

# **MICHIGAN GROUND-WATER QUALITY**

*By* D.H. Dumouchelle and T.R. Cummings, U.S. Geological Survey  
and  
G.R. Klepper, Michigan Department of Natural Resources

U.S. Geological Survey Open-File Report 87-0732

DEPARTMENT OF THE INTERIOR  
DONALD PAUL HODEL, *Secretary*

U.S. GEOLOGICAL SURVEY  
Dallas L. Peck, *Director*

---

For additional information:

Chief Hydrologist  
U.S. Geological Survey  
407 National Center  
Reston, VA 22092

For sale by:

U.S. Geological Survey  
Books and Open-File Reports Section  
Federal Center  
Box 25425  
Denver, Colorado 80225

Use of trade names in this report is for descriptive purposes only and  
does not constitute endorsement by the U.S. Geological Survey

## FOREWORD

This report contains summary information on ground-water quality in one of the 50 States, Puerto Rico, the Virgin Islands, or the Trust Territories of the Pacific Islands, Saipan, Guam, and American Samoa. The material is extracted from the manuscript of the *1986 National Water Summary*, and with the exception of the illustrations, which will be reproduced in multi-color in the *1986 National Water Summary*, the format and content of this report is identical to the State ground-water-quality descriptions to be published in the *1986 National Water Summary*. Release of this information before formal publication in the *1986 National Water Summary* permits the earliest access by the public.

## Contents

Ground-Water Quality .....	1
Water-Quality in Principal Aquifers .....	1
Background Water Quality .....	1
Effects of Land Use on Water Quality .....	2
Waste Disposal and Spills .....	2
Agricultural Practices .....	2
Salt Storage and Use .....	3
Water Withdrawal .....	3
Potential for Water-Quality Changes .....	3
Ground-Water-Quality Management .....	3
Selected References .....	4

## Illustrations

Figure 1.--Selected geographic feature and 1985 population distribution in Michigan. ....	5
Figure 2.--Principal aquifers and related water-quality data in Michigan. ....	6
Figure 3.--Selected waste sites and ground-water quality information in Michigan. ....	7
Figure 4.--Areal predominance of total recoverable iron in ground water in Michigan. ....	8

# MICHIGAN

## Ground-Water Quality

Ground water is the source of 17 percent of public-water supplies and almost 100 percent of the rural-domestic water supplies in Michigan (Bedell, 1982) (fig. 1.) About 43 percent of Michigan's residents depend on ground-water supplies (U.S. Geological Survey, 1985). Most natural ground water contains dissolved constituents in amounts that do not exceed the U.S. Environmental Protection Agency's national drinking-water standards (1986a,b); at some locations, however, the concentrations of dissolved solids, iron, manganese, and lead equal or exceed the standards (fig. 2). Ground water in the southeastern part of the State tends to have larger concentrations of dissolved solids, hardness, ammonia, barium, sodium, sulfate, and chloride than elsewhere. Statewide, the dissolved-solids concentrations of water are larger in bedrock aquifers than in glacial aquifers (Cummings, 1980). Ground-water quality is affected by waste disposal and spills, agricultural activities, storage and use of road salts, brine disposal, and pumping-induced movement of deeper lying saline waters (Deutsch 1961a,b; 1962; 1963).

The U.S. Environmental Protection Agency (1986c) has identified 56 National Priorities List (NPL) sites that require evaluation under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980 (fig. 3). At 42 sites, disposal of hazardous materials requires ground-water monitoring under the Federal Resource Conservation and Recovery Act (RCRA) of 1976. The U.S. Department of Defense (DOD) has identified 49 sites at 6 federally owned facilities as having potential for contamination. In addition, the Michigan Department of Natural Resources (1986b) has identified more than 1,000 sites with environmental contamination. Ground-water contamination has been detected at 49 of the NPL sites and at more than 700 of the State-identified locations.

### WATER QUALITY IN PRINCIPAL AQUIFERS

#### BACKGROUND WATER QUALITY

In a discussion of Michigan's ground-water resources, the U.S. Geological Survey (1985, p. 255-260) identified three glacial aquifers and five bedrock aquifers that yield significant quantities of water to wells (figs. 2A,B). Of the glacial aquifers, yields generally are largest from outwash and glaciofluvial deposits, although yields range from 1 to 1,000 gal/min (gallons per minute). Lacustrine sand aquifers typically yield less water (80 to 500 gal/min), and till aquifers (5 to 200 gal/min) still less. Among bedrock aquifers the Saginaw and Marshall Formations in the Lower Peninsula are the most productive; yields commonly range from 100 to 500 gal/min. In the Upper Peninsula, Silurian-Devonian rocks (10 to 300 gal/min), Cambrian-Ordovician rocks (10 to 100 gal/min), and Precambrian sandstone (5 to 50 gal/min) are important sources of water.

In 1974, the Geological Survey Division of the Michigan Department of Natural Resources (MDNR) and the U.S. Geological Survey began a cooperative program to investigate the natural characteristics of water in aquifers in the State. The program is a continuing one in which carefully selected wells are sampled each year. New wells also have been drilled in some of the principal aquifers to monitor both water quality and water levels. Laboratory analyses normally are made for more than 60 naturally occurring substances and properties. In addition, analyses are made for synthetic substances to determine their presence or absence. Frequency data for some of the substances and properties, based on the analyses of 113 samples collected statewide (Cummings, 1980), are given in the following table.

The table indicates how often values of a given magnitude may be expected in natural waters of Michigan. For example, 10

Constituent or property ( $\mu\text{g/L}$ , micrograms per liter; $\text{mg/L}$ , milligrams per liter; $^{\circ}\text{C}$ , degrees Celsius)	Maximum constituent or property value occurring for the indicated percentile				
	10	25	50	75	90
Aluminum, total recoverable ( $\mu\text{g/L}$ as Al)	7	19	31	56	150
Arsenic, total ( $\mu\text{g/L}$ as As)	0	0	1	2	5
Barium, total recoverable ( $\mu\text{g/L}$ as Ba)	0	0	0	84	127
Cadmium, total recoverable ( $\mu\text{g/L}$ as Cd)	0	0	1	2	9
Calcium, dissolved ( $\text{mg/L}$ as Ca)	20	34	48	64	97
Chloride, dissolved ( $\text{mg/L}$ as Cl)	.7	1.1	2.2	14	54
Chromium, total recoverable ( $\mu\text{g/L}$ as Cr)	2	8	9	10	11
Cobalt, total recoverable ( $\mu\text{g/L}$ as Co)	0	0	1	2	5
Copper, total recoverable ( $\mu\text{g/L}$ as Cu)	1	2	5	10	20
Cyanide, total ( $\text{mg/L}$ as CN)	.00	.00	.00	.00	.00
Fluoride, dissolved ( $\text{mg/L}$ as F)	0	0	1	.3	.6
Germanium, total ( $\mu\text{g/L}$ as Ge)	<2	<3	<4	<10	<23
Hardness ( $\text{mg/L}$ as $\text{CaCO}_3$ )	75	119	178	244	375
Iron, total recoverable ( $\mu\text{g/L}$ as Fe)	51	160	740	2,400	4,300
Lead, total recoverable ( $\mu\text{g/L}$ as Pb)	2	5	11	21	78
Manganese, total recoverable ( $\mu\text{g/L}$ as Mn)	6.5	9.8	36	120	200
Mercury, total recoverable ( $\mu\text{g/L}$ as Hg)	.0	.0	.4	.5	5
Nickel, total recoverable ( $\mu\text{g/L}$ as Ni)	0	2	5	9	16
Nitrogen, Ammonia, total ( $\text{mg/L}$ as N)	.00	.00	.04	.16	.37
Nitrogen, Nitrate, total ( $\text{mg/L}$ as N)	.00	.00	.00	.07	.24
pH (units)	7.3	7.5	7.7	7.9	8.1
Phenols ( $\mu\text{g/L}$ )	0	0	0	0	2
Phosphorus, total ( $\text{mg/L}$ as P)	.00	.00	.01	.03	.07
Selenium, total ( $\mu\text{g/L}$ as Se)	0	0	0	0	0
Silver, total recoverable ( $\mu\text{g/L}$ as Ag)	0	0	0	0	1
Sodium, dissolved ( $\text{mg/L}$ as Na)	1.1	1.9	3.4	12	55
Solids, residue at $180^{\circ}\text{C}$ , dissolved ( $\text{mg/L}$ )	106	145	223	360	630
Sulfate, dissolved ( $\text{mg/L}$ as $\text{SO}_4$ )	3.1	6.5	12	35	170
Titanium, total ( $\mu\text{g/L}$ as Ti)	1	2	5	14	120
Uranium, dissolved ( $\mu\text{g/L}$ as U)	.00	.03	.11	.24	.46
Zinc, total recoverable ( $\mu\text{g/L}$ as Zn)	6	13	65	240	710

percent of the chloride concentrations are equal to or less than 0.7 mg/L; 90 percent of the concentrations are equal to or less than 54 mg/L.

Concentrations of most substances are within the range common for ground water, with the exception of the concentrations of iron, aluminum, and titanium. Maximum concentrations of these substances were: iron, 29,000  $\mu\text{g/L}$  (micrograms per liter); aluminum, 44,000  $\mu\text{g/L}$ ; and titanium, 3,600  $\mu\text{g/L}$ .

National standards that specify the maximum concentration or level of a contaminant in a drinking-water supply have been established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. A comparison of the frequency data for natural water quality to these national drinking-water standards indicates that most substances and properties do not exceed the standards. However, there are exceptions. For example, 15 percent of the dissolved-solids concentrations equaled or exceeded the standard. Similarly, 44 percent of the iron concentrations, 30 percent of the manganese concentrations, and 13 percent of the lead concentrations did also.

Geologic conditions are a principal factor determining the areal variation in the natural quality of ground water throughout the State, although differences can also be due to hydrologic conditions. Data are inadequate, however, to establish the chemical characteristics of water in each glacial and bedrock aquifer or to permit conclusions regarding differences in quality. In general, chemical characteristics seem to be related more to mineralization than to a specific aquifer; however, areal variations in the concentrations of some substances are evident.

Some of the chemical characteristics of water of each aquifer are shown in figure 2C, which is a statistical summary of concen-

trations of dissolved solids, hardness, nitrate, chloride, and iron. The summary is based on selected chemical data available in the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE). Water of the Saginaw Formation has larger concentrations of dissolved solids, iron, and hardness than water from glacial deposits or other bedrock aquifers. This condition may be attributed to the fact that the Saginaw Formation contains considerable shale and coal and, at places, may contain saline water. A comparison of water from glacial deposits with that in bedrock aquifers by Cummings (1980) indicated that the mean dissolved-solids concentration of water from bedrock aquifers was 535 mg/L (milligrams per liter), whereas the mean dissolved-solids concentration of water from glacial deposits was 241 mg/L.

Analyses of data (Cummings, 1980) indicated that water-quality characteristics—such as iron, dissolved solids, lead, hardness, barium, and ammonia—exhibited distinguishable areal variations. For example, the variation in total recoverable iron concentrations statewide is shown in figure 4. In general, ground water has a larger iron concentration in the southeastern part of the Lower Peninsula and in the western and eastern parts of the Upper Peninsula than in other parts of the State. For other constituents, with the exception of lead, concentrations generally are larger in the southeastern part of the State. Many wells in this area obtain water from bedrock, which normally contains water that is more extensively mineralized. In addition to the characteristics cited, sodium, sulfate, and chloride concentrations also tend to be larger in the southeastern part of the State than elsewhere.

Statewide, waters having a small dissolved-solids concentration generally are calcium bicarbonate waters; that is, the calcium constitutes more than 50 percent of the cations and bicarbonate constitutes more than 50 percent of the anions if concentrations are converted to milliequivalents per liter. As the dissolved-solids concentration of a typical water increases, the proportion of sodium, sulfate, and chloride increases. Sulfate increases most rapidly when dissolved solids increase and that increase is accompanied by a proportional decrease in bicarbonate. A decrease in calcium is balanced by a corresponding increase in sodium. Magnesium does not change appreciably. In general, the concentrations of major dissolved substances increase as dissolved-solids concentration increases. Concentrations of most trace substances, however, seem to be unrelated to the dissolved-solids concentration of the water.

## EFFECTS OF LAND USE ON WATER-QUALITY

The chemical characteristics of ground water in Michigan are modified chiefly by industrial and municipal waste-disposal activities or accidental spills of hazardous materials, agricultural activities, use and storage of road salts, pumping-induced movement of deeper lying saltwaters into shallow freshwater aquifers, and improper handling of brines produced during oil drilling. Early studies by Deutsch (1961a,b; 1962; 1963) documented several instances of ground-water contamination in Michigan.

## Waste Disposal and Spills

Fifty-six (CERCLA) sites (fig. 3A) have been identified and included on the NPL in Michigan by the U.S. Environmental Protection Agency (1986c). Ground-water contamination has been detected at 49 of these sites. An additional six sites are proposed for inclusion on the NPL. Hazardous wastes are disposed in 42 RCRA sites (fig. 3A), most of which are located in the southeastern part of the Lower Peninsula. Ground water near older RCRA sites may be contaminated.

As of September 1985, 49 hazardous-waste sites at 6 federal facilities in Michigan have been identified by the DOD as part of their Installation Restoration Program (IRP) as having potential for contamination. The IRP, established in 1976, parallels the U.S. Environmental Protection Agency (EPA) Superfund program under the

CERCLA. The EPA presently ranks these sites under a hazard ranking system and may include them in the NPL. Of the 49 sites evaluated under the program, 9 contained contaminants but did not present a hazard to people or the environment. Nine sites at 3 facilities (fig. 3A) were considered to present a hazard significant enough to warrant response action in accordance with CERCLA.

The MDNR has identified more than 1,000 sites where air, soil, or water has been contaminated (fig. 3B) (Michigan Department of Natural Resources, 1986b). Many of the sites are located near major cities such as Detroit, Grand Rapids, Kalamazoo, Lansing, and Pontiac. Ground-water contamination has been detected at 739 sites; the principal causes of the contamination (Michigan Department of Natural Resources, 1986b) are identified:

Cause of ground-water contamination	Percentage of contamination (739 sites)
Petroleum-related	26
Landfills	15
Metal plating and production	9
Chemical production—manufacturing	7
Salt storage	3
Agricultural and food-related	3
Laundromats	2
Hazardous-waste handling	1
Unknown	24
Other (miscellaneous industrial products)	10

Causes identified as petroleum related include, but are not limited to, brines, gasoline, and fuel-oil contamination. Metal plating wastes include trace metals such as copper, chromium, nickel, mercury, and arsenic. The other wastes consist of a wide variety of contaminants including trace metals, organics, nitrates, phenols, paints, polychlorinated biphenols (PCB's), polybrominated biphenols (PBB's), oils, and solvents. Sources of contaminants (Michigan Department of Natural Resources, 1986b) are:

Source of ground-water contamination	Percentage of contamination (739 sites)
Underground tanks	17
Landfills	16
Lagoons	14
Surface discharges	11
Above-ground tanks	6
Barrels	5
Unknown	27
Other (containers, movement of water from deep geologic formations, piles, pipelines, and pits)	4

In addition to the 1,000 sites where air, soil, or water has been contaminated, the MDNR has also identified more than 600 municipal, commercial, and industrial landfills (fig. 3C), most of which are located in the more populated Lower Peninsula. Some of these landfills may also be State-identified contamination sites. Only 95 landfills currently are active. There also are 133 demolition debris landfills, some of which may contain hazardous wastes (Michigan Department of Natural Resources, 1986a).

## Agricultural Practices

Studies of the effect of agricultural activities on ground-water resources in Michigan have largely described the fate of applied fertilizers and the increase in nitrate concentrations in shallow aquifers. Unpublished data in State and county files have indicated that concentrations of nitrate exceeding the U.S. Environmental Protection Agency (1986a) primary drinking-water standard occur at sites throughout the State, although most commonly in areas of intensive agriculture. Cummings and others (1984), in a study of Van Buren County, concluded that nitrate concentrations of ground water

were related to the amount of fertilizer applied but that equally important was the amount of irrigation water used. About 22 percent of the wells sampled in the southern part of the county yielded water having a nitrate concentration exceeding the primary standard of 10 mg/L as nitrogen. Rajagopal (1978), in a study of nitrate concentrations in ground water of Grand Traverse County in the northern part of Michigan's Lower Peninsula, found an average nitrate concentration of 18 mg/L in an area of intensely fertilized cherry orchards. He concluded that permeable soil, along with years of fertilizer application, were principal reasons for the large concentrations detected. D'Itri and others (1985), using nitrate data from the Michigan Department of Public Health (MDPH), studied concentration trends in ground water in the Lower Peninsula. Three periods (1933–70, 1971–74, and 1975–84) were separately considered. Average concentrations during 1975–84 exceeded those of earlier periods; large concentrations were evident in the west-central, southwestern, northwestern, and northeastern parts of the Lower Peninsula.

### Salt Storage and Use

Among States spreading rock salt (sodium chloride) for road deicing, Michigan ranks in the top five in quantity used (VanderMeulen, 1984). Storage of rock salt has caused ground-water contamination, particularly when it has been stored unprotected from rain and without runoff controls. The Michigan Department of Natural Resources (1986b) has identified 29 salt-storage facilities that have caused ground-water contamination, or about 3 percent of the known sites in the State (fig. 3B). In one instance, the contamination plume was 350 feet wide and about 3,000 feet long and was moving at a rate of 350 to 400 feet per year (Curry, 1972). The maximum chloride concentration in ground water at the site was 2,800 mg/L; water from at least 8 wells had chloride concentrations exceeding the standard of 250 mg/L for drinking water.

In Michigan, only a few studies link highway salt applications to ground-water contamination. One Michigan Department of Transportation (MDOT) study found chloride levels in ground water increasing, then stabilizing, adjacent to deiced highways. The stabilized chloride concentrations rarely exceeded 250 mg/L (D. Malotte, Michigan Department of Transportation, oral commun., 1986).

### Water Withdrawal

Bedrock formations underlying glacial deposits in Michigan commonly contain very mineralized water. U.S. Geological Survey data indicate that near Lakes Erie, St. Clair, and Huron, and near Saginaw Bay, saline water lies at an average depth below land surface of about 200 feet. At a few locations near Saginaw Bay, very mineralized water has been detected near the land surface. Twenter and Cummings (1985) found the water of one well to have a dissolved-solids concentration larger than 80,000 mg/L; depth to water below land surface was only 29 feet. In smaller areas in southwestern Michigan, saline water is also within 200 feet of land surface. In the northwestern part of the Lower Peninsula, however, the depth to saline water is as much as 900 feet. In much of the Upper Peninsula, the depth to saline water is about 400 feet.

Extremely mineralized water has been induced into freshwater aquifers in several areas by excessive pumping. When pumping decreases the hydraulic head in the freshwater aquifer, saline water may migrate toward the well. In the Flint area, upward migration of saline water increased the chloride concentration of water from a well by 300 percent, requiring abandonment of the Saginaw Formation as a water source (Deutsch, 1963). Intensive pumping near the city of Pontiac caused water in the Coldwater Shale, which contained a large sulfate concentration, to migrate into the glacial drift aquifer. Changing the pumping pattern decreased the sulfate concentrations.

Saline water has also migrated through unplugged wells or leaky casings when pumping was intensive. In 1956, the city of Lansing drilled a water-supply well into the Saginaw Formation. After 2 months of pumping, the chloride concentration of the water had increased from less than 100 mg/L to about 900 mg/L. The source of the chloride was a brine well drilled in 1867 which had been abandoned and buried. (The brine well had produced water containing more than 4,500 mg/L of chloride.) After plugging the brine well, the chloride concentration of water in the aquifer began to decrease (Deutsch, 1963).

Oil and gas test wells are drilled through bedrock formations that commonly contain brines. Brines have been disposed by injection into rock formations, by surface impoundment, or by spreading on unpaved roads. Surface disposal of brines has resulted in ground-water contamination, and old unplugged abandoned wells have provided avenues of migration. Although the plugging of wells is now regulated (Michigan Department of Public Health, 1984), corrosion of casings may still allow leakage.

### POTENTIAL FOR WATER-QUALITY CHANGES

Development of ground-water protection strategies by State and local units of government, as well as closer monitoring of the use, storage, and disposal of hazardous materials, probably will decrease the potential for contamination of freshwater aquifers in the future. Inevitably, accidental spills will continue, but prompt reporting and remedial response will eliminate some of the problems of the past. The potential for contamination of aquifers will remain greatest in those areas where sandy, permeable materials form unconfined surficial glacial deposits. Unconfined aquifers in the northern and western parts of the Lower Peninsula and in the eastern half of the Upper Peninsula, where outwash and glaciofluvial deposits are the principal surficial deposits, are most susceptible to contamination from surface sources. Similar deposits of smaller areal extent occur along the Lake Huron shoreline as well as in southeastern and south-central Michigan. About half of the State's aquifers are susceptible to contamination because fine-grained till or glaciolacustrine clay, which tends to restrict downward movement of contaminants, is absent. In these areas, contaminants can percolate directly to the water table. In addition, the unconfined aquifers commonly consist of coarse-grained deposits in which the relatively rapid rate of water movement contributes to the spread of any contaminant that reaches the water table.

Excessive pumping of public water-supply and irrigation wells, primarily in the southern part of the Lower Peninsula, could cause saline water to migrate upward, contaminating freshwater supplies. Where natural fractures or improperly plugged old wells exist, upward movement could be accelerated. In counties surrounding Saginaw Bay, upward migration of saline water could develop without drastic changes in current withdrawals because saline water occurs at shallow depths.

### GROUND-WATER-QUALITY MANAGEMENT

Recognizing existing and potential problems, Governor Blanchard, in his 1984 State of the State message, identified protection of the State's drinking-water supply as a priority activity and directed his Cabinet Council on Environmental Protection to develop a State policy on ground water and an initiative for implementing that policy. This initiative advanced ground-water management by supplementing cleanup efforts with an enhanced prevention program. It proposes ground-water management goals, a policy aimed at achieving those goals, and a specific strategy that identifies areas where legal authority or programs can be improved. The keys to this policy are:

- Controlling surface and underground storage of chemicals;
- Isolating high-risk activities from underground sources of drinking water;

- Working intensively with individual small businesses, local governments, and their associations to provide information on proper storage and handling of potentially polluting materials;
- Educating the public; and
- Developing comprehensive data on the quality, quantity, and movement of ground water.

Authority for the State's ground-water-quality program is derived from several State laws. State legislation includes the Water Resources Commission Act (Act 245, P.A. 1929), the Solid Waste Management Act (Act 641, P.A. 1978), the Hazardous Waste Management Act (Act 64, P.A. 1979), the Environmental Response Act (Act 307, P.A. 1982), and Servicing of Septic Tanks, Seepage Pits, or Cesspools Act (Act 243, P.A. 1951). These Acts are administered primarily by the MDNR.

Some ground-water-management activities are conducted as part of the Public Water Supply Program under the regulations of the Federal Safe Drinking Water Act (Public Law 93-523) and the State Safe Drinking Water Act (Act 399, P.A. 1976). The MDPH, under the authority of Act 399, has been granted primary enforcement responsibility by the EPA for the implementation of the Federal Safe Drinking Water Act.

The MDNR, Environmental Response Division, responds to contamination problems by taking the lead for compliance with ground-water pollution control statutes, implementation of CERCLA, and compliance with the Michigan Environmental Response Act (Act 307, P.A. 1982). The Waste Management Division is also responsible for issuing State ground-water discharge permits under Act 245, P.A. 1929, as amended.

The serious nature of some contamination problems caused the State to focus on cleanups and other remedial actions. Maximum advantage has been taken of CERCLA; in addition, Michigan has created a similar fund, under its own Environmental Response Act (Act 307), to prioritize sites to receive State funding.

Ground-water-quality management practices in the State are governed by several factors:

- A nondegradation policy for proposed ground-water discharges;
- A very heterogeneous hydrogeologic setting; policies and commitments to the protection of aquifers for existing and potential use as drinking-water supplies;
- Protection of public health by limiting, to the extent possible, exposures to critical materials through water supplies; and
- A policy of assuring that insofar as possible those who may be liable for causing ground-water contamination will bear the cost of remedial action.

As a result, decisions regarding activities potentially affecting ground water and the remediation of existing ground-water contamination problems usually require the development of substantial onsite ground-water-quality data. Existing data are commonly helpful in designing specific studies but rarely are sufficient for decision making. A statewide ground-water data base system is being developed to improve the use of ground-water-quality data generated throughout the State.

#### SELECTED REFERENCES

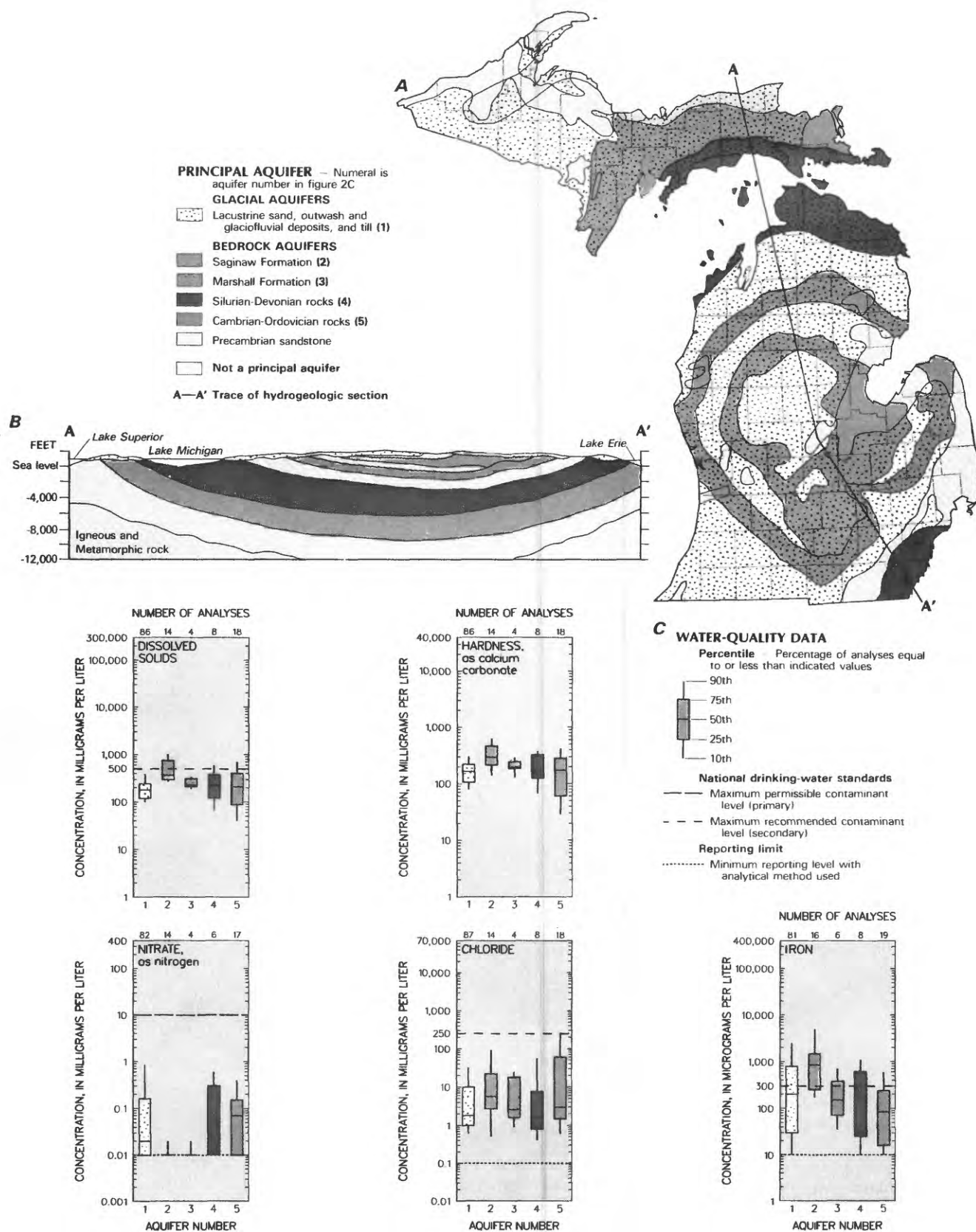
- Bedell, D.J., 1982, Municipal water withdrawals in Michigan: Michigan Department of Natural Resources, Water Management Division, 43 p.
- Cummings, T.R., 1980, Chemical and physical characteristics of natural ground waters in Michigan—A preliminary report: U.S. Geological Survey Open-File Report 80-953, 34 p.
- Cummings, T.R., and Twenter, F.R., 1986, Assessment of ground-water contamination at Wurtsmith Air Force Base, Michigan: U.S. Geological Survey Water-Resources Investigations Report 86-4188, 109 p.
- Cummings, T.R., Twenter, F.R., and Holtschlag, D.J., 1984, Hydrology and land use in Van Buren County, Michigan: U.S. Geological Survey Water Resources Investigations Report 84-4112, 124 p.
- Curry, R.G., 1972, Report of water well contamination problem at Indian River Cheyboygan County Road Commission garage, Indian River: Lansing, Michigan Department of Transportation, Testing and Research Division Report TG-31, p. 1-5.
- Deutsch, Morris, 1961a, Hydrogeological aspects of ground-water pollution: Water Well Journal, v. 15, no. 9.
- 1961b, Incidents of chromium contamination of ground water in Michigan: U.S. Public Health Service Technical Report W61-5, p. 98-104.
- 1962, Phenol contamination of an artesian glacial-drift aquifer at Alma, Michigan: British Society of Water Treatment and Examination, Annual General Meeting, London, 1962, Proceedings, v. 11, p. 94-100.
- 1963, Ground-water contamination and legal controls in Michigan: U.S. Geological Survey Water-Supply Paper 1691, 72 p.
- D'Itri, F.M., Kittleson, K.M., and Kruska, R.L., 1985, Spatial analysis of Michigan Department of Public Health nitrate data: East Lansing, Michigan State University, Institute of Water Research, 21 p.
- Farrand, W.D., 1982, Quaternary geology of southern Michigan—Quaternary geology of northern Michigan: Ann Arbor, University of Michigan, Department of Geological Sciences, 2 sheets.
- Grannemann, N.G., and Twenter, F.R., 1985, Geohydrology and ground-water flow at Verona Well Field, Battle Creek, Michigan: U.S. Geological Survey Water-Resources Investigations Report 85-4056, 54 p.
- Michigan Department of Natural Resources, 1986a, Controlled site listing: Lansing, Groundwater Quality Division, 188 p.
- 1986b, Michigan sites of environmental contamination priority lists: Lansing, Groundwater Quality Division, 219 p.
- Michigan Department of Public Health, 1984, Ground-water quality control, Part 127 of Act 368, P.A. 1978, as amended, and rules: Lansing, 30 p.
- Rajagopal, R., 1978, Impact of land use on ground-water quality in the Grand Traverse Bay region of Michigan: Journal of Environmental Quality, v. 7, no. 1, p. 93-98.
- Stark, J.R., Cummings, T.R., and Twenter, F.R., 1983, Ground-water contamination at Wurtsmith Air Force Base, Michigan: U.S. Geological Survey Water-Resources Investigations Report 83-4002, 93 p.
- Twenter, F.R., and Cummings, T.R., 1985, Quality of ground water in Monitor and Williams Townships, Bay County, Michigan: U.S. Geological Survey Water Resources Investigations Report 85-4110, 39 p.
- Twenter, F.R., Cummings, T.R., and Grannemann, N.G., 1983, Ground-water contamination in East Bay Township, Michigan: U.S. Geological Survey Water-Resources Investigations Report 85-4064, 63 p.
- U.S. Department of Defense, 1986, Status of the Department of Defense Installation Restoration Program—Information paper: Washington, D.C., U.S. Department of Defense, Office of the Assistant Secretary of Defense (Acquisition and Logistics), Environmental Policy Directorate, February 35 p.
- U.S. Environmental Protection Agency, 1986a, Maximum contaminant levels (subpart B of Part 141, National interim primary drinking-water regulations): U.S. Code of Federal Regulations, Title 40, Parts 100 to 149, revised as of July 1, 1986, p. 524-528.
- 1986b, Secondary maximum contaminant levels (section 143.3 of part 143, national secondary drinking-water regulations): U.S. Code of Federal Regulations, Title 40, Parts 100 to 149, revised as of July 1, 1986, p. 587-590.
- 1986c, Amendment to National Oil and Hazardous Substances Contingency Plan national priorities list, final rule and proposed rule: Federal Register, v. 51, no. 111, June 10, 1986, p. 21053-21112.
- U.S. Geological Survey, 1985, National water summary 1984—Hydrologic events, selected water-quality trends, and ground-water resources: U.S. Geological Survey Water-Supply Paper 2275, 467 p.
- VanderMeulen, Joe, 1984, Salt and road deicing on the Michigan state highway system: Legislative Service Bureau, 34 p.

Prepared by D.H. Dumouchelle and T.R. Cummings, U.S. Geological Survey, and G.R. Klepper, Michigan Department of Natural Resources

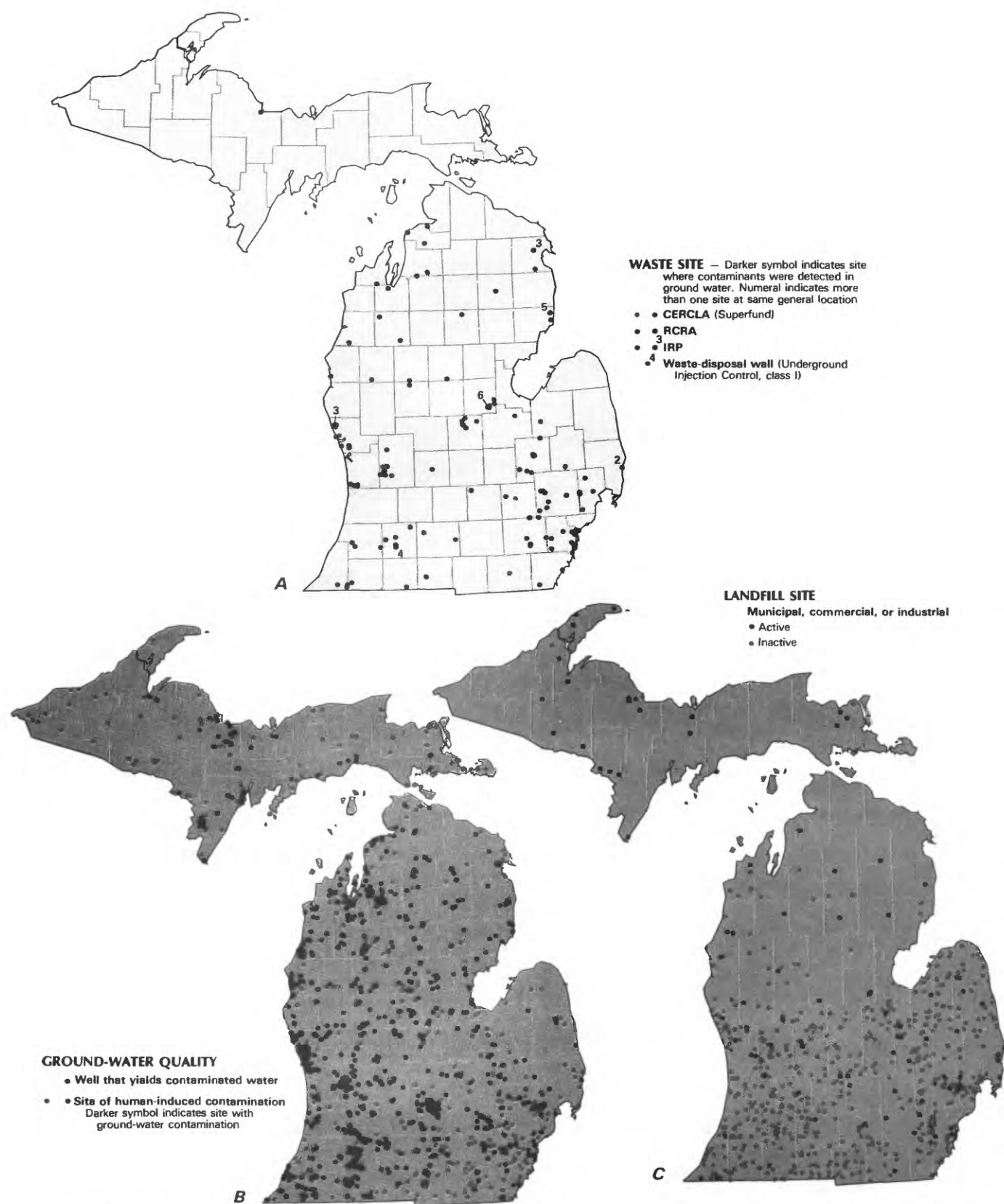
FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, 6520 Mercantile Way, Suite 5, Lansing, Michigan 48911



**Figure 1.** Selected geographic features and 1985 population distribution in Michigan. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)



**Figure 2.** Principal aquifers and related water-quality data in Michigan. *A*, Principal aquifers. *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, as of 1965-85. (Sources: *A*, Farrand, 1982. *B*, Compiled by N.G. Grannemann from U.S. Geological Survey files. *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986a,b.)



**Figure 3.** Selected waste sites and ground-water-quality information in Michigan. *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites, as of 1986; Resource Conservation and Recovery Act (RCRA) sites, as of 1986; and Department of Defense Installation Restoration Program (IRP) sites; and other selected waste sites, as of 1985. *B*, Sites of human-induced contamination, and distribution of wells that yield contaminated water as of July 1986. *C*, Municipal, commercial, and industrial landfills, as of July 1986. (Sources: *A*, U.S. Environmental Protection Agency, 1986c; Michigan Department of Natural Resources, 1986b; U.S. Department of Defense, 1986. *B*, Michigan Department of Natural Resources, 1986b. *C*, Michigan Department of Natural Resources, 1986a.)



**Figure 4.** Areal predominance of total recoverable iron in ground water in Michigan. (Source: Cummings, 1980.)