streams into the valley alluvium into sinkholes or other large openings, and the movement of atmospheric moisture.

Acre-foot. A unit for measuring the volume of water, is equal to the quantity of water required to cover 1 acre to a depth of 1 foot and is equal to 43,560 cubic feet or 325,851 gallons. The term is commonly used in measuring volumes of water used or stored.

Alluvium. A general term for clay, silt, sand, gravel, or similar unconsolidated material, deposited during comparatively recent geologic time by a stream or other body of running water, as a sorted or semisorted sediment in the bed of the stream or on its flood plane or delta.

Anisotropic. Having some physical property that varies with direction. All crystals are anisotropic relative to some properties, e.g. propagation of sound waves.

Anthropogenic. Relating to, or influenced by the impact of humans on nature.

Aquifer. A geologic formation, group of formations or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

Aquifer test. An aquifer test is a controlled field experiment to determine the hydraulic properties of waterbearing and associated rocks. The test is made by observing ground-water flow produced by known hydraulic boundary conditions, such as variations of head along a connected stream, pumping wells, changes in weight imposed on the land surface, or changes in recharge.

Average discharge. In the annual series of the Geological Survey's reports on surface-water supply--the arithmetic average of all complete water years of record whether or not they are consecutive. Average discharge is not published for less than 5 years of record. The term "average" is generally reserved for average of record and "mean" is used for averages of shorter periods, namely, daily mean discharge.

Baseflow. Sustained or fair-weather flow of a stream, whether or not affected by the works of humans.

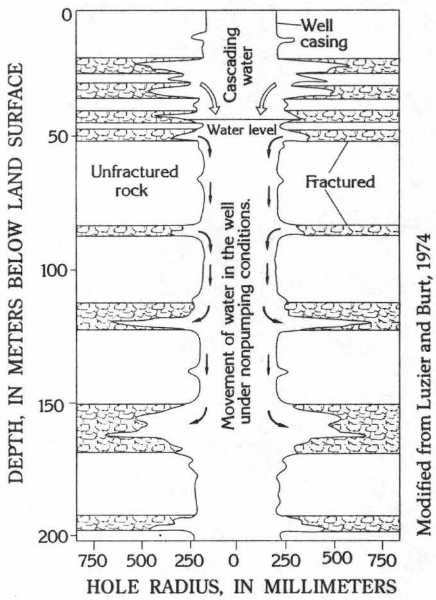
Bedrock. General terms for consolidated (solid) rock that underlies soils or other unconsolidated material.

Box plot. A type of graph describing the characteristics of a single group of data. The graph consists of a box showing the median and the middle half of the data, and lines extending from the box showing values outside the middle half of the data.

Carbonate [mineral]. A mineral compound characterized by a fundamental anionic structure of CO_3^{-2}.

Carbonate {rock}. Rock consisting chiefly of carbonate minerals, such as limestone or dolomite. A sedimentary rock composed of more than 50 percent by weight of carbonate minerals.

Cascading water. Ground water that falls from a fracture that is above the water level in a well.



Cation. An ion having a positive charge. Cations in a liquid subjected to electric potential collect at the negative pole or cathode.

Coliform bacteria. Group of several types of bacteria that are found in the alimentary tract of warm-blooded animals. The bacteria commonly are used as an indicator of animal and fecal contamination of water.

Concentration. The ratio of the quantity of any substance present in a sample of a given volume or a given weight compared to the volume or weight of the sample.

Confining bed. A layer of rock having very low hydraulic conductivity that hampers the movement of water into and out of an aquifer.

Constituent. A component such as a chemical species or biological population whose magnitude in water, sediment, biota, or other matrix is determined by an analytical method.

Contributing area. The area in a drainage basin that contributes water to streamflow or recharge to an aquifer.

Correlation. The process of establishing a relation between a variable and one or more related variables. Correlation is simple if there is only one independent variable; multiple, if there is more than one independent variable. For gaging station records, the usual variables are the short-term gaging-station records.

Dedolomization. Replacement of dolomite by calcite during diagenesis or chemical weathering.

Delta value. The difference between the isotope ratio in a sample and that in a standard, divided by the ratio in the standard expressed as parts per thousand

Direct runoff. The runoff entering stream channels promptly after rainfall or snowmelt. Superposed on base runoff, it forms the bulk of the hydrography of a flood. The terms base runoff and direct runoff are time classifications of runoff.

Discharge. In its simplest concept discharge means outflow; therefore, the use of this term is not restricted as to course or location, and it can be applied to describe the flow of water from a pipe or from a drainage basin. If the discharge occurs in some course or channel, it is correct to speak of the discharge of a canal or of a river. It is also correct to speak of the discharge of a canal or stream into a lake, a stream, or an ocean. The data in the reports of the Geological Survey on surface water represent the total fluids measured. Thus, the terms discharge, streamflow, and runoff represent water with the solids dissolved in it an the sediment mixed with it. Of these terms, discharge is the most comprehensive.

Domestic water use. Water used for household purposes, such as drinking, food preparation, bathing, washing clothes and dishes, flushing toilets, and watering lawns and gardens. Also called residential water use. The water can be obtained from a public supply or be self-supplied.

Drainage area. The drainage area of a stream at a specified location is that area, measured in a horizontal plane, which is enclosed by a drainage divide.

Drainage basin. A part of the surface of the earth that is occupied by a drainage system, which consists of a surface stream or a body of impounded surface water together with all tributary surface streams and bodies of impounded surface water.

Drought. Commonly defined as being a time of less-than-normal or expected rainfall; depending on the effect and cause, may be characterized as agricultural, hydrological, meteorological, or sociological:

- **Agricultural**. A shortage of water in the root zone of plants such that plant yield is reduced considerably.
- **Hydrological**. An extended period during which streamflow, lake and reservoir storage, and ground-water levels are below normal.
- **Meteorological**. An extended period during which precipitation is below normal.
- **Sociological**. Meteorologic and hydrologic conditions under which less water is available than is anticipated and relied on for the normal level of social and economic activity of a region.

Evaporation. The process by which water is changed from the liquid or the solid state into the vapor state. In hydrology, evaporation is vaporization that takes place at a temperature below the boiling point.

Flow-duration curve. A cumulative frequency curve that shows the percentage of time that specified discharges are equaled or exceeded.

Gaging station. A particular site on a stream, canal, lake or reservoir where systematic observations of gage height or discharge are obtained.

Glacial drift. A general term applied to all materials transported by a glacier and deposited directly by the ice or by running water emanating from a glacier. Includes unstratified material and stratified material.

Glaciofluvial. Pertaining to the meltwater streams flowing from wasting glacier ice and esp. to the deposits and landforms produced by such streams.

Glaciolacustrine. Pertaining to, derived from, or deposited in glacial lakes; esp. said of the deposits and landforms composed of suspended material brought by meltwater steams flowing into lakes bordering the glacier.

Ground water. Water in the ground that is in the zone of saturation, from which wells, springs, and ground-water runoff are supplied.

Ground-water outflow. That part of the discharge from a drainage basin that occurs through the ground water. The term "under-flow" is often used to describe the ground-water outlfow that takes place in valley alluvium and thus is not measured as a gaging station.

Hardness [water]. A property of water that causes the formation of an insoluble residue when the water is used with soap and a scale in vessels in which water has been allowed to evaporate. It is due primarily to the presence of ions of calcium and magnesium. Generally expressed as milligrams per liter as calcium carbonate ($CaCO_3$).

A general hardness scale is:

Description	Milligrams per liter as $CaCO^3$
Soft	0-60
Moderately hard	61-120
Hard	121-180
Very hard	more than 180

Hydrograph. A graph showing state, flow, velocity, or other property of water with respect to time.

Hydraulic conductivity. The capacity of a rock to transmit water. It is expressed as the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

Hydraulic gradient. Change in head per unit of distance measured in the direction of the steepest change.

Infiltration. The flow of a fluid into a substance through pores or small openings.

Isotope. One of two or more species of the same chemical element, i.e. having the same number of protons in the nucleus, but differing from one another by having a different number of neutrons. The isotopes of an element have slightly different physical and chemical properties, owing to their mass differences, by which they can be separated.

Karst. A type of topography that results from dissolution and collapse of limestone, dolomite, or gypsum bed and is characterized by closed depressions or sinkholes, caves, and underground drainage.

Lithologic. The gross physical character of a rock. The microscopic study, description, and classification of rock.

Maximum contaminant level (MCL). Maximum permissible level of a contaminant in water that is delivered to any user of a public water system, established by a regulatory agency such as the U.S. Environmental Protection Agency. These contaminants affect the health of people drinking the water; therefore, the levels are enforceable.

Mean. The arithmetic mean of a set of observations, unless otherwise specified; an average of quantity.

Median. The middle item when items are arranged according to rank; an average of positions.

Molar. A concentration in which 1 molecular weight in grams (1 mole) of a substance is dissolved in enough solvent to make 1 liter of solution.

Observation well. A special well drilled in a selected location for the purpose of observing parameters such as fluid levels and pressure changes.

Palmer drought-severity index. Method of computing drought severity as a monthly index that indicates the severity of a wet or dry period, based on a balance between moisture supply and demand.

Peak stage. The maximum height of a water surface above an established datum plane. Same as peak gage height.

Permeability. The capacity of a rock for transmitting a fluid; a measure of the relative ease of fluid flow in a porous medium.

Petroliferous. Bearing crude oil or natural gas. The term may be applied to a province, geologic structure, or a geologic formation or unit.

Porosity. The ratio of the volume of the voids in a rock to the total volume, expressed as a decimal fraction or as a percentage. The term "effective porosity" refers to the amount of interconnected pore spaces or voids in a rock or in soil and it is expressed as a percentage of the total volume occupied by the interconnecting pores.

Potable water. Water that is safe and palatable for human consumption.

Potentiometric surface. An imaginary surface representing the total head of ground water and defined by the level to which water will rise in a well. The water table is a particular potentiometric surface.

Public supply. Water withdrawal for all uses by public and private water supplies are delivered to users that do not supply their own water. Water supplies provide water for a variety of uses, such as domestic, commercial, thermoelectric power, industrial, and public water use.

Quartile. The value of the boundary at the 25th, 50th, or 75th percentiles of a frequency distribution divided into four parts, each containing a quarter of the population.

Recharge (ground water). An area in which water infiltrates the ground and reaches the saturated zone.

Redox. Short form of term oxidation-reduction, as in redox reactions, redox conditions, etc.

Runoff. That part of water yield that appears in streams.

Saturated zone. A subsurface zone in which all the interstices or voids are filled with water under pressure greater than that of the atmosphere.

Sea level. Long-term average position of the sea surface. Sea level varies from place to place and with the time period for which the average is calculated. In this report with respect to the conterminous United States, it refers to the National Geodetic Vertical Datum of 1929.

Secondary maximum contaminant level (SMCL). Maximum recommended level of a contaminant in the water that is delivered to any user of a public water system. These contaminants affect the esthetic quality of the water such as odor or appearance; therefore, the levels are intended as guidelines.

Sedimentary rock. Rock resulting from the accumulation of sedimentary particles in layers either mechanically, by precipitation from solution, or from the remains or secretions of plants and animals. Sedimentary rocks constitute one of the three main classes into which all rocks are divided.

Sinkhole. A circular depression in a karst area. Its drainage is subterranean, its size is measured in meters or tens of meters, and it is commonly funnel- shaped.

Standard deviation. Statistical measure of the dispersion or scatter of a series of values, such as streamflow and precipitation. It is the square root of the variance, which is calculated as the sum of the squares of the deviations from the arithmetic mean, divided by the number of values in the series minus one.

Stoichiometry. With reference to a compound or a phrase, pertaining to the exact proportions of its constituents specified by its chemical formula.

Stream. A general term for a body of flowing water. In hydrology, the term is generally applied to the water flowing in a natural channel as distinct from a canal. More generally as in the term steam gaging, it is applied to the water flowing in any channel, natural or artificial.

Gaining reach of a stream. A stream or reach of a stream that receives water from the zone of saturation

Losing reach of a stream. A stream or reach of a stream that contributes water to the zone of saturation.

Steam-gaging station. A gaging station where a record of discharge of a steam is obtained. Within the Geological Survey this term is used only for those gaging stations where a continuous record of discharge is obtained.

Subcrop. An occurrence of strata in contact with the undersurface of an inclusive stratigraphic unit that succeeds an important unconformity on which overstep is conspicuous, a "subsurface outcrop" that describe the areal limits of a truncated rock unit a buried surface of unconformity.

Surface runoff. That part of the runoff which travels over the soil surface to the nearest steam channel. It is also defined as that part of the runoff of a drainage basin that has not passed beneath the surface since precipitation. The term is misused when applied in the sense of direct runoff.

Transmissivity. The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of an aquifer under a unit hydraulic gradient. It equals the hydraulic conductivity multiplied by the aquifer thickness.

Unconsolidated material. A sediment that is loosely arranged or unstratified, or whose particles are not cemented together, occurring either at the surface or at depth.

Vugs. A small cavity in a vein or in rock, usually lined with crystals of a different mineral composition from the enclosing rock.

Water year. In Geologic Survey reports dealing with surface-water supply, the 12-month period, October 1 through September 30. The water year is designated by the calendar year in which it ends and which includes 9 of the 12 months. Thus, the year ended September 30, 1992, is called the "1992 water year."

Weighted mean. A value obtained by multiplying each of a series of values by its assigned weight and dividing the sum of these products by the sum of the weights. In the ordinary arithmetic mean, each value is assigned a weight of 1.

Well log. A graphic record of the measured or computed physical characteristics of the rock section encountered in a well plotted as a continuous function of depth.

APPENDIX 1:

Borehole Geophysical Logs

Figures 1-5. Graphs showing:

Electrical resistivity and natural-gamma radiation are physical properties of rocks and unconsolidated sediments that are commonly measured in boreholes. Electrical- resistivity properties are a function of a number of factors including the degree of water saturation (porosity), specific conductance of pore fluids, and the amount electrically-conductive mineral phases (layer silicates, sulfides, and so forth) present in the rock or sediment matrix. A change of any of these factors results in a change in electrical resistivity. In places where the geologic materials are water saturated and the specific conductance of pore fluid is relatively constant, electrical resistivity is generally a function of the physical properties of rock or sediment. Natural-gamma radiation is emitted during decay of radiogenic minerals. The amount of gamma radiation emitted is a function of mineral constituents and the amount of radiogenic mineral(s) present in rock or sediment matrix. When used conjunctively, gamma-ray and electrical-resistivity logs can be used to assist in the delineation of contacts of different lithologies and in the identification of rock type and related physical properties.

Natural Gamma-ray and electrical-resistivity logs (16-in. and 64-in. normal resistivity) were run in seven of the 33 boreholes drilled by the U.S. Geological Survey in Monroe County, Mich. (well numbers G6, G21, G22, G23, G24, G25, and G27). The 16-in. and 64-in. normal resistivity logs are virtually the same for each site, so only the 64 in. normal resistivity logs are included with this report to avoid redundancy (figs. A1-A5). Vertical profiles of specific conductance were measured of ground water in boreholes at three sites (G6, G22, and G27) under static conditions and during pumping. The objectives were to provide data (1) to assist in the interpretation of hydrogeology of Silurian and Devonian rock units in the study area, (2) to determine if water quality differs as a function of formation or rock type, (3) to determine if water quality is variable as a function of depth, and (4) to determine if permeable intervals (either high matrix porosity or fractured zones) contributing ground water to wells during pumping could be delineated.

Five boreholes near Petersburg, Mich. (well numbers G21 through G25, fig. A2-A5) were logged to determine the degree of stratigraphic continuity and hydrogeologic heterogeneity of the Detroit River carbonate aquifer and overlying glacial deposits at the scale of several square miles. Gamma-ray and electrical-resistivity logs show that the same general stratigraphic sequence is present at each of the five sites logged. Glacial sand (11 to 17 ft) overlies a clay-dominant confining unit (glacial till) that ranges from 30 to 40 ft in thickness. Drillers' logs indicate that a 5- to 10-ft-thick aggregate of gravel, clay, limestone clasts, and (or) broken limestone is present between glacial deposits and bedrock; it is not possible to verify the presence of this mixture of lithologies on the basis of geophysical-log data. Geophysical logs at all sites in the Petersburg State Game Area indicate that a 2- to 3-ft-thick shale bed is present a few feet below the zone of mixed lithologies that is reported on drillers' logs. At four of the five sites (all boreholes except G22), geophysical logs show that high resistivity (greater than 1,100 to 1,600 ohm-m), low porosity, massive carbonate unit overlies a lower resistivity (750 to 1,100 ohm-m) and probably higher porosity carbonate unit. Vertical profiles of specific conductance measured of ground water before and during pumping (approximately 12 gal/min) show that mineralization of water changes as a function of depth. Water quality changes abruptly at 71 ft below land surface. Ground water has a higher specific conductance below this depth and, consequently, a higher dissolved-solids concentration. The difference in specific conductance of ground water above and below 71 ft is small (approximately 75 uS/cm).

Geophysical logs run at two sites where the uncased, open interval of borehole exceeds 135 ft illustrate lithologic contrasts of geologic units of the study area. At one site (Exeter Township, well number G6), approximately 60 ft of limestone (Amherstburg Formation) overlies intercalated sandstone, sandy limestone, and limestone (Sylvania Sandstone). Electrical resistivities of sandstones range from 400 to 500 ohm-m, generally higher than electrical resistivities of sandstone aquifers in other areas of the Michigan Basin (general range of freshwater-bearing Pennsylvanian and Mississippian sandstones is 115 to 400 ohm-m; see Westjohn, 1989). Limestones seem to have substantially higher porosities at this site than at other areas because electrical resistivities are substantially lower (500 to 800 ohm-m). Vertical profiles of specific conductance of ground water measured before and during pumping at the Exeter Township site show that water quality is homogeneous over the entire open interval of the borehole.

The deepest borehole drilled by the U.S. Geological Survey is in Summerfield Township (well number G27, 208 ft in depth). Electrical-resistivity and gamma-ray logs of this borehole indicate that very clean Sylvania Sandstone (approximately 40 ft) overlies an intercalated sequence of shale and massive carbonate (Bass Islands Dolomite). Electrical resistivities of carbonate strata underlying the Sylvania Sandstones are high (1,000 to 2,500 ohm-m) indicating that porosity is low and that fractures, if present, are minor. Vertical profiles of specific conductance measured during pumping indicate that ground water in the Sylvania Sandstone has a higher dissolved solids concentration than ground water in underlying carbonates. It also appears that ground water with the lowest dissolved-solids concentration enters the well during pumping from a zone above the Sylvania Sandstone, either from carbonates that overlie the sandstone sequence, or possibly from leakage from the surficial glacial deposits.

Discrete fracture zones contributing ground water to wells could not be identified on the basis of vertical profiles of specific conductance measured during pumping. Differences in specific conductance measured during pumping are small (less than 100 uS/cm), and it was not possible to determine if local fractures contribute water with different dissolved-solids concentrations. Water quality does differ as a function of depth at two of the sites where vertical profiles of specific conductance were measured. As mentioned previously, dissolved solids concentrations increase with depth at one site (Petersburg State Game Area), but the inverse situation was also observed (well number G27). Differences in water quality seem to be stratigraphically controlled, indicating that ground water may be compartmentalized into different geologic units. Geophysical logs also show that stratigraphic continuity is mappable at least at the local scale (Petersburg area). Drillers' logs provide fairly accurate general descriptions of lithologies; however, geophysical logs show that hydrogeology is more complex than drillers' logs indicated. For example, shale beds that probably function as confining units are clearly present in some areas, although these lithologies are not reported on drillers' logs at all sites where geophysical logs show they are present.

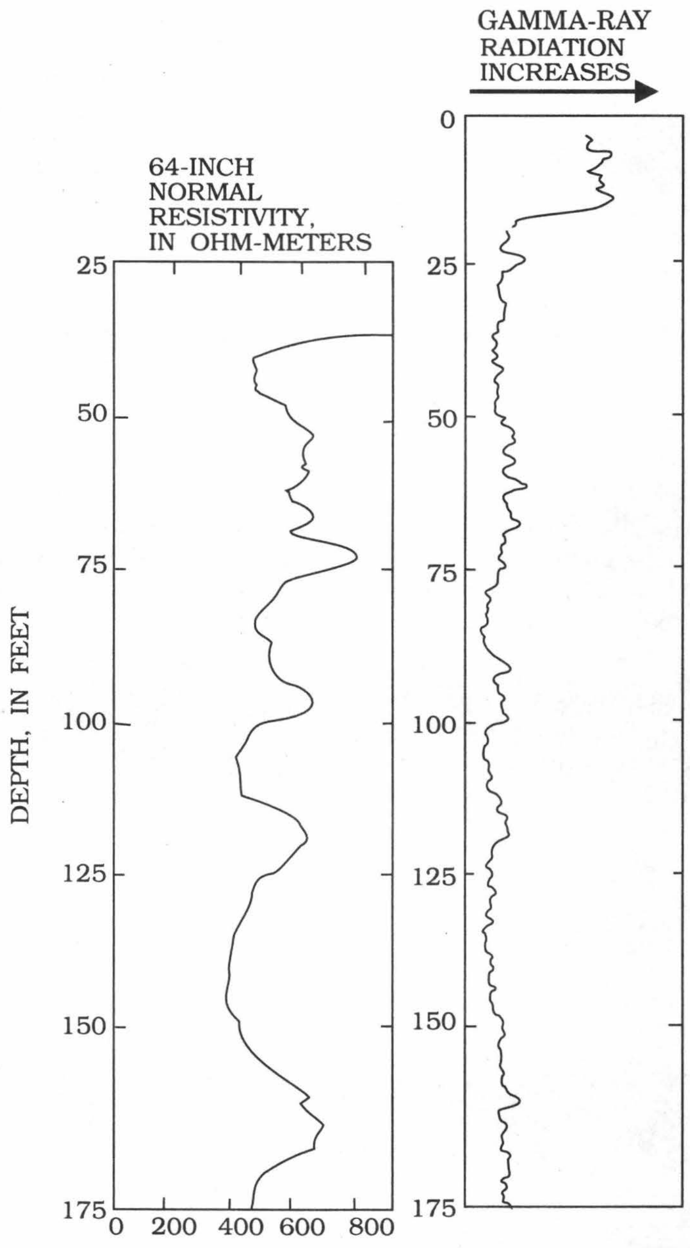


Figure 1. Electrical-resistivity and gamma-ray logs for well G6, Monroe County, Michigan.

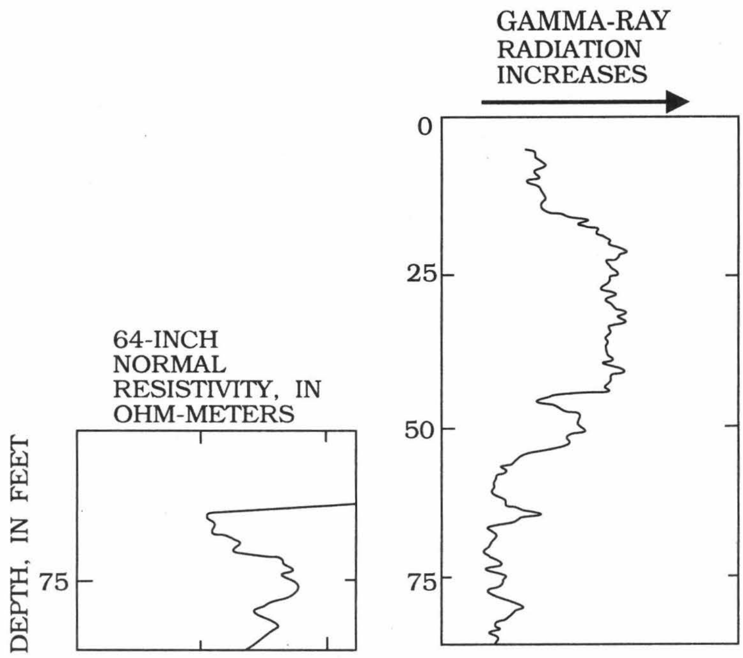


Figure 2. Electrical-resistivity and gamma-ray logs for well G22, Monroe County, Michigan.

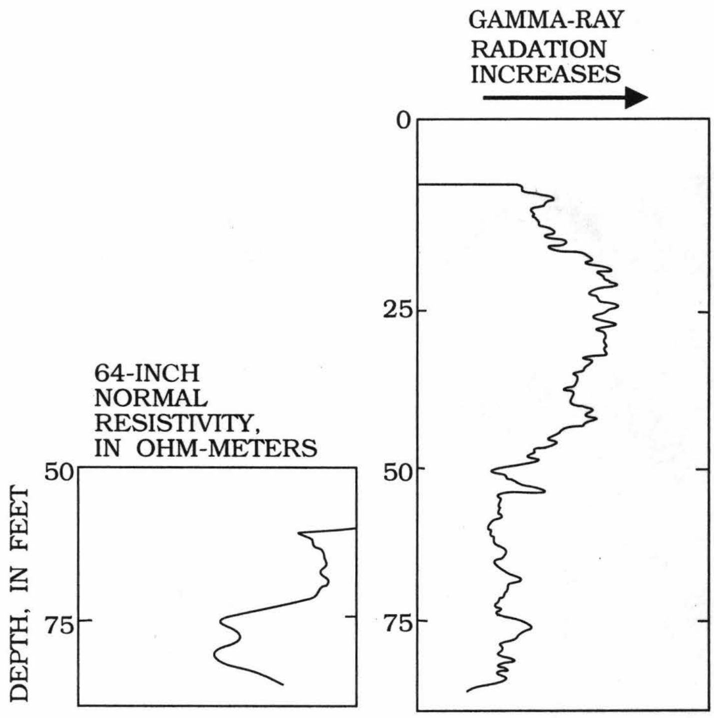


Figure 3. Electrical-resistivity and gamma-ray logs for well G24, Monroe County, Michigan.

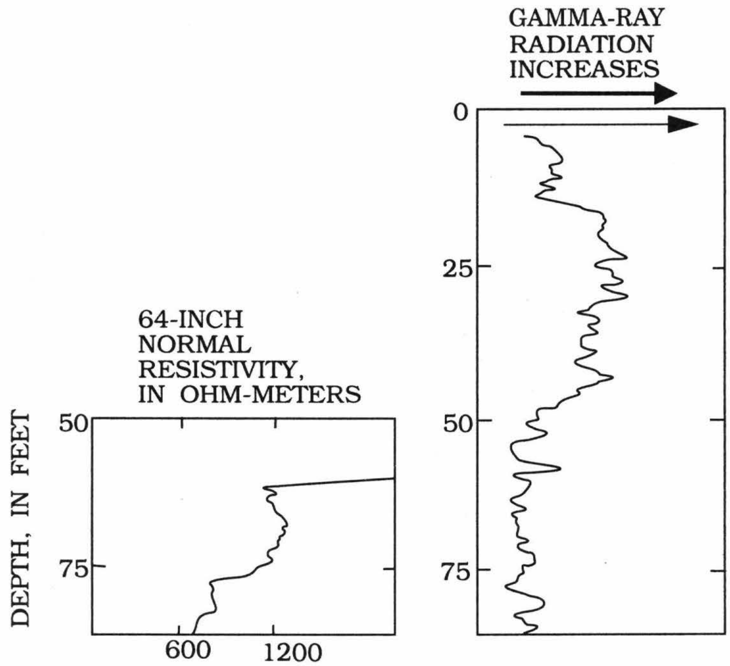


Figure 4. Electrical-resistivity and gamma-ray logs for well G25, Monroe County, Michigan.

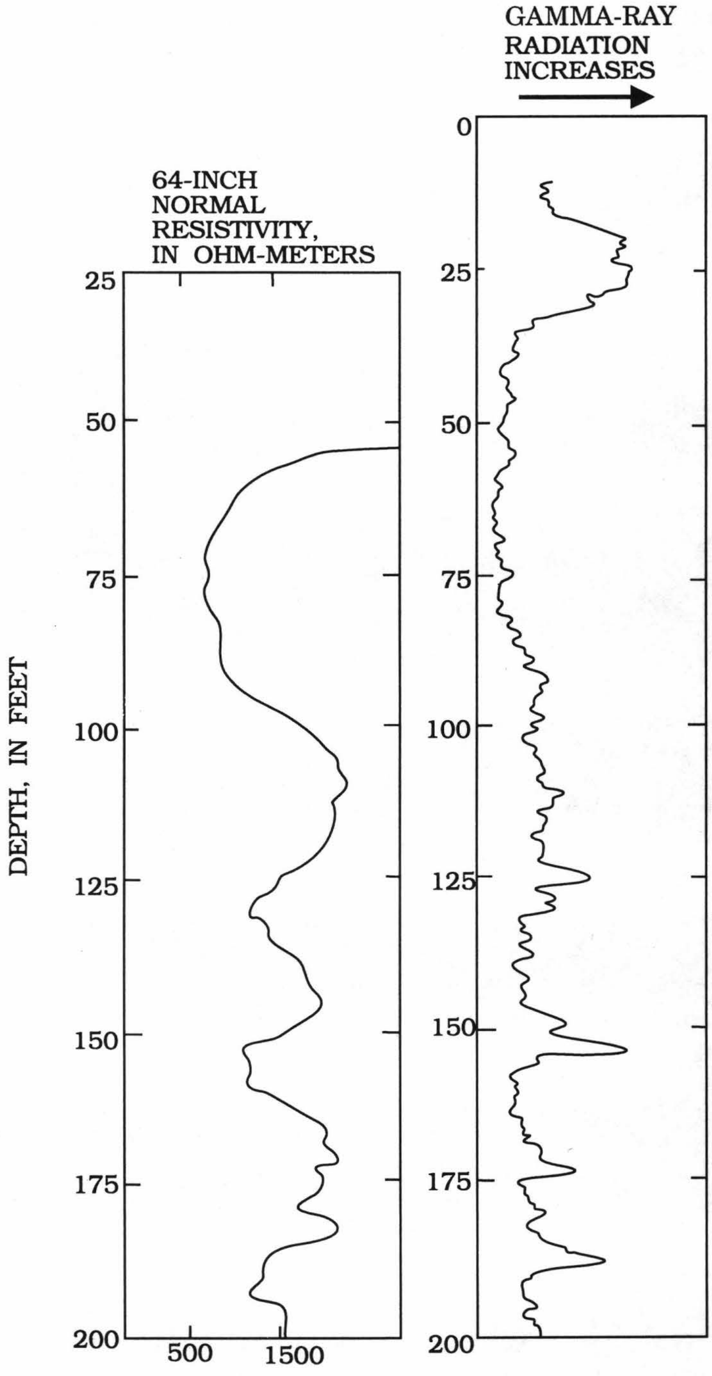


Figure 5. Electrical-resistivity and gamma-ray logs for well G27, Monroe County, Michigan.

APPENDIX 2:

Lithologic Logs

Well: G1

Location: NW1/4, NE1/4, NW1/4 of Section 26, T. 5 S., R. 10 E., Berlin Township, Monroe County, Michigan. Southeast corner of intersection of Sigler Road and U.S. Turnpike.

Elevation: 575 feet above sea level.

	Thickness (feet)	Depth (feet)
Glacial deposits:		
Clay - yellowish-brown to dark-yellow; calcareous.	9	9
Clay - medium-gray, calcareous; some gravel.	3	12
Clay - medium-gray, sandy.	12	24
Bedrock:		
Sandstone - white to light-gray, fine-grained, friable, calcareous; interbedded with dark-gray limestone.	10	34
Limestone - medium- to light-gray, microcrystalline, sandy, dolomitic, vuggy; interbedded with dark-gray microcrystalline limestone, brown sandy dolomite, and sandstone.	6	40
Limestone - medium- to light-gray, microcrystalline, sandy, dolomitic, fossiliferous, vuggy; interbedded with dark-gray microcrystalline limestone, brown sandy dolomite, and sandstone.	3	43
Limestone - gray, microcrystalline, dolomitic, fossiliferous, vuggy; interbedded with light-gray microcrystalline limestone, brown sandy dolomite, and sandstone; celestite and fracture at 44 feet.	7	50

Well: G2

Location: SE1/4, SW1/4 of Section 31, T. 5 S., R. 10 E., Berlin Township, Monroe County, Michigan. Berlin Township Park on west side of Brandon Road.

Elevation: 592 feet above sea level.

	Thickness (feet)	Depth (feet)
Glacial deposits:		
Clay- yellow.	12	12
Clay and gravel- gray.	11	23
Bedrock:		
Limestone - fractured.	2	25
Dolomite - light- to medium-gray, mottled, microcrystalline, occasionally laminated to shaley; interbedded with darker dolomite; porous zone at 32 to 34 feet.	35	60

Well: G3

Location: SW1/4, NW1/4, SW1/4 of Section 1, T. 5 S., R. 9 E., Ash Township, Monroe County, Michigan. Evergreen Cemetery northeast of Port Creek Road.

Elevation: 605 feet above sea level.

	Thickness (feet)	Depth (feet)
Glacial deposits:		
Clay - dark-yellow, slightly calcareous.	10	10
Clay - medium-gray, calcareous.	4	14
Clay - medium-gray, calcareous.	10	24
Till - medium- to dark-gray, calcareous.	6	30
Bedrock:		
Limestone - sandy.	8	38
Dolomite - light- to medium-gray, microcrystalline, stylolitic, vuggy, fractured; sandy in part.	17	55
Dolomite - medium-gray, microcrystalline, massive, vuggy; interbedded with dark-gray to black shale.	5	60
Sandstone - white to light-gray, well-sorted, fine-grained, slightly calcareous.	25	85

Well: G4

Location: SW1/4, NE1/4, NE1/4, Section 17, T. 5 S., R. 9 E., Ash Township, Monroe County, Michigan. Ash Street Cemetery in Carleton, Michigan.

Elevation: 615 feet above sea level.

		Thickness (feet)	Depth (feet)
Fill:			
	Muck and fill.	7	7
Glacial deposits:			
	Till - medium-gray, poorly sorted, calcareous; coarsening downward.	27	34
Bedrock:			
	Sandstone - white to light-gray, well-sorted, friable, calcareous, fractured, pyritic; fracture at 50 feet.	31	65

Well: G5

Location: SW1/4, SW1/4, SE1/4 of Section 2, T. 5 S., R. 8 E., Exeter Township, Monroe County, Michigan. One mile west of Carleton West Road on Colf Road

Elevation: 629 feet above sea level.

	Thickness (feet)	Depth (feet)
Glacial deposits:		
Clay - yellow.	13	13
Clay - gray, mixed with sand.	22	35
Sand and gravel.	1	36
Bedrock:		
Limestone - tan, fractured from 44 to 45 feet.	18	54
Limestone - tan, sandy, fractured from 67 to 68 feet.	16	70
Limestone - gray, sandy, fractured from 73 feet.	6	76
Limestone - tan.	4	80

Descriptions are based on the driller's log.

Well: G6

Location: NE1/4, SE1/4, NE1/4 of Section 29, T. 5 S., R. 8 E., Exeter Township, Monroe County, Michigan

Elevation: 635 feet above sea level.

	Thickness (feet)	Depth (feet)
Glacial deposits:		
Clay- yellowish-brown, noncalcareous.	11	11
Clay- medium-gray, calcareous; occasional light-gray sand.	3	14
Bedrock:		
Dolomite- light-gray, mottled, microcrystalline, sandy, petroliferous, vuggy.	19	33
Dolomite- light-gray to tan, mottled, microcrystalline, sandy, petroliferous, vuggy.	39	72
Sandstone- light- to medium-gray, fine-grained, carbonaceous, some celestite.	16	88
Limestone- medium-gray, microcrystalline; sandy; some celestite.	10	98
Sandstone- light-gray to white, fine-grain; some celestite; interbedded with medium-gray limestone.	10	108
Limestone- light-gray to tan, microcrystalline, sandy; secondary calcite.	12	120
Sandstone- white to light-gray, fine-grained; interbedded with limestone.	41	161
Limestone- gray, microcrystalline, sandy, vuggy, fractured; secondary calcite, celestite, gypsum.	4	165
Limestone- medium- to dark-gray, sandy.*	4	169
Sandstone.*	16	185

*Descriptions based on the drillers log.

Well: G7

Location: NW1/4, NW1/4, NE1/4 of Section 10, T. 5 S., R. 7 E., London Township, Monroe County, Michigan. London Township Hall.

Elevation: 665 feet above sea level.

		Thickness (feet)	Depth (feet)
Glacial deposits			
	Sand - yellowish-brown, medium-grained, slightly calcareous; becoming more calcareous with depth.	17	17
	Clay- medium-gray, highly calcareous.	41	58
	Till - sandy.	7	65
Bedrock:			
	Broken limestone - medium-gray; some clay.	2	67
	Limestone - medium-gray to brown, microcrystalline, fossiliferous; minor amounts of coarse calcite crystals, white microcrystalline limestone and chert; fractures at 65 to 67 feet, at 89 feet, and at 94 feet	28	95

Well: G8

Location: SW1/4, SW1/4, NE1/4 of Section 20, T. 5 S., R. 7 E., London Township, Monroe County, Michigan. Plank Road Cemetery.

Elevation: 670 feet above sea level.

	Thickness (feet)	Depth (feet)
Glacial deposits:		
Sand - yellowish-brown, moderately calcareous, medium-grained, well-sorted.	21	21
Clay- dark-gray, highly calcareous, sandy; some gravel.	40	61
Bedrock:		
Fractured limestone with medium gray clay.	4	65
Limestone - greenish-brown, dolomitic, cherty.		
Limestone - green to brown, microcrystalline to medium crystalline, dolomitic, occasionally sucrosic; interbedded with dark gray to black shaley limestone; trace of white chert.	13	78
Limestone - medium-brown, crystalline, stylolitic, petroliferous; crystal size and amount of white chert increases with depth.	6	84
Dolomite - light- to medium-gray, mottled, sucrosic; minor interbeds of brown crystalline limestone.	9	93
Limestone - brown, coarse crystalline, petroliferous, slightly dolomitic; massive with occasional shaley parting, brown calcite veins; small vugs present with euhedral calcite crystals; grades into the mottled gray dolomite.	2	95

Well: G9

Location: NE1/4, NE1/4, SE1/4 of Section 26, T. 5 S., R. 6 E., Milan Township, Monroe County, Michigan. About 450 feet west on Couper Road from intersection of Couper Road and Ann Arbor Road and about 80 feet south of Couper Road.

Elevation: 671 feet above sea level.

	Thickness (feet)	Depth (feet)
Glacial deposits:		
Clay - yellowish-brown, slightly carbonaceous.	4	4
Sand - yellowish-brown, well-sorted, carbonaceous	2	6
Till - medium-gray, highly carbonaceous, poorly sorted, subrounded to angular.	41	47
Clay - medium-gray, highly carbonaceous, poorly-sorted, sandy in part.	30	77
Bedrock:		
Broken bedrock and clay.	18	95
Limestone - medium-gray to brown, carbonaceous, shaley, sparsely fossiliferous; sandy in part; secondary white calcite in fracture fill.	57	152
Limestone - light-gray to tan, carbonaceous, microcrystalline, sandy; some coral fossils, vugs and secondary calcite; occasionally cherty.	42	194
Limestone - light- to medium-brown; secondary calcite, stylolitic; silty to sandy in part.	6	200

Well: G10

Location: NE1/4, SE1/4, SE1/4 of Section8, T.5S, R.6 E, Milan Township, Monroe County, Michigan. Dennison Road Cemetery.

Elevation: 708 feet above sea level.

	Thickness (feet)	Depth (feet)
Glacial deposits		
Clay- yellowish-brown, calcareous.	11	11
Sand- medium-brown, medium- to coarse-grained, well-sorted, calcareous.	13	24
Sand- medium-brown, medium- to fine-grained, occasionally coarse, calcareous; unit becomes grayer with depth; at 45 feet, gravel, poorly sorted, subrounded to angular.	34	58
Coarse sand to gravel- medium-brown to gray, poorly sorted.	16	74
Clay- medium-gray, calcareous, mixed with gravel and sand.	7	81
Sand- medium-brown, well-sorted, fine-grained, calcareous.	26	107
Coarse sand to gravel- medium-brown, moderately sorted, calcareous.	4	111
Bedrock:		
Shale- medium-gray, calcareous.	1	112

Well: G11

Location: SE1/4, SE1/4, NW1/4 of Section 23, T. 6 S., R. 6 E., Dundee Township, Monroe County, Michigan. Maple Grove Cemetery.

Elevation: 667 feet above sea level.

	Thickness (feet)	Depth (feet)
Glacial deposits:		
Clay - yellow, sandy.	13	13
Clay - gray, sandy.	19	32
Bedrock:		
Limestone - brown.	4	36
Limestone - broken; no water.	2	38
Limestone - brown, fractures with water at 47 feet and 72 to 76 feet.	56	94
Sandstone - brown.	16	110

Descriptions based on the driller's log.

Well: G12

Location: NE1/4, NE1/4, NE1/4 of Section 35, T. 6 S., R. 6 E., Summerfield Township, Monroe County, Michigan. Oak Grove Cemetery.

Elevation: 676 feet above sea level.

	Thickness (feet)	Depth (feet)
Glacial deposits:		
Sand - yellow.	7	7
Sand - medium-gray.	6	13
Sand - medium-gray, subrounded, poorly sorted, clayey, highly calcareous.	28	41
Sand and gravel.	5	46
Bedrock:		
Limestone - brown.	18	64
Limestone - brown.	7	71
Limestone - light tan.	2	73
Limestone - medium-brown; fracture at 81 to 82 feet.	13	86
Limestone - medium-brown; fracture at 91 feet.	14	100

Descriptions based on the driller's log.

Well: G13

Location: SW1/4, SW1/4, SW1/4 of Section 13, T. 6 S., R. 7 E., Raisinville Township, Monroe County, Michigan. Rath Cemetery.

Elevation: 644 feet above sea level.

	Thickness (feet)	Depth (feet)
Glacial Deposits:		
Sand - yellow.	7	7
Clay - yellow.	4	11
Clay and gravel - gray.	1	12
Bedrock:		
Limestone - gray, sandy.	17	29
Sandstone - brown, fracture at 50 feet.	47	76
Sandstone.	12	88
Limestone - gray, hard.	9	97
Sandstone.	13	110

Descriptions are based on the driller's log.

Well: G14

Location: SE1/4, NW1/4, SW1/4 of Section 2, T. 6 S., R. 8 E., Raisinville Township, Monroe County, Michigan. McIntyre Cemetery.

Elevation: 627 feet above sea level.

		Thickness (feet)	Depth (feet)
	Fill.	2	2
Glacial deposits:			
	Sand and clay - yellow.	9	11
Bedrock:			
	Sandstone - brown.	16	27
	Sandstone - gray, medium- to fine-grained; petroliferous and carbonaceous in part; traces of gypsum; interbedded with medium-gray, calcareous sandstone.	21	48
	Sandstone - gray, medium- to fine-grained; petroliferous; occasional gypsum.	17	65

Well: G15

Location: NE1/4, NE1/4, NW1/4 of Section 16, T. 6 S., R. 9 E., Frenchtown Township, Monroe County, Michigan. Frenchtown Township Fire Station.

Elevation: 604 feet above sea level.

	Thickness (feet)	Depth (feet)
Glacial deposits:		
Clay - yellowish-brown; calcareous; some sand.	11	11
Bedrock:		
Sandstone - brown.*	3	14
Limestone - light- to dark-gray, mottled, microcrystalline, stylolitic; interbedded with a dark-gray to black shale.	15	29
Limestone - light- to dark-gray, mottled, microcrystalline, stylolitic; interbedded with crystalline limestone, white calcite, brown anhydrite, and light-brown, sucrosic dolomite.	1	30
Limestone - light-gray, microcrystalline, dolomitic; secondary calcite; fracture at 41 feet.	17	47
Limestone - medium-brown to gray-brown, microcrystalline, vuggy; secondary calcite.	3	50

* Description based on the driller's log.

Well: G16

Location: NW1/4, SE1/4, SE1/4 of Section 23, T. 6 S., R. 6 E., Frenchtown Township, Monroe County, Michigan. Frenchtown Township Park along Nadeau Road.

Elevation: 586 feet above sea level.

		Thickness (feet)	Depth (feet)
Glacial drift:			
	Clay - yellowish-brown, poorly sorted, highly calcareous; interbedded with fine-grained sand and gravel.	12	12
	Clay - medium-gray, poorly sorted, highly calcareous.	5.5	17.5
	Gravel - medium-brown, highly calcareous, well-sorted, angular.	.5	18
Bedrock:			
	Limestone - medium-brown, microcrystalline, dolomitic, vuggy, stylolitic; interbedded with light-gray microcrystalline limestone; highly fractured from 18 to 32 feet.	28	46
	Limestone - light- to medium-brown, microcrystalline, massive, vuggy; secondary sulfur.	5	51
	Dolomite - dark-gray, grades to light- to medium-gray dolomitic shale.	2	53
	Dolomite - medium-gray, microcrystalline; interbedded with minor beds of light-gray, sandy, stylolitic limestone occasional chert; grades to medium-brown, microcrystalline limestone; fracture at 58 feet.	37	90

Well: G17

Location: SE1/4, SW1/4, SW1/4 of Section 2, T. 7 S., R. 8 E., Monroe Township, Monroe County, Michigan. Monroe Township Hall.

Elevation: 605 feet above sea level.

	Thickness (feet)	Depth (feet)
Glacial deposits:		
Clay -yellowish-brown, carbonaceous; with some gravel.	2	2
Clay and sand - yellow.	5	7
Clay - medium-gray, highly carbonaceous, sandy.	5	12
Bedrock:		
Limestone - medium-brown to gray, occasionally light gray, mottled, microcrystalline, stylolitic, vuggy, petroliferous, occasionally fossiliferous; secondary calcite.	81	93
Shale - dark gray.	2	95

Well: G18

Location: SW1/4, NW1/4, SE1/4 of Section 22, T.7 S., R. 8 E., LaSalle Township, Monroe County, Michigan. LaSalle Township Cemetery.

Elevation: 605 feet above sea level.

	Thickness (feet)	Depth (feet)
Glacial deposits:		
Sand - yellowish-brown, well-sorted, fine-grained.	11	11
Clay - medium-gray, poorly sorted, highly calcareous, sandy.	13	24
Bedrock:		
Limestone - light-brown, microcrystalline, fractured; secondary calcite; shaley in part.	5	29
Dolomite - medium-gray, microcrystalline, massive; with occasional laminations.	13	42
Limestone - dark-gray, mottled, microcrystalline occasionally finely laminated; secondary calcite in vugs, very porous at 50 feet.	8	50

Well: G19

Location: SE1/4, NE1/4, NE1/4 of Section 3, T. 7 S., R. 7 E., Ida Township, Monroe County, Michigan. Ida Township Hall.

Elevation: 640 feet above sea level.

		Thickness (feet)	Depth (feet)
	Cinders and fill	3	3
Glacial deposits:			
	Clay - yellowish-brown, calcareous; increasing sand with depth.	8	11
	Sand - yellowish-brown, medium- to coarse-grained. highly calcareous.	4	15
	Gravel - yellow.	2	17
	Clay - medium-gray, highly calcareous; mixed with sand and gravel.	11	28
Bedrock:			
	Broken rock.	6	34
	Limestone - medium-gray, microcrystalline, dolomitic.	13	47
	Dolomite - medium-gray to brown, sandy, stylolitic; grades into a light-gray, dolomitic sandstone.	17	64
	Sandstone - light-gray, fine-grained, slightly argillaceous; fractured at 62 feet, 70 feet, 78 feet and 79 feet; sulfur odor; secondary calcite in pores.	16	80

Well: G20

Location: SW1/4, NE1/4, NE1/4 of Section 17, T. 7 S., R. 7 E., Ida Township, Monroe County, Michigan. Lulu Cemetery.

Elevation: 655 feet above sea level.

	Thickness (feet)	Depth (feet)
Glacial deposits:		
Sand - brownish-yellow, medium grained.	7	7
Sand - medium-gray, medium-grained, carbonaceous.	3	10
Clay - dark-gray, highly calcareous; mixed with gravel.	15	25
Bedrock:		
Limestone - light-gray, microcrystalline, occasionally oolitic and dolomitic; becoming sandier with depth.	28	53
Limestone - brown, microcrystalline, sandy, dolomitic, fossiliferous; fractured at 56 feet, 59 feet, 63 feet, and 65 feet.	4	57
Sandstone* - brown.	7	64
Sandstone* - gray.	6	70

*Descriptions between 57 and 70 feet are based on the driller's log.

Well G21

Location: SE1/4, SE1/4, SE1/4 of Section 34, T. 6 S., R. 6 E., Summerfield Township, Monroe County, Michigan. Summerfield Cemetery.

Elevation: 677 feet above sea level.

	Thickness (feet)	Depth (feet)
Glacial deposits:		
Sand - yellow to brown, medium-grained, slightly calcareous.	6	6
Sand - medium-gray, medium-grained, highly calcareous.	5	11
Clay - medium-gray, calcareous, highly carboneous, sandy.	31	42
Bedrock:		
Limestone - light-gray, microcrystalline, highly fractured.	1.5	43.5
Limestone - medium- to dark-gray, mottled, microcrystalline, fractured.	16.5	60
Limestone - brown, microcrystalline, massive. Fracture at 63 feet.	4	64
Limestone - light- to medium-gray, microcrystalline, slightly dolomitic, occasionally finely laminated, vuggy.	6	70
Limestone - light- to medium-gray, microcrystalline, slightly dolomitic, finely laminated, stylolitic; secondary calcite; highly fractured.	5	75

Well: G22

Location: NW1/4, NW1/4, NE1/4, Section 15, T. 7 S., R. 6 E., Summerfield Township, Monroe County, Michigan. Petersburg State Game Area.

Elevation: 680 feet above sea level.

	Thickness (feet)	Depth (feet)
Glacial deposits:		
Sand - dark-yellow, moderate- to well-sorted, slightly calcareous, medium grained.	12	12
Sand - Light gray, moderate to well-sorted, calcareous, medium-grained.	5	17
Clay - medium-gray, calcareous, sandy.	28	45
Clay - medium-gray, calcareous; gravel, and limestone.	8	53
Bedrock:		
Limestone - brown, microcrystalline, fossiliferous; interbedded with gray, microcrystalline, sandy fossiliferous limestone.	4	57
Dolomite - brown, microcrystalline, vuggy; secondary calcite.	3	60
Dolomite - light-gray, microcrystalline, vuggy, secondary calcite; fractured; interbedded with dark gray dolomite.	8	68
Dolomite - light-gray, microcrystalline, vuggy; secondary calcite; fractured; interbedded with dark-gray dolomite.	4	72
Dolomite - light-gray, microcrystalline, vuggy; secondary calcite; fractured at 74 feet; interbedded with dark -ray shale and dark-gray dolomite.	4	76
Dolomite - light-gray, microcrystalline, vuggy; secondary calcite; sandy; fractured at 82 feet,; interbedded with dark-gray shale, dark-gray dolomite, and light- to medium-gray, sandy limestone.	7	83

Well: G22 - Continued

	Thickness (feet)	Depth (feet)
Dolomite - light-gray, sandy, shaley; fractured between 84 and 85 feet; grading to dolomitic sandstone.	4	87

Well: G23

Location: NW1/4, SE1/4, NE1/4 of Section 15, T. 7 S., R. 6 E., Summerfield Township, Monroe County, Michigan. Petersburg State Game Area.

Elevation: 679 feet above sea level.

	Thickness (feet)	Depth (feet)
Glacial deposits:		
Sand - yellowish-brown, well-sorted, fine-grained, slightly calcareous.	7	7
Sand - medium-gray, well-sorted, fine-grained, highly calcareous.	7	14
Clay - medium-gray, moderately sorted, highly calcareous; interbedded with sand.	27	41
Till.	8	49
Bedrock:		
Limestone - light-gray to tan, microcrystalline, stylolitic, dense.	2	51
Limestone - gray and tan; porous zone at 63 feet; fracture containing yellow sulfur at 71 feet.	37	88
Limestone - gray, sandy.	2	90

Core samples collected from 60 to 90 feet.

Well: G24

Location: SW1/4, NE1/4, NE1/4 of Section 15, T. 7 S., R. 6 E., Summerfield Township, Monroe County, Michigan. Petersburg State Game Area.

Elevation: 680 feet above sea level.

	Thickness (feet)	Depth (feet)
Glacial deposits:		
Sand - yellow.*	7	7
Sand - medium-gray, fine- to coarse-grained, poorly sorted, highly calcareous.	7	14
Clay - gray; some sand.*	28	42
Gravel and clay.*	1.5	43.5
Gray clay and gravel.*	4.5	48
Bedrock:		
Limestone - Tan, fractured.*	4	52
Limestone - Tan with gray streaks; fracture at 60 feet.*	17	69
Dolomite - medium-gray, microcrystalline, stylolitic, vuggy, fractured; secondary calcite; native sulfur in fractures at 69 feet, 75 feet and 79 feet.	18	87

*Descriptions are based on the driller's log.

Well: G25

Location: SE1/4, NE1/4, NE1/4 of Section 15, T. 7 S., R. 6 E., Summerfield Township, Monroe County, Michigan. Petersburg State Game Area.

Elevation: 679 feet above sea level.

	Thickness (feet)	Depth (feet)
Glacial deposits:		
Sand - yellowish-brown, medium- to fine-grained, well-sorted.	9	9
Sand - medium-gray, clayey, highly calcareous.	1	10
Sand - medium-gray, fine- to coarse-grained, highly calcareous.	6	16
Sand and gravel - medium-gray, medium- to coarse-grained, subrounded, highly calcareous.	7	23
Clay - medium-gray, highly calcareous; some sand and gravel.	14	37
Clay - medium-gray, highly calcareous; some gravel.	11	48
Gravel.	2	50
Bedrock:		
Dolomite - medium- to light-gray, occasionally mottled, fine to microcrystalline; interbedded with a light-gray fossiliferous limestone and sandy dolomite; becoming light-gray, microcrystalline dolomite with dog tooth calcite; laminated in part; petroliferous in part; stylolitic; calcareous in part; fractured at 73 feet and78 feet; vugs from 63 to 68 feet with secondary calcite.	36	86
Limestone - light-gray, mottled, microcrystalline, stylolitic.	1	87

Well: G26

Location: SW1/4, SW1/4, SE1/4 of Section 17, T. 7 S., R. 6 E., Summerfield Township, Monroe County, Michigan.

Elevation: 682 feet above sea level.

	Thickness (feet)	Depth (feet)
Glacial deposits:		
Sand - dark-yellow, noncalcareous.	10	10
Clay - medium-gray, calcareous; mixed with sand and gravel.	29	39
Clay - medium-gray, calcareous.	9	48
Bedrock:		
Limestone - light-gray, microcrystalline; interbedded with dark-gray shale.	4	52
Limestone - light-gray, mottled, microcrystalline, dolomitic, fossiliferous; interbedded shales.	28	80

Well: G27

Location: NE1/4, SW1/4, SW1/4, Section 24, T. 7 S., R. 6 E., Summerfield Township, Monroe County, Michigan.

Elevation: 676 feet above sea level.

	Thickness (feet)	Depth (feet)
Glacial deposits:		
Sand - yellowish-brown, fine-grained, slightly calcareous, coarsening downward.	10	10
Sand - gray, medium-grained, calcareous.	5	15
Gravel - medium-gray, subrounded to angular, moderately sorted, clayey, calcareous.	7	22
Till - medium-gray, highly calcareous.	8	30
Bedrock:		
Limestone - gray, fractured.	5	35
Limestone - light- to dark-gray, mottled, microcrystalline; becomes sandy with depth.	13	48
Sandstone - white to light-gray, friable, calcareous; interbedded with gray limestone; fractured at 58 to 83 feet, 77 feet, and 79 feet.	39	87
Limestone - light-brown to tan, dolomitic, stylolitic; massive with very fine laminations; cherty in part; secondary calcite in vugs; interbedded with sandy limestone and dark gray shale; fractured at 110 feet.	41	128
Limestone - medium-brown, microcrystalline, vuggy; secondary calcite.	25	153
Dolomite - light-gray to tan, microcrystalline, laminated, pyritic; secondary calcite in vugs; interbedded with mottled gray limestone.	20	173
Shale - medium gray.	2	175

	Thickness (feet)	Depth (feet)
Limestone - brown to gray, microcrystalline, massive, vuggy, stylolitic; fractured between 186 and 187 feet.	13	188
Dolomite - light-brown to gray, microcrystalline, stylolitic; secondary calcite in vugs; finely laminated.	7	195
Limestone - medium-gray; some white ooids; petroliferous; interbedded with fissile, shaley limestone.	11	206
Dolomite - light-gray to tan, microcrystalline, bioturbated, stylolitic, laminated.	2	208

Well: G28

Location: NW1/4, SE1/4, SE/14 of Section 7, T. 8 S., R. 6 E., Whiteford Township, Monroe County, Michigan. Lakeview Cemetery.

Elevation: 688 feet above sea level.

	Thickness (feet)	Depth (feet)
Glacial deposits:		
Clay - yellowish-brown, noncalcareous; minor sand and gravel, coarsening downward.	12	12
Sand - light-brown, calcareous, coarse-grained.	4	16
Bedrock:		
Limestone- brown, hard.*	24	40
Limestone - gray to light brown, microcrystalline, dolomitic, stylolitic; interbedded with gray, shaley limestone; fractured at 25 feet.	13	53
Limestone - light gray, mottled, microcrystalline, dolomitic, stylolitic, fractures at 60 feet and 67 feet.	17	70
Dolomite - gray, microcrystalline, stylolitic.	5	75

*Description based on the driller's log.

Well: G29

Location: NW1/4, NW1/4, NW1/4 of Section 31, T. 8 S. R. 7 E., Bedford Township, Monroe County, Michigan. Bedford Township Cemetery.

Elevation: 662 feet above sea level.

	Thickness (feet)	Depth (feet)
Glacial deposits:		
Sand - yellowish-brown, medium- to fine-grained, slightly carbonaceous.	12	12
Clay - medium-gray, highly carbonaceous, sandy.	2	14
Sand - gray, medium- to fine-grained, slightly carbonaceous.	5	19
Clay - medium-gray, highly carbonaceous, sandy.	4	23
Bedrock:		
Limestone - medium-grey, fractured.	4	27
Limestone - medium-gray-brown, microcrystalline, shaley, stylolitic; secondary calcite in fractures; occasionally fossiliferous; finely laminated in part; fractures at 45 feet, 60 feet, 62 feet, 68 feet and 70 feet.	38	65
Limestone - light-brown to tan, microcrystalline, dolomitic, occasional finely laminations.	5	70
Limestone - gray.	1	71

Well: G30

Location: NE1/4, SW1/4, SE1/4 of Section 19, T. 8 S., R. 7 E., Bedford Township, Monroe County, Michigan. Parmalee Park.

Elevation: 670 feet above sea level.

	Thickness (feet)	Depth (feet)
Glacial deposits:		
Sand - yellowish-brown, medium-grained, slightly calcareous.	8	8
Sand - light-gray, fine-grained, slightly calcareous.	8	16
Sand - medium-gray, calcareous.	3	19
Clay and gravel - medium-gray, calcareous.	7	26
Bedrock:		
Limestone - medium-gray, fractured.	1	27
Limestone - light-gray, shaley.	10.5	37.5
Limestone - light-gray, mottle dark-gray; microcrystalline; interbedded with dark-gray shale.	9.5	47
Limestone - light-brown, microcrystalline, stylolitic, laminated.	5	52
Limestone - grayish-brown, microcrystalline, pyritic, vuggy, laminated.	24	76
Limestone - medium-brown, microcrystalline, stylolitic.	7	83
Limestone - medium-gray, mottled, microcrystalline, massive, stylolitic; interbedded with brown, microcrystalline limestone.	7	90
Shale - dark-gray to black, calcareous, fissile.	6	96
Limestone - medium- to dark-gray, microcrystalline, laminated, pyritic, stylolitic.	43	139

Well: G30 -- Continued

	Thickness (feet)	Depth (feet)
Dolomite - light-brown to tan, microcrystalline, laminated, silty, stylolitic.	9	148
Limestone - dark-gray, shaley, pyritic.	3	151
Limestone - grayish-brown, mottled, silty, pyritic; secondary calcite in vugs.	4	155

Well: G31

Location: SW1/4, SE1/4, SW1/4 of Section 3, T. 8 S., R. 7 E., Bedford Township, Monroe County, Michigan. Samaria Community Center.

Elevation: 647 feet above sea level.

	Thickness (feet)	Depth (feet)
Glacial deposits:		
Sand - yellow.	2	2
Clay - yellowish-brown, carbonaceous.	6	8
Clay - medium-gray, highly calcareous, sandy.	4	12
Bedrock:		
Limestone - medium-brown, microcrystalline, stylolitic, pyritic; fractured from 12 to 14 feet, laminated in part; vuggy in part.	18	30
Limestone - medium-gray, microcrystalline, stylolitic; interbedded with dark-gray to black shale.	12	42
Limestone - brown, microcrystalline, dolomitic, fossiliferous; vuggy; secondary calcite; porous zone from 48 to 52 feet.	11	53
Limestone - dark-gray, shaley, petroliferous; stylolitic in part; secondary calcite; fractured at 59 feet.	27	80

Well: G32

Location: NE1/4, SW1/4, SW1/4 of Section 8, T. 8 S., R. 8 E., Erie Township, Monroe County, Michigan. 1,100 feet north of Erie Road on US#24, west side of road.

Elevation: 600 feet above sea level.

		Thickness (feet)	Depth (feet)
Glacial Deposits:			
	Clay - yellowish-brown, occasional clasts.	9	9
	Clay - medium-gray, highly carbonaceous; sandy in part.	13	22
	Clay - medium-gray, highly carbonaceous; mixed with gravel.	20	42
Bedrock:			
	Limestone - medium-brown, microcrystalline, dolomitic; pinpoint porosity; stylolitic; interbeds with dark-gray shale; secondary calcite in vugs.	17	59
	Dolomite - light-brown, microcrystalline, sucrosic, vuggy; secondary calcite and celestite; interbedded with dark, shaley dolomite.	5	64
	Limestone - medium-gray, microcrystalline, dense; interbedded with darker shale.	11	75

Well: G33

Location: NE1/4, SW1/4, SW1/4 of Section 28, T. 8 S., R. 8 E., Erie Township, Monroe County, Michigan. South Erie Park.

Elevation: 574 feet above sea level.

	Thickness (feet)	Depth (feet)
Glacial deposits:		
Clay - yellowish-brown.	11	11
Clay - medium-gray, highly carbonaceous.	21	32
Sand and gravel - dark-gray to black, coarse-grained, highly carbonaceous.	6	38
Bedrock:		
Broken bedrock - medium-gray, highly carbonaceous.	2	40
Limestone - medium-gray to blue, microcrystalline.	10	50
Limestone - tan, microcrystalline, fine laminations; dark secondary calcite in vugs.	25	75
Dolomite - dark-brown to gray, microcrystalline massive; petroliferous; fractured; vuggy in part; secondary calcite; shaley in part.	10	85

Well: D1

Location: SW1/4, SW1/4, SE1/4 of Section 20, T. 7 S., R. 6 E., Summerfield Township, Monroe County, Michigan. Between Alt Road and Railroad Road on Ida-Center Road.

		Thickness (feet)	Depth (feet)
Glacial deposits:			
	Sand.	18	18
	Clay - dark.	24	42
	Sand and gravel.	5	47
Bedrock:			
	Limestone - gray.	13	60

Well: D2

Location: SE1/4, SW1/4, SE1/4 of Section 17, T. 7 S., R. 6 E., Summerfield Township, Monroe County, Michigan. Two blocks east of Alt Road, seven-eighths mile west of Stull Road on north side of Ida-Center Road.

		Thickness (feet)	Depth (feet)
Glacial deposits:			
	Sand.	12	12
	Clay.	40	52
Bedrock:			
	Limestone.	17	69

Well: D3

Location: NE1/4, NW1/4, NE1/4 of Section 10, T. 5 S., R. 7 E., London Township, Monroe County, Michigan. 13604 Tuttle-Hill Road.

		Thickness (feet)	Depth (feet)
Glacial deposits:			
	Sand.	14	14
	Clay.	9	23
	Sand.	2	25

Well: D4

Location: SE1/4, SE1/4, SE1/4 of Section 13, T. 7 S., R. 8 E., Monroe Township, Monroe County, Michigan. One-eighth mile south of Albain Road and one hundred feet east of Hull Road.

		Thickness (feet)	Depth (feet)
Glacial deposits:			
	Clay - yellow.	25	25
Bedrock:			
	Limestone - gray.	75	100

Well: D5

Location: SW1/4, NE1/4, NE1/4 of Section 6, T. 8 S., R. 7 E., Bedford Township, Monroe County, Michigan. One-eighth mile west of Secor Road and 1 1/2 miles east of Summerfield Road on School Road.

		Thickness (feet)	Depth (feet)
Glacial deposits:			
	Top soil.	6	6
	Sand - brown.	4	10
	Sand - coarse.	6	16
	Clay and gravel.	13	29
Bedrock:	Bedrock.	28	57

Well: D6

Location: SW1/4, SW1/4, SW1/4 of Section 24, T. 8 S., R. 7 E., Bedford Township, Monroe County, Michigan. Between Substation Road and Dean Road on east side of Crabb Road.

		Thickness (feet)	Depth (feet)
Glacial deposits:			
	Loam	1	1
	Clay - soft.	19	20
	Clay mixed with pebbles.	10	30
Bedrock:			
	Limestone - broken.	4	34
	Limestone.	38	72

Well: D7

Location: NE1/4, SE1/4, SE1/4 of Section 28, T. 5 S., R. 9 E., Ash Township, Monroe County, Michigan. One-eighth mile north of Labo Road.

		Thickness (feet)	Depth (feet)
Glacial deposits:			
	Clay - yellow.	12	12
	Clay - blue.	12	24
Bedrock:			
	Limestone - broken.	2	26
	Sandstone and limestone - broken.	1	27
	Sandstone.	29	56
	Limestone - gray.	3	59

Well: D8

Location: NW1/4, SE1/4, NW1/4 of Section 17, T. 6 S., R. 10 E., Frenchtown Township, Monroe County, Michigan. One block north of Langton Road on Leroux Road.

	Thickness (feet)	Depth (feet)
Glacial deposits:		
Clay - yellow.	12	12
Clay - gray.	1	13
Bedrock:		
Limestone - dark gray.	6	19
Limestone - light gray.	2	21
Limestone - white.	1	22
Limestone - gray.	13	35
Limestone - white.	26	61

Well: D9

Location: NE1/4, SW1/4, SW1/4 of Section 15, T. 5 S., R. 8 E., Exeter Township, Monroe County, Michigan. Between Fay Road and Scofield-Carlton Road on Sumpter Road.

	Thickness (feet)	Depth (feet)
Glacial deposits:		
Sand.	9	9
Clay - gray; small gravel.	7	16
Clay - gray; large gravel.	17	33
Bedrock:		
Rock - soft.	2	35
Limestone.	2	37

Well: D10

Location: SW1/4, SE1/4, NW1/4 of Section 15, T. 6 S., R. 8 E., Raisinville Township, Monroe County, Michigan. Between Sheick Road and Raisinville Road on Stewart Road.

	Thickness (feet)	Depth (feet)
Fill.	2	2
Glacial deposits:		
Sand.	2	4
Clay.	23	27
Bedrock:		
Sandstone - broken.	1	28
Sandstone.	38	66

Well: D11

Location: SW1/4, NE1/4, NW1/4 of Section 15, T. 6 S., R. 6 E., Dundee Township, Monroe County, Michigan. One mile west of U.S. 23 on M50 at Jehovah Witness Hall.

	Thickness (feet)	Depth (feet)
Top soil - black.	1	1
Glacial deposits:		
Clay - yellow.	18	19
Clay - gray.	15	34
Clay - gummy.	26	60
Bedrock:		
Limestone.	5	65

Well: D12

Location: NE1/4, NE1/4, NW1/4 of Section 15, T. 4 S., R. 6 E., Whiteford Township, Monroe County, Michigan. One third mile west of Sylvania-Petersburg Road on Yankee Road.

		Thickness (feet)	Depth (feet)
Glacial deposits:			
	Clay - yellow.	7	7
Bedrock:			
	Limestone - gray.	103	110

Well: D13

Location: SW1/4, SW1/4, SE1/4 of Section 13, T. 7 S., R. 7 E., Ida Township, Monroe County, Michigan. Between Geiger Road and Minx Road on Ida-Center Road.

		Thickness (feet)	Depth (feet)
	Fill.	3	3
Glacial deposits:			
	Clay.	27	30
Bedrock:			
	Limestone - broken.	3	33
	Limestone.	37	70

APPENDIX 3:

Altitude of water levels in U.S. Geological Survey observation wells, Monroe County, Michigan, 1990-93

Appendix 3. Altitude of water levels in U.S. Geological Survey observation wells, Monroe County, Michigan, 1990-93.

[Altitude is in feet above sea level]

Well number	Date	Altitude of water (feet)	Well number	Date	Altitude of water (feet)
G1	12-01-90	541.14	G2	12-01-90	574.50
	04-01-91	539.27		04-01-91	564.73
	06-01-91	539.35		05-01-91	564.47
	07-01-91	539.68		06-01-91	564.27
	08-01-91	538.22		07-01-91	563.09
	12-01-91	536.92		08-01-91	560.60
	01-22-92	536.88		12-01-91	560.15
	02-13-92	537.03		01-22-92	560.96
	03-23-92	536.87		02-13-92	561.59
	04-14-92	536.62		03-23-92	563.63
	04-28-92	536.72		04-14-92	563.88
	04-27-92	536.68		04-28-92	565.03
	05-14-92	536.77		04-27-92	565.10
	05-27-92	536.83		05-14-92	564.10
	06-15-92	536.67		05-27-92	563.71
	07-17-92	536.63		06-16-92	562.66
	08-26-92	536.71		07-17-92	561.52
	09-30-92	536.77		08-26-92	560.94
	01-22-93	537.85		09-22-92	560.97
	03-29-93	537.44		11-25-92	563.66
	04-28-93	537.44		01-22-93	564.72
	05-26-93	537.82		02-26-93	562.91
	06-16-93	536.72		03-29-93	564.83
	07-14-93	536.70		04-28-93	565.01
	07-26-93	536.73		05-26-93	563.00
				06-16-93	561.46
				07-14-93	560.48
				07-26-93	560.05
G3	12-01-90	585.41	G4	12-01-90	592.60
	04-01-91	585.46		04-01-91	591.72
	05-01-91	585.14		05-01-91	591.72
	06-01-91	584.43		06-01-91	591.55
	07-01-91	584.36		07-01-91	590.99
	08-01-91	583.20		08-01-91	589.96
	12-01-91	583.15		12-01-91	589.64
	01-23-92	583.97		01-22-92	589.96
	02-13-92	583.95		02-13-92	590.21
	03-23-92	584.83		03-23-92	590.69
	04-14-92	584.69		04-14-92	590.78
	04-28-92	585.40		04-28-92	591.32
	05-14-92	584.49		05-14-92	591.13
	05-27-92	584.12		05-27-92	591.06
	06-16-92	583.76		06-16-92	590.78
	07-17-92	583.42		06-29-92	590.82
	08-25-92	583.34		07-17-92	590.81
	09-22-92	583.64		08-04-92	590.99
	10-20-92	583.73		08-25-92	590.75
	11-25-92	585.20		09-22-92	590.99
	01-22-93	585.01		10-20-92	590.96
	02-26-93	583.41		11-25-92	591.67
	03-29-93	607.00		01-22-93	592.37
	04-28-93	584.84		02-26-93	592.52
	05-26-93	583.86		03-29-93	592.49
	06-16-93	582.74		04-28-93	592.27
	07-14-93	582.43		05-26-93	591.55
	07-26-93	582.33		06-16-93	591.20
				07-14-93	591.20
				07-26-93	591.11

Appendix 3. Altitude of water levels in U.S. Geological Survey observation wells, Monroe County, Michigan, 1990-93.

Well number	Date	Altitude of water (feet)	Well number	Date	Altitude of water (feet)
G5	12-01-90	613.40	G6	12-01-90	609.30
	05-01-91	615.49		05-01-91	609.69
	06-01-91	615.13		06-01-91	609.32
	03-18-92	613.05		07-01-91	608.68
	04-14-92	613.02		08-01-91	607.12
	04-28-92	613.43		03-18-92	607.70
	05-14-92	613.35		04-14-92	607.59
	05-27-92	612.90		04-28-92	608.04
	06-16-92	612.58		05-14-92	607.97
	07-17-92	612.20		05-27-92	607.80
	08-26-92	611.90		06-16-92	607.35
	09-22-92	612.39		07-17-92	607.30
	10-20-92	612.25		08-25-92	607.15
	11-25-92	612.25		09-22-92	607.31
	01-22-93	613.18		10-20-92	607.27
	02-26-93	612.62		11-25-92	607.71
	03-29-93	612.86		01-22-93	608.02
	04-28-93	612.75		02-26-93	611.00
	05-26-93	612.71		03-29-93	607.71
	06-16-93	609.88		04-28-93	607.52
	07-14-93	610.39		05-26-93	606.86
	07-26-93	609.42		06-16-93	606.43
				07-14-93	606.43
				07-26-93	606.47
G7	12-01-90	617.80	G8	12-01-90	614.00
	04-01-91	616.49		05-01-91	612.83
	05-01-91	616.49		06-01-91	612.16
	06-01-91	615.72		07-01-91	610.62
	07-01-91	614.01		08-01-91	608.49
	08-01-91	611.83		12-01-91	609.38
	12-01-91	612.96		01-23-92	610.28
	01-23-92	613.82		02-13-92	609.74
	02-13-92	613.30		03-23-92	610.16
	03-23-92	613.80		04-14-92	610.05
	04-14-92	613.67		04-28-92	610.53
	04-28-92	614.18		05-14-92	610.44
	05-14-92	614.10		05-27-92	610.13
	05-27-92	613.70		06-16-92	609.76
	06-16-92	613.29		07-24-92	609.42
	06-29-92	613.30		08-26-92	609.41
	07-24-92	612.90		09-22-92	609.37
	08-04-92	613.12		10-20-92	609.37
	08-25-92	612.47		11-25-92	609.70
	09-22-92	612.83		01-22-93	610.23
	10-20-92	612.66		02-26-93	609.55
	11-25-92	613.15		03-29-93	610.08
	01-22-93	613.64		04-28-93	609.73
	02-26-93	612.99		05-26-93	608.78
	03-29-93	613.48		06-16-93	608.07
	04-28-93	613.08		07-14-93	607.54
	05-26-93	611.94		07-26-93	606.56
	06-16-93	611.11			
	07-14-93	610.52			
	07-26-93	609.41			

Appendix 3. Altitude of water levels in U.S. Geological Survey observation wells, Monroe County, Michigan, 1990-93.

Well number	Date	Altitude of water (feet)
G9	12-01-90	614.20
	08-01-91	612.00
	12-01-91	613.00
	01-21-92	613.52
	02-13-92	613.52
	03-23-92	614.05
	04-14-92	613.92
	04-28-92	614.58
	04-28-92	614.49
	05-14-92	614.29
	05-27-92	613.89
	06-16-92	613.46
	07-24-92	613.37
	08-26-92	612.79
	09-21-92	613.41
	10-20-92	613.25
	11-25-92	613.80
	01-28-93	614.29
	02-26-93	613.27
	03-18-93	613.22
	04-30-93	613.73
	05-21-93	611.95
	06-21-93	611.97
	07-22-93	610.04
G10	12-01-90	694.60
	05-01-91	693.66
	06-01-91	693.72
	07-01-91	693.47
	08-01-91	692.68
	12-01-91	691.40
	01-21-92	691.29
	02-13-92	691.28
	03-23-92	691.81
	04-14-92	692.01
	04-28-92	692.43
	05-14-92	692.48
	05-27-92	692.50
	06-16-92	692.31
	07-24-92	692.48
	08-26-92	692.27
	09-21-92	692.61
	10-20-92	692.65
	11-25-92	693.18
	01-28-93	694.57
	02-26-93	694.13
	03-18-93	694.12
	04-30-93	695.18
	05-21-93	694.91
	06-21-93	693.26
	07-22-93	693.60
G11	12-01-90	628.20
	04-01-91	627.49
	05-01-91	627.35
	06-01-91	627.67
	07-01-91	626.92
	08-01-91	623.99
	12-01-91	623.26
	01-21-92	624.32
	02-13-92	624.44
	03-23-92	625.32
	04-14-92	625.53
	04-28-92	626.35
	05-14-92	626.25
	05-27-92	624.93
	06-16-92	625.63
	07-24-92	625.43
	08-26-92	625.13
	09-16-92	625.17
	09-16-92	625.37
	10-22-92	625.26
	11-25-92	626.44
	01-28-93	627.57
	02-26-93	626.75
	03-18-93	626.69
	04-30-93	628.15
	05-21-93	627.61
	06-21-93	626.33
	07-22-93	625.14
G12	12-01-90	638.50
	04-01-91	640.99
	05-01-91	640.10
	06-01-91	641.11
	07-01-91	639.64
	08-01-91	635.12
	12-01-91	635.04
	01-21-92	635.74
	02-13-92	636.03
	03-23-92	637.63
	04-14-92	638.10
	04-28-92	639.87
	05-14-92	639.35
	05-27-92	638.96
	06-16-92	638.10
	07-24-92	637.76
	08-25-92	636.72
	09-15-92	637.01
	10-22-92	637.31
	11-25-92	640.74
	01-28-93	643.20
	02-26-93	639.96
	03-18-93	640.56
	04-30-93	643.38
	05-21-93	640.84
	06-21-93	638.39
	07-22-93	636.64

Appendix 3. Altitude of water levels in U.S. Geological Survey observation wells, Monroe County, Michigan, 1990-93.

Well number	Date	Altitude of water (feet)	Well number	Date	Altitude of water (feet)
G13	12-01-90	631.80	G14	12-01-90	610.40
	04-01-91	632.40		04-01-91	613.66
	06-01-91	631.25		05-01-91	613.66
	07-01-91	630.13		06-01-91	613.82
	08-01-91	627.69		08-01-91	609.25
	12-01-91	629.58		12-01-91	608.02
	01-21-92	630.10		01-22-92	608.92
	02-13-92	629.96		02-13-92	609.32
	03-23-92	630.85		03-23-92	611.17
	04-14-92	630.81		04-14-92	611.92
	04-28-92	631.12		04-28-92	613.47
	04-28-92	631.97		04-28-92	613.49
	05-14-92	631.19		05-14-92	613.81
	05-27-92	630.42		05-27-92	613.36
	06-16-92	629.76		06-16-92	612.15
	07-24-92	631.18		07-17-92	611.32
	08-25-92	629.42		08-26-92	610.63
	09-22-92	629.66		09-21-92	610.06
	10-20-92	630.65		10-20-92	609.90
	11-25-92	631.95		11-25-92	612.25
	01-22-93	632.22		01-22-93	614.40
	02-24-93	630.42		02-24-93	613.29
	03-29-93	632.75		03-29-93	616.35
	04-28-93	631.89		04-28-93	616.57
				05-26-93	614.61
				06-16-93	613.66
				07-14-93	612.71
				07-26-93	611.99
G15	12-01-90	595.40	G16	12-01-90	578.35
	04-01-91	595.67		04-01-91	581.41
	05-01-91	594.72		05-01-91	580.49
	06-01-91	594.13		06-01-91	579.98
	07-01-91	592.92		07-01-91	579.14
	08-01-91	591.19		08-01-91	577.89
	12-01-91	592.93		12-01-91	580.04
	01-22-92	593.34		01-23-92	580.49
	02-13-92	593.54		02-13-92	580.13
	03-23-92	594.70		03-23-92	580.81
	04-14-92	594.68		04-14-92	580.52
	04-28-92	595.79		04-28-92	581.37
	05-14-92	594.45		04-28-92	581.68
	05-27-92	594.21		05-14-92	580.33
	06-16-92	593.05		05-27-92	580.68
	07-17-92	594.06		06-16-92	579.74
	08-26-92	592.34		06-29-92	579.11
	09-24-92	593.81		07-17-92	579.87
	12-01-92	595.22		08-04-92	579.70
	01-19-93	595.30		09-23-92	580.22
	02-24-93	594.20		12-01-92	580.92
	03-30-93	596.00		01-19-93	580.70
	04-27-93	595.55		02-24-93	579.71
	05-20-93	594.26		03-30-93	581.68
	06-23-93	593.38		04-27-93	580.79
	07-22-93	591.91		05-20-93	579.83
				06-23-93	579.41
				07-22-93	578.14

Appendix 3. Altitude of water levels in U.S. Geological Survey observation wells, Monroe County, Michigan, 1990-93.

Well number	Date	Altitude of water (feet)
G17	12-01-90	598.75
	06-01-91	599.52
	07-01-91	598.48
	08-01-91	594.69
	12-01-91	599.10
	01-23-92	600.13
	02-14-92	599.72
	03-26-92	601.17
	04-20-92	600.72
	05-07-92	600.53
	05-26-92	599.97
	06-19-92	599.00
	07-21-92	599.06
	08-24-92	597.93
	09-23-92	598.07
	12-01-92	600.66
	01-28-93	601.34
	02-24-93	599.55
	03-30-93	601.70
	04-27-93	600.92
	05-21-93	599.60
	06-23-93	599.75
	07-22-93	597.55
G18	12-01-90	596.60
	06-01-91	594.43
	07-01-91	593.61
	08-01-91	592.17
	12-01-91	594.81
	01-23-92	595.13
	02-14-92	595.05
	03-26-92	595.50
	04-20-92	595.55
	05-07-92	595.39
	05-22-92	594.95
	06-05-92	595.22
	06-19-92	594.37
	07-02-92	594.00
	07-16-92	594.43
	09-24-92	594.75
	12-01-92	595.62
	01-28-93	595.78
	02-24-93	595.25
	03-30-93	596.42
	04-27-93	595.89
	05-21-93	594.86
	06-23-93	595.16
	07-22-93	593.69
G19	12-01-90	629.40
	05-01-91	633.44
	06-01-91	632.03
	07-01-91	630.66
	08-01-91	626.49
	12-01-91	626.85
	01-21-92	628.09
	02-13-92	628.34
	03-26-92	631.65
	04-20-92	631.38
	05-07-92	632.06
	05-26-92	631.17
	06-05-92	631.12
	06-19-92	630.80
	07-02-92	629.57
	07-15-92	629.68
	08-13-92	629.77
	09-15-92	628.90
	10-22-92	629.87
	11-25-92	632.37
	01-28-93	633.02
	02-26-93	631.36
	03-18-93	632.36
	04-30-93	633.28
	05-20-93	632.17
	06-23-93	630.79
	07-22-93	618.87
G20	12-01-90	633.20
	05-01-91	635.91
	06-01-91	635.87
	07-01-91	634.01
	08-01-91	628.53
	12-01-91	628.58
	01-22-92	629.88
	02-13-92	630.18
	03-26-92	634.37
	04-20-92	634.31
	05-07-92	635.33
	05-26-92	634.29
	06-19-92	633.85
	07-21-92	632.59
	08-13-92	632.16
	09-17-92	631.20
	10-22-92	632.40
	11-25-92	635.60
	01-29-93	637.19
	02-26-93	634.83
	03-18-93	635.64
	04-30-93	637.49
	05-20-93	636.22
	06-23-93	633.94
	07-22-93	631.64

Appendix 3. Altitude of water levels in U.S. Geological Survey observation wells, Monroe County, Michigan, 1990-93.

Well number	Date	Altitude of water (feet)	Well number	Date	Altitude of water (feet)
G21	12-01-90	634.50	G22	12-01-90	643.50
	04-01-91	634.13		04-01-91	638.40
	05-01-91	634.18		05-01-91	644.71
	06-01-91	634.05		06-01-91	642.34
	07-01-91	633.25		08-01-91	636.85
	08-01-91	630.65		12-01-91	639.25
	12-01-91	630.45		01-28-92	639.59
	01-21-92	630.83		02-14-92	639.76
	02-13-92	630.84		03-13-92	641.05
	03-23-92	631.70		04-20-92	641.51
	04-14-92	631.78		04-29-92	642.30
	04-28-92	632.81		05-07-92	641.61
	05-14-92	632.53		05-22-92	640.47
	05-27-92	632.20		06-19-92	639.67
	06-16-92	631.66		07-21-92	639.77
	07-24-92	631.50		08-17-92	639.20
	08-25-92	630.93		09-15-92	639.14
	09-17-92	631.15		10-22-92	640.28
	10-22-92	631.20		11-25-92	642.33
	11-25-92	632.92		01-29-93	644.05
	01-28-93	634.20		02-26-93	643.02
	02-26-93	632.80		03-18-93	643.22
	03-18-93	632.85		04-30-93	644.75
	04-30-93	634.50		05-20-93	642.96
	05-20-93	633.65		06-21-93	642.49
	06-21-93	632.46		07-22-93	639.91
	07-22-93	631.18			
G23	12-01-90	640.50	G24	12-01-90	641.00
	04-01-91	643.51		06-01-91	643.39
	06-01-91	643.04		08-01-91	637.93
	07-01-91	640.64		12-01-91	640.31
	08-01-91	637.60		01-28-92	640.68
	12-01-91	639.96		02-14-92	640.86
	01-28-92	640.32		03-13-92	642.13
	02-14-92	640.44		04-20-92	642.59
	03-13-92	641.75		05-07-92	642.69
	04-20-92	642.24		05-22-92	641.55
	04-29-92	642.99		06-19-92	640.76
	05-07-92	642.34		07-21-92	640.33
	05-22-92	641.20		08-17-92	640.32
	06-19-92	640.46		09-15-92	640.24
	07-21-92	639.98		10-22-92	641.41
	08-17-92	639.95		11-25-92	643.42
	09-15-92	639.88		01-29-93	645.20
	10-22-92	641.04		02-26-93	644.17
	11-25-92	643.05		03-18-93	644.35
	01-29-93	644.81		04-30-93	645.91
	02-26-93	643.79		05-20-93	644.16
	03-18-93	643.97		06-21-93	643.89
	04-30-93	645.52		07-22-93	640.83
	05-20-93	643.72			
	06-21-93	642.96			
	07-22-93	639.70			

Appendix 3. Altitude of water levels in U.S. Geological Survey observation wells, Monroe County, Michigan, 1990-93.

Well number	Date	Altitude of water (feet)
G25	12-01-90	639.50
	04-01-91	641.74
	05-01-91	641.74
	06-01-91	642.79
	07-01-91	640.12
	08-01-91	637.06
	12-01-91	639.72
	01-28-92	640.14
	02-14-92	640.33
	03-13-92	641.59
	04-20-92	642.10
	05-07-92	642.25
	05-22-92	641.06
	06-19-92	640.09
	07-21-92	639.59
	08-17-92	639.64
	09-15-92	639.68
	10-22-92	640.86
	11-25-92	642.92
	01-29-93	644.77
	02-26-93	643.69
	03-18-93	643.84
	04-30-93	645.48
	05-20-93	643.45
	06-21-93	643.08
	07-22-93	641.57
G26	12-01-90	633.90
	04-01-91	641.79
	06-01-91	636.79
	07-01-91	635.90
	08-01-91	634.12
	12-01-91	635.71
	01-28-92	635.11
	02-14-92	636.69
	03-13-92	638.20
	04-20-92	639.42
	04-29-92	639.97
	05-07-92	639.65
	05-22-92	639.04
	06-19-92	638.71
	07-21-92	636.71
	08-17-92	636.15
	09-15-92	635.91
	10-22-92	635.91
	11-25-92	635.91
	01-29-93	635.91
	02-26-93	635.91
	03-18-93	635.91
	04-30-93	641.96
	05-20-93	640.84
	06-23-93	637.60
	07-22-93	637.50
G27	12-01-90	635.40
	05-01-91	639.53
	08-01-91	630.35
	01-30-92	631.74
	02-14-92	631.60
	03-13-92	635.62
	04-20-92	636.65
	04-29-92	638.48
	05-07-92	638.01
	05-22-92	636.88
	06-19-92	636.43
	07-21-92	634.76
	08-17-92	633.67
	09-15-92	633.28
	10-22-92	634.70
	11-25-92	638.47
	01-29-93	640.42
	02-26-93	637.67
	03-18-93	638.58
	04-30-93	641.36
	05-20-93	639.90
	06-21-93	637.14
	07-22-93	634.15
G28	12-01-90	645.20
	05-01-91	662.11
	06-01-91	660.38
	07-01-91	656.90
	08-01-91	642.65
	12-01-91	643.47
	01-21-92	643.76
	02-14-92	644.29
	03-26-92	658.15
	04-20-92	654.30
	05-07-92	659.36
	05-22-92	656.25
	06-05-92	656.62
	06-19-92	656.39
	07-06-92	650.40
	07-15-92	653.17
	08-13-92	651.25
	09-15-92	648.98
	10-22-92	655.36
	11-25-92	663.84
	01-29-93	666.83
	02-26-93	660.23
	03-18-93	664.61
	04-30-93	667.08
	05-21-93	663.31
	06-21-93	659.62
	07-22-93	653.13

Appendix 3. Altitude of water levels in U.S. Geological Survey observation wells, Monroe County, Michigan, 1990-93.

Well number	Date	Altitude of water (feet)	Well number	Date	Altitude of water (feet)
G29	12-01-90	642.80	G30	12-01-90	648.40
	05-01-91	643.96		05-01-91	653.74
	06-01-91	642.50		06-01-91	653.29
	07-01-91	639.75		07-01-91	652.07
	08-01-91	636.96		08-01-91	650.49
	12-01-91	641.33		12-01-91	647.58
	01-21-92	642.31		01-21-92	651.94
	02-14-92	642.77		02-14-92	651.93
	03-26-92	644.44		03-26-92	653.35
	04-20-92	644.20		04-20-92	653.62
	05-07-92	644.30		04-28-92	653.83
	05-22-92	642.42		05-07-92	653.91
	06-19-92	641.12		05-22-92	653.24
	07-15-92	640.45		06-18-92	652.70
	08-13-92	641.28		07-15-92	652.01
	09-15-92	641.07		08-13-92	652.57
	10-22-92	642.22		09-11-92	652.23
	12-01-92	644.79		10-07-92	652.65
	01-19-93	645.15		12-01-92	654.22
	02-24-93	644.10		01-19-93	654.30
	03-30-93	646.21		02-24-93	653.96
	04-27-93	645.26		03-30-93	655.00
	05-21-93	642.42		04-27-93	654.40
	06-21-93	642.64		05-21-93	653.45
	07-23-93	639.72		06-21-93	653.01
				07-23-93	652.08
G31	12-01-90	634.30	G32	12-01-90	600.00
	05-01-91	636.72		05-01-91	601.45
	06-01-91	634.09		06-01-91	597.19
	07-01-91	631.07		07-01-91	598.65
	08-01-91	628.68		08-01-91	596.49
	12-01-91	630.25		12-01-91	597.82
	01-23-92	630.47		01-22-92	597.89
	02-14-92	629.99		02-14-92	598.32
	03-26-92	634.09		03-26-92	600.10
	04-20-92	634.20		04-20-92	600.14
	05-07-92	634.83		04-28-92	601.27
	05-22-92	633.25		05-07-92	602.00
	06-05-92	633.97		05-22-92	600.74
	06-18-92	633.09		06-05-92	600.73
	07-02-92	631.05		06-18-92	599.95
	07-15-92	630.85		07-02-92	595.12
	08-13-92	630.32		07-15-92	599.26
	09-11-92	630.70		08-13-92	598.72
	10-07-92	630.65		09-17-92	598.77
	12-01-92	634.57		10-20-92	599.18
	01-21-93	636.00		12-01-92	600.75
	02-24-93	633.90		01-21-93	601.35
	03-30-93	637.68		02-24-93	600.08
	04-27-93	635.96		03-30-93	601.80
	05-31-93	634.58		04-27-93	601.94
	06-21-93	634.50		05-21-93	600.34
	07-23-93	629.73		06-23-93	600.22
				07-23-93	594.87

Appendix 3. Altitude of water levels in U.S. Geological Survey observation wells, Monroe County, Michigan, 1990-93.

Well number	Date	Altitude of water (feet)
G33	12-01-90	569.40
	06-01-91	569.16
	07-01-91	568.22
	08-01-91	566.10
	12-01-91	567.21
	01-23-92	568.63
	02-14-92	568.61
	03-26-92	569.66
	04-20-92	570.05
	04-28-92	570.01
	05-07-92	569.98
	05-22-92	569.70
	07-02-92	568.48
	07-15-92	568.87
	08-13-92	568.94
	09-17-92	568.70
	10-20-92	568.63
	12-01-92	569.64
	01-19-93	570.05
	02-24-93	570.16
	03-30-93	570.76
	04-27-93	570.73
	05-21-93	570.11
	06-23-93	569.04
	07-23-93	567.98

APPENDIX 4:

Concentration limits defined by U.S. Environmental Protection Agency primary and secondary drinking-water regulations and implications for water use and ground-water geochemistry for selected properties and constituents in water samples collected at Monroe County, Michigan

Appendix 4. Concentration limits defined by U.S. Environmental Protection Agency Primary and Secondary Public Drinking-Water Regulations and implications for water use and ground-water geochemistry for selected properties and constituents in water samples collected in Monroe County, Michigan

[USEPA, U.S. Environmental Protection Agency; MCL, Maximum contaminant level; SMCL, Secondary maximum contaminant level; mg/L, milligrams per liter; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; NTU, nephelometric turbidity units]. MCL's and SMCL's are based on drinking water standards set by the U.S. Environmental Protection Agency (1992). MCL's are enforceable, health-based standards. SMCL's are non-enforceable recommended standards that are based on primarily on aesthetic criteria (color, taste, odor, staining potential) related to the public's acceptance of drinking water. Geochemical implications of each water property or constituent as they relate to this study are based on results given in the text and the discussion of natural water chemistry given by Hem (1989)].

Constituent or Property	Concentration Limits and Water Use Implications	Implications for Ground-Water Geochemistry
Specific conductance, µS/cm	Regulatory standards not established.	Proportional to total ion concentration in solutions and can be used to indicate relative concentrations of dissolved solutes between different water samples.
pH, standard units	Esthetic--SMCL standard is range from 6.5 to 8.5. Values outside of this range may contribute to corrosive water and corrosion of pipes.	General measure of the acidity or alkalinity of a water sample. One of the most important properties with respect to regulating the transport of metals, organics, and other dissolved constituents in ground water. Also controls dissolution-precipitation reactions in the aquifer.
Temperature, °C (Celsius)	Regulatory standards not established.	Needed for speciation and saturation-state calculations. May be used to identify recharge-discharge zones.
Turbidity, NTU(s)	Health-MCL is 0.5-1.0 NTU. Excessive turbity may interfere with disinfection processes and is measured to monitor the efficiency of public-water-supply filtration systems used to remove parasites and viruses in water.	No implications, although turbid ground water may be found in poorly constructed wells screened in fine-grained sediments. In carbonate aquifers, persistent, elevated turbidity may indicate that the aquifer is affected by direct recharge of stormwater or waste-waters through nearby sinkholes or fractures. Such wells may be vulnerable to contamination.
Dissolved oxygen, mg/L	Regulatory standards not established with respect to drinking water.	Atmospheric oxygen dissolves in shallow groundwater and its presence at concentrations exceeding reporting limits indicates highly oxidizing conditions. Oxygen reacts with organic matter, ferrous iron, or sulfide-bearing minerals. The presence of dissolved oxygen in deep parts of an aquifer indicates rapid recharge rates or a lack of oxidizable material in aquifer rocks and sediments.

Appendix 4. Concentration limits defined by U.S. Environmental Protection Agency Primary and Secondary Public Drinking-Water Regulations and implications for water use and ground-water geochemistry for selected properties and constituents in water samples collected in Monroe County, Michigan--Continued

Constituent or Property	Concentration Limits and Water Use Implications	Implications for Ground-Water Geochemistry
Hardness, mg/L as $CaCO_3$	Esthetic--Hard water precipitates carbonate mineral deposits, scale, and crusts on pipes, hot water heaters, boilers and cooking utensils. Also causes increased soap consumption. Public water supplies typically softened water with hardness concentrations greater than 100 mg/L.	Hardness is caused by high concentrations of calcium magnesium, and strontium. Waters with hardness greater than 200 or 300 mg/L are typically associated with carbonate- or gypsum-bearing aquifers such as the Silurian-Devonian carbonate aquifer of Monroe County.
Alkalinity, mg/L as $CaCO_3$	Regulatory standards not established. No health or esthetic implications for the range of concentrations found in this study. Alkalinity is a measure of the capacity of a water to neutralize acid.	In carbonate-bearing aquifers, most alkalinity is due to the presence of the bicarbonate ion (HCO_3^-) which is derived from the dissolution of carbonates by carbonic acid. Minor contributors to alkalinity include the carbonate (CO_3^{2-}) and hydroxide (OH^-) ions.
Dissolved solids, sum of constituents, mg/L	Esthetic--SMCL is 500 mg/L. Concentrations greater than 1,000 mg/L may cause objectionable tastes and have laxative effects. May also cause foaming or may corrode some metals.	General indicator of water quality and can be used to classify water types. Calculated from analytical sum of dissolved consituents. Value should be close to the solids concentration determined by evaporating a known volume of sample at 180°C.
Calcium, dissolved, mg/L	Esthetic--Regulatory standards not established. Major contributor to hardness and scale formation.	In carbonate-bearing aquifers, is derived from the dissolution of calcite or dolomite and, in some instances, gypsum. Concentrations of calcium are usually regulated by equilibria with carbonate minerals, pH and pCO_2.
Magnesium, dissolved, mg/L	Esthetic--Regulatory standards not established. Contributes to hardness and scale formation. At high concentrations (> 125 mg/L) may cause laxative effects, especially to transient users.	In the carbonate-bearing-Silurian aquifers, most magnesium is derived from the dissolution of dolomite or high-Mg calcite.
Sodium, dissolved, mg/L	Health-Health advisory level is 20 mg/L for persons with medical reasons for moderating dietary intake of sodium. Otherwise, sodium in water is not dangerous to human health.	May be derived from the dissolution of sodium-bearing aluminosilicate minerals or halite. In carbonate aquifers, high sodium concentrations are commonly indicative of the effects of human activities such as road deicing or leaking septic tanks.
Potassium, dissolved, mg/L	Regulatory standards not established. No health or esthetic implications for the range of concentrations found in this study.	Typically derived from the dissolution of K-bearing aluminosilicate minerals. Concentrations are typically low because of the low reactivity of the K-bearing silicate minerals. Elevated concentrations may be caused by sylvite (KCl) in road salt.

Appendix 4. Concentration limits defined by U.S. Environmental Protection Agency Primary and Secondary Public Drinking-Water Regulations and implications for water use and ground-water geochemistry for selected properties and constituents in water samples collected in Monroe County, Michigan--Continued

Constituent or Property	Concentration Limits and Water Use Implications	Implications for Ground-Water Geochemistry
Sulfate, dissolved mg/L	Esthetic-SMCL is 250 mg/L. Combines with calcium to form scale in water heaters and boilers. At concentrations exceeding 500-600 mg/L, imparts a bitter taste and may cause laxative effects in some individuals. A proposed MCL of 500 mg/L is currently under review by USEPA.	Derived from dissolution of gypsum or the oxidation of sulfide minerals such as pyrite. Stable under oxidizing conditions; however, under reducing conditions, can be converted to H_2S.
Hydrogen sulfide, mg/L as S	Regulatory limits not established. Hydrogen sulfide imparts an objectionable rotten-egg odor to water. H_2S concentrations less 0.1 a mg/L are noticeable to most people. Can also corrode metal pipes and fixtures. Waters with excessive H_2S are commonly aerated to remove H_2S.	H_2S is produced in aquifers by the reduction of sulfate. Sulfate reduction is usually bacterially mediated and is particularly prevalent in aquifers that contain abundant sources of organic carbon (such as petroleum, lignite).
Chloride, dissolved, mg/L	Esthetic-SMCL is 250 mg/L. At concentrations greater than 250 to 400 mg/L, imparts a salty taste to water. High concentrations are corrosive to most metals.	Derived from the dissolution of halite. High concentrations indicate inputs of saline brine of either natural or human origin.
Fluoride, dissolved, mg/L	Health--MCL is 4.0 mg/L. SMCL is 2.0 mg/L. Beneficial to development and health of children's teeth at concentrations below 2.0 mg/L. At higher concentrations, causes mottling of teeth enamel and skeletal fluorosis.	Major source is fluorite. Fluoride is also derived from F-bearing micas and phosphate minerals. Fluorite is a minor component of carbonate rocks in the Silurian-Devonian aquifer in Monroe County.
Silica, dissolved mg/L	No health or esthetic implications for the range of concentrations determined in this study.	Used to evaluate controls on silica concentration.
Nitrite, dissolved mg/L as N	Health--MCL is 1.0 mg/L as N. Concentrations exceeding the MCL may cause methemoglobinemia (blue-baby syndrome) in bottle-fed infants.	Not found naturally in most aquifers. Presence of nitrite at elevated concentrations (>0.10 mg/L) is indicative of anthropogenic sources of nitrogen (fertilizer, septic-tank leakage) and vulnerability of the aquifer is to infiltration by surface drainage. Rapidly oxidized to nitrate.
Nitrate, dissolved, mg/L as N	Health--MCL is 10.0 mg/L as N. Concentrations exceeding the MCL may cause methemoglobinemia (blue-baby syndrome) in bottle-fed infants.	Presence of nitrate indicates oxidizing conditions in an aquifer. Elevated concentrations (>0.50 mg/L) are indicative of anthropogenic sources of nitrate (fertilizer, septic tank leakage) and vulnerability of the aquifer to infiltration of surface drainage.

Appendix 4. Concentration limits defined by U.S. Environmental Protection Agency Primary and Secondary Public Drinking-Water Regulations and implications for water use and ground-water geochemistry for selected properties and constituents in water samples collected in Monroe County, Michigan--Continued

Constituent or Property	Concentration Limits and Water Use Implications	Implications for Ground-Water Geochemistry
Aluminum, dissolved, µg/L	Esthetic--SMCL is 0.05-0.2 mg/L. Elevated concentrations can cause discoloration of plumbing fixtures. No health or esthetic implications for the range of concentrations found in this study.	Virtually insoluble at near-neutral pH.
Arsenic, dissolved, µg/L	Health--MCL is 50 µg/L, but is currently under review. High toxicity effects dermal and nervous system. No health implications for the range of concentrations found in this study.	Unlikely to be present at more than trace concentrations in the aquifer materials of Monroe County. Anthropogenic sources include pesticides and industrial wastes.
Barium, dissolved, µg/L	Health--MCL of 2,000 µg/L is based on effects to the circulatory system. No health implications for the range of concentrations found in this study.	Maximum concentrations are typically limited by the solubility of barite. Barite is a minor constituent in carbonate rocks that compose the Silurian-Devonian aquifer in Monroe County.
Beryllium, dissolved, µg/L	Health--MCL of 4 µg/L is based on toxicity effects. No health implications for the range of concentrations found in this study.	Unlikely to be present at more than trace concentrations in the aquifer materials of Monroe County.
Cadmium, dissolved, µg/L	Health--MCL of 5 µg/L is based on toxic effects to the kidneys. No health implications for the range of concentrations observed in this study.	Unlikely to be present at more than trace concentrations in the aquifer materials of Monroe County. Anthropogenic sources of cadmium include metal-plating wastes and corrosion of metal plumbing fixtures.
Chromium, dissolved, µg/L	Health-MCL of 100 µg/L is based on toxic effects to the skin, liver, kidneys, and digestive system. No health implications for the range of concentrations found in this study.	Unlikely to be present at more than trace concentrations in the aquifer materials of Monroe County. Anthropogenic sources include metal finishing, textile and leather industries.
Cobalt, dissolved, µg/L	No regulatory standards established.	Unlikely to be present at more than trace concentrations in the aquifer materials of Monroe County.
Copper, dissolved, µg/L	Esthetic-SMCL is 1,000 µg/L because of taste effects and potential for staining of porcelain fixtures. At extreme concentrations may cause stomach and intestinal distress.	Unlikely to be present at more than trace concentrations in the aquifer materials of Monroe County. Anthropogenic sources include copper pipes and plumbing fixtures.

Appendix 4. Concentration limits defined by U.S. Environmental Protection Agency Primary and Secondary Public Drinking-Water Regulations and implications for water use and ground-water geochemistry for selected properties and constituents in water samples collected in Monroe County, Michigan--Continued

Constituent or Property	Concentration Limits and Water Use Implications	Implications for Ground-Water Geochemistry
Iron, dissolved, µg/L	Esthetic--SMCL is 300 µg/L. At concentrations exceeding the SMCL iron contributes to a metallic taste and staining of fixtures, utensils, and laundry. Higher concentrations form reddish-brown ferric hydroxide sediment, coatings, and stains.	General redox indicator. Dissolved iron concentrations are below detection limits in oxygenated waters at near neutral pH. Under more reducing conditions dissolved-iron concentrations can exceed several mg/L. Oxidation of pyrite and dissolution of iron hydroxide coatings on sediments are the main natural sources of iron.
Lead, dissolved, µg/L	Health--The MCL was 50 µg/L, but proposed legislation would lower the MCL to 5 µg/L. Action level (concentration at which action must be taken to remove lead from drinking water) is currently 15 µg/L. Lead affects the kidneys and nervous system and is highly toxic to infants and pregnant women.	May be derived from trace amounts of the lead sulfide mineral galena in carbonate rocks of the Silurian Devonian aquifer; however, a more likely source of lead in drinking water is lead pipes in older buildings and houses.
Lithium, dissolved, µg/L	No regulatory limits established. Lithium concentrations in irrigation water that exceed 100 µg/L have been known to cause toxic effects on certain plant groups. No health or esthetic implications for the range of concentrations found in this study.	Rare element that is unlikely to be present at more than trace concentrations in the aquifer materials of Monroe County. Lithium may be found in road salt at trace concentrations.
Manganese, dissolved, µg/L	esthetic--SMCL is 50 µg/L. At concentrations exceeding the SMCL, manganese may cause dark brown or black staining of laundry, utensils, and porcelain fixtures.	Concentrations controlled by various oxide and oxy-hydroxide equilibria. Dissolution of Mn-oxide coatings under reducing conditions is a likely source of dissolved manganese.
Molybdenum, dissolved, µg/L	No regulatory standards established. No health or esthetic implications for range of concentrations found in this study.	Rare element that is unlikely to be present at more than trace concentrations in aquifer materials of Monroe County.
Nickel, dissolved, µg/L	Health--MCL of 100 µg/L is based on health effects. No health implications for the range of concentrations found in this study.	Minor element that is unlikely to be present at more than trace concentrations in aquifer materials of Monroe County. Often precipitates with iron hydroxides.
Silver, dissolved, µg/L	Health--SMCL is 100 µg/L. Concentrations exceeding the SMCL may result in skin discoloration.	Unlikely to be present at more than trace levels in aquifer materials of Monroe County. Anthropogenic sources include chemicals used to process photographic materials and industrial waste.

Appendix 4. Concentration limits defined by U.S. Environmental Protection Agency Primary and Secondary Public Drinking-Water Regulations and implications for water use and ground-water geochemistry for selected properties and constituents in water samples collected in Monroe County, Michigan--Continued

Constituent or Property	Concentration Limits and Water Use Implications	Implications for Ground-Water Geochemistry
Strontium, dissolved, mg/L	No regulatory standards established, listed for future regulation by USEPA. No health implications for the range of concentrations found in this study, although high Sr concentrations of Silurian-Devonian waters make significant contributions to the overall hardness of ground water in Monroe County.	Unusually high concentrations of strontium in some ground water samples collected from the Silurian-Devonian aquifer reflect the presence of celestite. In sulfate-rich waters, strontium concentrations are regulated by celestite solubility, whereas in more dilute bicarbonate waters, strontium concentrations may reflect equilibrium with strontionite.
Vanadium, dissolved, µg/L	No regulatory standards established. No health or esthetic implications for the range of concentrations found in this study.	Minor element unlikely to be found at more than trace concentrations in aquifer materials of Monroe County.
Zinc, dissolved, µg/L	Esthetic--SMCL is 5,000 µg/L is based on taste considerations.	May be derived from oxidation of trace amounts of sphalerite in carbonate rocks of the Silurian Devonian aquifer. Anthropogenic sources include galvanized steel and paint.
Dissolved organic carbon mg/L	Regulatory limits not established. No health or esthetic implications for the range of concentrations found in this study.	Concentrations greater than 3-4 mg/L are unusual for ground water and may indicate the presence of hydro-carbon compounds of natural or anthropogenic origin.
δD, $\delta^{18}O$, $\delta^{13}C$, $\delta^{34}S$, stable isotope ratios, per mil	Not applicable.	Used to evaluate sources of water, dissolved carbon and sulfur.
Tritium ^{3}H, tritium units	Regulatory limits not established. No health or aesthetic implications for the range of concentrations found in this study.	Radioactive isotope of hydrogen produced naturally in the upper atmosphere and also produced during the period of atomic-bomb testing in early 1950's and 1960's. Used to estimate approximate recharge age of ground water.
Carbon-14 (^{14}C), percent modern carbon	Not applicable.	Radioactive isotope of carbon produced naturally in the upper atmosphere of the earth and by atomic-bomb testing. With a half-life of 5700 years it can be used to date waters as much as 50,000 years old.

Appendix 4. Concentration limits defined by U.S. Environmental Protection Agency Primary and Secondary Public Drinking-Water Regulations and implications for water use and ground-water geochemistry for selected properties and constituents in water samples collected in Monroe County, Michigan--Continued

Constituent or Property	Concentration Limits and Water Use Implications	Implications for Ground-Water Geochemistry
Fecal coliform bacteria, colonies per 100 milliliters water	Health-Current regulatory standards for drinking water suppliers are based on presence or absence of total coliform bacteria. Fecal coliform determinations are required on any sample testing total coliform positive. Coliform bacteria are indicator organisms used to indicate the presence of viruses and other pathogenic organisms. More than 1 fecal coliform colony indicates that the water supply may be vulnerable to contamination by human or animal fecal waste. For surface waters, a set of contact-based standards are applied. These are discussed in the surface-water quality section.	

APPENDIX 5:

Field and laboratory procedures for water quality samples collected by the U.S. Geological Survey in Monroe County, Michigan, 1990-92

Appendix 5. Field and laboratory procedures for water-quality samples collected by the U.S. Geological Survey in Monroe County, Michigan, 1990-92

Temperature, specific conductance, pH, dissolved-oxygen concentration (DO) concentration, and alkalinity of ground-water samples were determined in the field according to methods given by Wood (1976). Specific conductance, pH, and DO were measured in a closed flow through cell to prevent degassing of carbon dioxide and other dissolved gases that could affect measurement of pH. Samples were collected after three well volumes had been purged from the well and after temperature, specific conductance, pH, and DO had stabilized. Samples collected for the determination of major and minor cations and anions were collected in 1-L polypropylene bottles. Samples used to determine concentrations of major cations and selected trace metals were filtered through 0.45-µm membrane filters (142 mm in diameter) and were acidified to a pH of 1.0 to 2.0 with ultrapure nitric acid. Filtered samples for major-anion determinations were not acidified, and samples used to determine alkalinity were neither filtered nor acidified. Samples for determination of hydrogen sulfide were stabilized for transport by the addition of zinc acetate. For dissolved nitrogen species, 125 mL of filtered, unacidified sample was treated with mercuric chloride to prevent bacterial activity; these samples were placed in ice-filled coolers and shipped to the USGS laboratory. Samples collected for determination of dissolved organic carbon were filtered with 0.45-µm silver membrane filters by use of a stainless steel, nitrogen-pressurized filter chamber, and placed in 125-ml amber glass bottles.

For determination of hydrogen and oxygen stable isotope ratios, 125 mL of raw water was placed in a polypropylene bottle with a polyseal cap. For tritium determinations, 1 L of unfiltered water was placed in a glass bottle with a polyseal cap. Water samples for determination of $^{13}C/^{12}C$ ratios and ^{14}C activities were collected by adding sodium hydroxide and strontium chloride to 20 to 60 L of ground water so that all dissolved inorganic carbon in the sample would precipitate as strontium carbonate. Sulfur isotope ratios of dissolved sulfate in ground water were determined on solid barium sulfate precipitates that were obtained by adding barium chloride to a filtered, acidified sample.

Surface-water-quality samples were collected by use of a D-77 water sampler if stream depth and velocity permitted or by use of a DH-81 sampler if the stream depth was less than 2 ft (Ward and Harr, 1990). Depending on stream width and depth, from three to six vertically integrated subsamples were collected and subsequently integrated to form one composite sample. Temperature, specific conductance, pH, and DO were measured in the field by use of a Hydrolab[1] four-parameter meter that was calibrated according to the manufacturer's instructions (Hydrolab Corporation, 1979). All measurements were made by placing the meter sensors a few inches below the stream surface, either from a bridge or by wading. Samples for determination of fecal coliform bacteria concentrations were collected in a manner that minimized contamination of the sterile sample bottles (Britton and Greeson, 1987). Bacteriological samples were kept in the original sample containers until they were analyzed. Water samples for chemical analysis were placed in clean polypropylene bottles. Bacteriological and chemical samples were both placed in ice chests and maintained at 4 °C until analysis. Mercuric chloride was added to samples used for nitrogen species determinations.

Laboratory analyses for major ions, metals, nitrogen species, pH, alkalinity, dissolved solids, specific conductance, and dissolved organic carbon were done at the USGS National Water Quality Laboratory in Arvada, Colo. Descriptions of analytical and standardization techniques, analytical equipment used, and precision and reliability of the analytical results can be found in Fishman and Friedman (1989) and Friedman and Erdmann (1982). Stable isotope analyses for oxygen and hydrogen in water were done at the USGS Stable Isotope Laboratory in Reston, Va. Stable-isotope analyses for carbon and sulfur were done at USGS laboratories in Menlo Park, Calif., and Denver, Colo., respectively; tritium and ^{14}C determinations were done by USGS contract laboratories.

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[1] Any use of trade, product, firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

APPENDIX 6:

Pesticides analyzed for in ground-water samples collected by Michigan Department of Agriculture, Monroe County, Michigan, September 1991

Appendix 6.--Pesticides analyzed for in ground-water samples collected by the Michigan Department of Agriculture, Monroe County, Michigan, September, 1991.

[Detection limits in milligrams per liter]

Analyte	Detection limit	Analyte	Detection limit
Alachlor	0.001	Fluometuron	0.001
Ametryn	.001	Hexazinone	.005
Atrazine	.001	Linuron	.001
Barban	.005	Metolachlor	.001
Bromacil	.002	Metribuzin	.001
Butachlor	.002	Neburon	.001
Butylate	.002	Prometon	.001
Carboxin	.002	Pronamide	.001
Chlorothalonil	.001	Propachlor	.003
Cyanazine	.001	Propanil	.002
Cycloate	.002	Propazine	.001
Dacthal	.001	Propham	.005
Diphenamid	.001	Simazine	.001
Disulfoton	.002	Tebuthiuron	.005
Diuron	.001	Terbacil	.002
Fenamiphos	.001		

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PREPARED IN COOPERATION WITH
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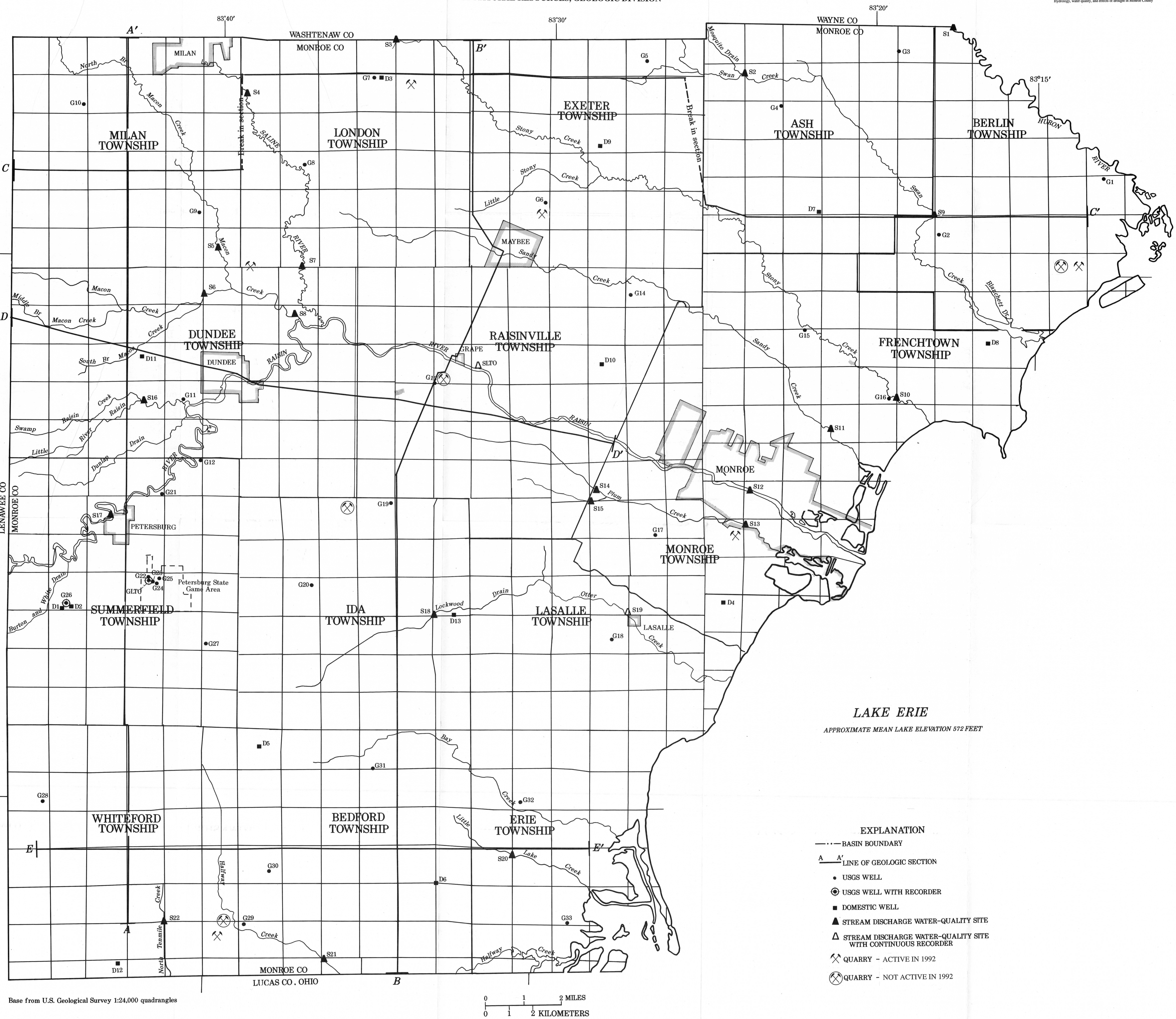
OF NATURAL RESOURCES, GEOLOGIC DIVISION

WATER-RESOURCES INVESTIGATIONS REPORT 94-4161
Hydrology, water quality, and effects of drought–PLATE 1
Nicholas, J.R., Rowe, G.L., and Brannen, J.R., 1996,
Hydrology, water quality, and effects of drought in Monroe County



Base from U.S. Geological Survey 1:24,000 quadrangles

LOCATION OF DATA-COLLECTION SITES AND OTHER FEATURES OF MONROE COUNTY, MICHIGAN.

By
J.R. Nicholas, Gary L. Rowe, and J.R. Brannen
1996

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MONROE COUNTY, THE TOWNSHIPS OF MONROE COUNTY, THE CITY OF PETERSBURG,
THE CITY OF MONROE, AND THE MICHIGAN DEPARTMENT
OF NATURAL RESOURCES, GEOLOGIC DIVISION

WATER-RESOURCES INVESTIGATIONS REPORT 94-4161
Hydrology, water quality, and effects of drought–PLATE 2
Nicholas, J.R., Rowe, G.L., and Brannen, J.R., 1996,
Hydrology, water quality, and effects of drought in Monroe County

FENCE DIAGRAM IN MONROE, COUNTY, MICHIGAN.

By
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1996

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