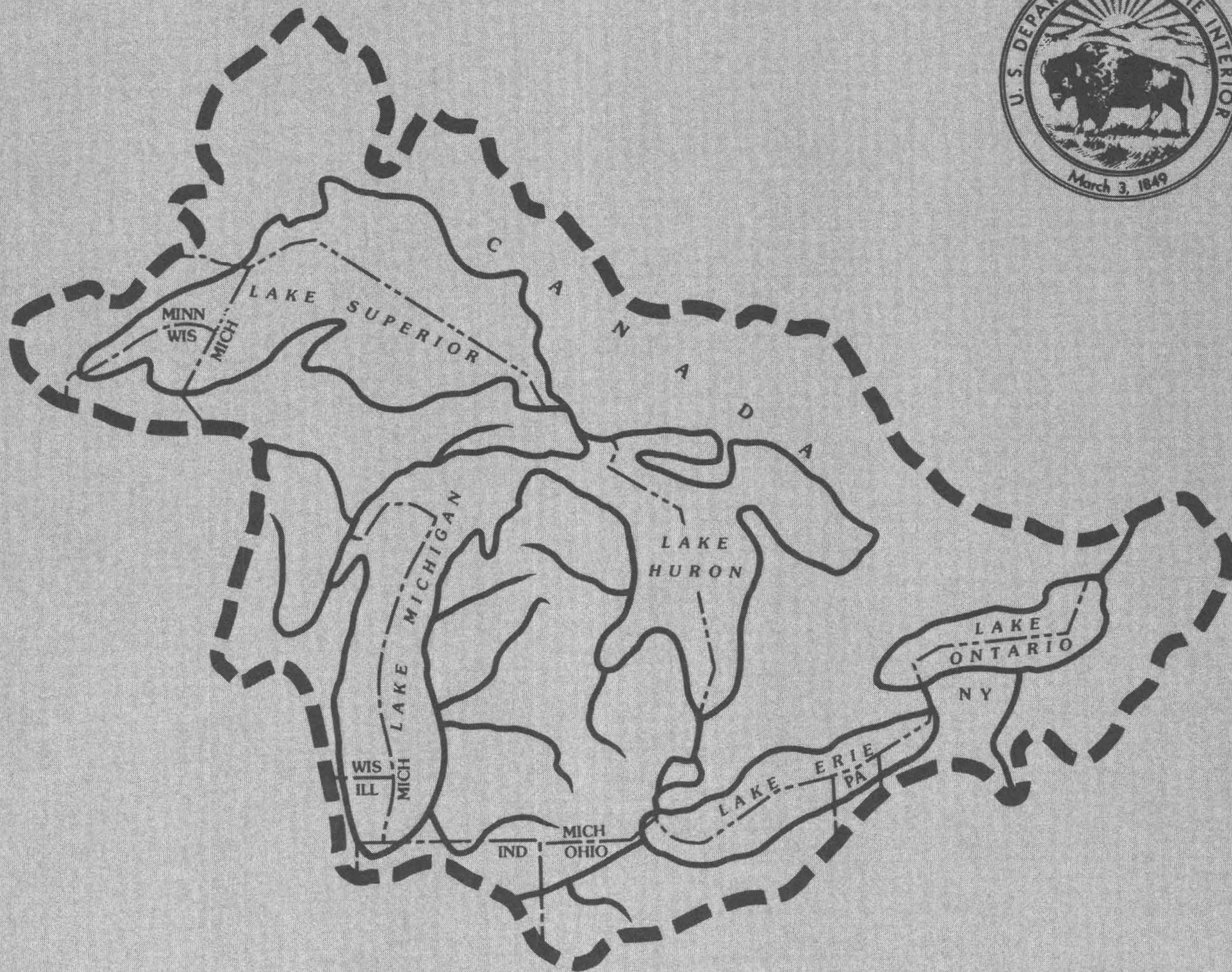
Summary Appraisals of the Nation's Ground-Water Resources— Great Lakes Region

GEOLOGICAL SURVEY PROFESSIONAL PAPER 813-J



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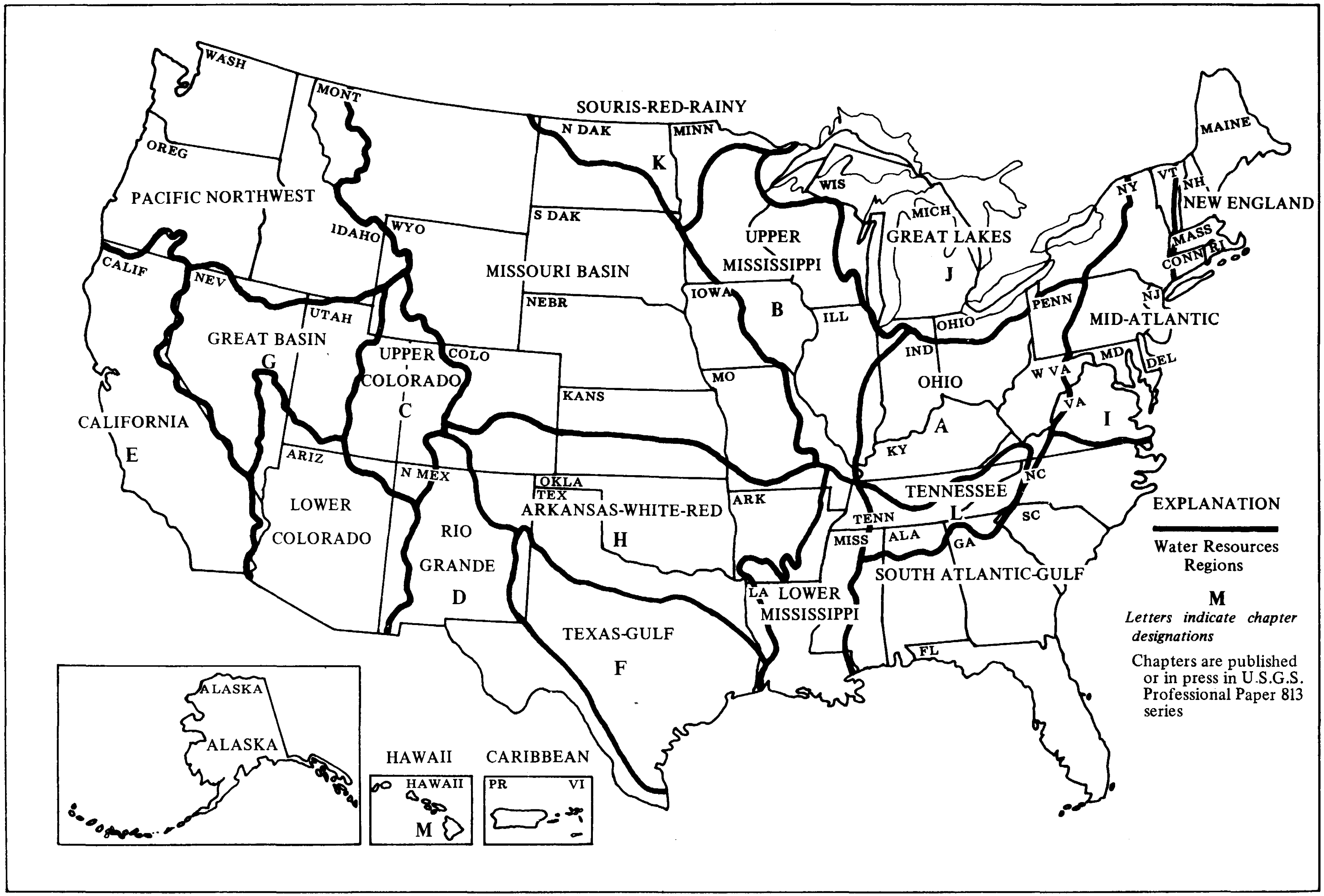

Geographic Index to the Series, U.S. Geological Survey Professional Paper 813, *Summary Appraisals of the Nations Ground-Water Resources.*

Boundaries shown are those established by the United States Water-Resources Council for Water-Resources Regions in the United States.

Summary Appraisals of the Nation's Ground-Water Resources— Great Lakes Region

By WILLIAM G. WEIST, JR.

GEOLOGICAL SURVEY PROFESSIONAL PAPER 813-J

The role of ground water in the region's water-related problems

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In this report, units of measure are given in English units. The following table gives factors to convert English units to SI (metric) units:

Multiply English units	*By*	*To obtain SI units*
inches (in)	25.4	millimeters (mm)
feet (ft)	.3048	meters (m)
miles (mi)	1.609	kilometers (km)
square feet (ft^2)	.0929	square meters (m^2)
square miles (mi^2)	2.59	square kilometers (km^2)
acres	.4047	hectares (ha)
cubic feet (ft^3)	.0283	cubic meters (m^3)
gallons (gal)	3.785	liter (L)
acre-feet (acre-ft)	1.233×10^{-6}	cubic kilometers (km^3)
gallons per minute (gal/min)	.06309	liters per second (L/s)
million gallons per day (Mgal/d)	.0438	cubic meters per second (m^3/s)
cubic feet per second (ft^3/s)	.02832	cubic meters per second (m^3/s)
cubic feet per second per square mile ($(ft^3/s)/mi^2$)	.0109	cubic meters per second per square kilometer ($(m^3/s)/km^2$)
degrees Fahrenheit [(°F)−32]	.556	degrees Celsius (°C)

SUMMARY APPRAISALS OF THE NATION'S GROUND-WATER RESOURCES—GREAT LAKES REGION

By WILLIAM G. WEIST, JR.

ABSTRACT

The Great Lakes Regions, as a whole, has abundant supplies of water. Nearly 805,000 billion cubic feet of water is contained in the Great Lakes. An additional 35,000 billion cubic feet of potable ground water is available from storage in the region. Estimated ground-water discharge to the streams and lakes of the region is 26 billion gallons per day.

Despite this abundance of water, the United States part of the Great Lakes basin is faced with many water-related problems, most of which involve water quality and water supply. Other problems concern periods of low flow in streams, preservation of wetlands, detrimental effects of erosion, and flooding. The significance of ground water in these problems is often overlooked.

Ground water can be an alternative to surface water as a source of supply, or it can be used conjunctively with surface water to provide flexibility in water-supply management. Ground water supplied approximately 1,800 million gallons per day of the 39,900 million gallons per day used in the Great Lakes Region in 1970. The ground-water contribution was only 4.5 percent of the water used. Thus, ground water represents a potential source of supply for much of the region. It also can be used, where conditions permit, to maintain lake levels and flow in streams, to dilute poor quality surface water, and to maintain or create wetlands and ponds.

In managing water resources, ground water and surface water should be considered parts of a single system. Management includes not only planning and controlling the development but also monitoring the effects of this development. Recent advances in ground-water hydrology have provided methods to resolve some of the development and management questions that formerly slowed the development of ground water.

All of the States in the Great Lakes Region have some regulations to control the development or protect the quality of the ground water. These regulations, however, are not as comprehensive as those governing surface water. Future legislation could be designed to encourage the development of ground water and, at the same time, to protect the resource.

Efficient development and management of ground-water resources requires a through knowledge of the system. Reports on ground water are available for about 80 percent of the Great Lakes Region. Most of these reports, however, are not sufficiently detailed to be useful in comprehensive planning. As ground-water development continues, quantitative ground-water studies, utilizing models as predictive tools, will enable this development to proceed in an efficient manner.

INTRODUCTION

In 1971, the U.S. Geological Survey began a broad-perspective analysis of the Nation's ground-water resources. This analysis was designed to emphasize the extensive occurrence and availability of ground water and the significant role it can play in regional development. The results are being published in the Geological Survey professional paper series, "Summary Appraisals of the Nation's Ground-Water Resources." This comprehensive summary of ground water in the United States should aid in orderly planning and development of the Nation's water resources.

This report discusses ground-water resources for the part of the Great Lakes basin that is in the United States. The report is intended neither as a source of data nor a comprehensive discussion of water availability in the different aquifers in the region. Rather, it builds on previous reports by focusing on water-related problems and the role ground water can play in meeting these problems. A comprehensive summary of ground-water availability in the Great Lakes basin, including an extensive bibliography, was recently published by the Great Lakes Basin Commission (Waller and Allen, 1975).

Most of the material in this report is based on published reports and on information gathered through meetings with State and Federal personnel and members of regional planning commissions throughout the Great Lakes Region—the people who are gathering and using the water-resources data. The author gratefully acknowledges their contributions.

DESCRIPTION OF THE REGION

The Great Lakes basin (fig. 1) is an international basin containing 295,800 mi^2 in Canada and the United States. The Great Lakes Region discussed in this report includes only the 173,470 mi^2 in the United States, of which 60,602 mi^2 is water surface.

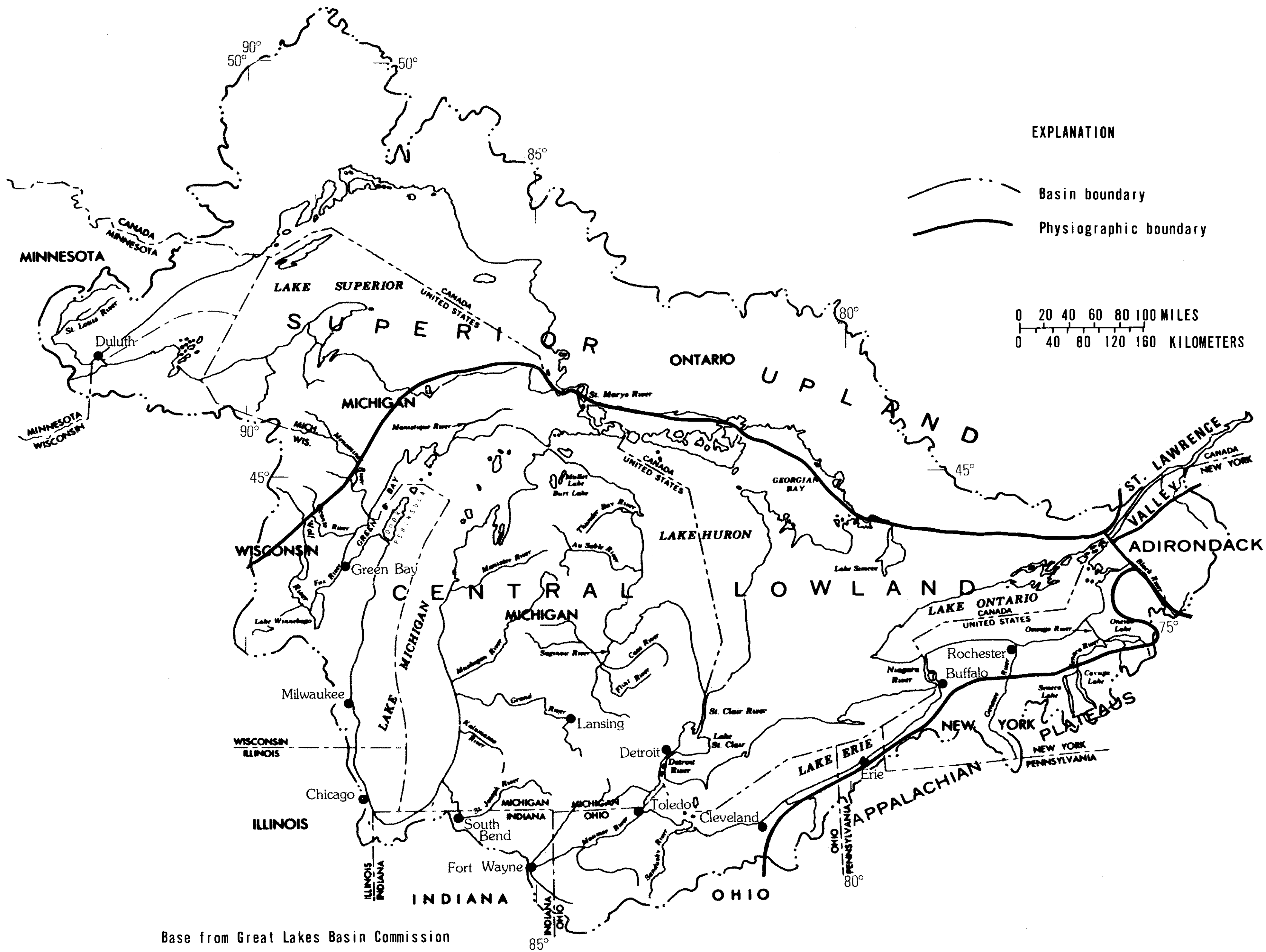


FIGURE 1.—The Great Lakes basin.

PHYSIOGRAPHIC SETTING

Most of the Great Lakes Region lies in the Central Lowland physiographic province (fig. 1). Parts of the region in Wisconsin, Minnesota, and the Upper Peninsula of Michigan are in the Superior Upland province, and parts of Ohio, Pennsylvania, and New York are in the Appalachian Plateau, Adirondack, and St. Lawrence Valley provinces. Most of the region is characterized by generally flat or gently rolling lowlands and lake plains. Areas along the western, eastern, and southeastern borders are dissected plateaus with varied relief and prominent escarpments. Most of the region is less than 1,000 ft above mean sea level. The highest point (4,621 ft) is in the Adirondack Mountains, and the lowest (150 ft) is along the St. Lawrence River. The highest elevation in the headwaters is 2,301 ft, in Minnesota.

The region underwent four major periods of glaciation. As much as 1,100 ft of glacial deposits overlie the bedrock surface. Streams have partly reworked these deposits, leaving alluvium along their channels. Local relief and much of the drainage was modified by the glaciation. The irregularity of the glacial deposits has resulted in an imperfect drainage pattern, with numerous lakes, ponds, marshes, and bogs. Major drainage is toward the Great Lakes and the St. Lawrence River. Twelve tributary river basins have drainage areas of about 6,000 mi^2 each; the rest have drainage areas ranging from a few to several hundred square miles (Waller and Allen, 1975, p. 1).

Bedrock consists of a series of sedimentary formations overlying crystalline rocks, except where the crystalline rocks are exposed in parts of Minnesota, Wisconsin, Michigan, and New York. The major structural bedrock feature is a deep sedimentary basin centered in Michigan.

HYDROLOGIC SETTING

The Great Lakes Region has an abundant supply of water (table 1). Because so much water is available in the Great Lakes and the streams that drain to them, the large amount of available ground water is frequently overlooked.

All the water resources of the region are part of a single hydrologic system, in which a change in one phase will cause changes in the other phases. Because this system is very complex, precipitation, surface water, and ground water are generally investigated and described separately. The next three sections give a brief picture of these three phases in the Great Lakes Region.

CLIMATE

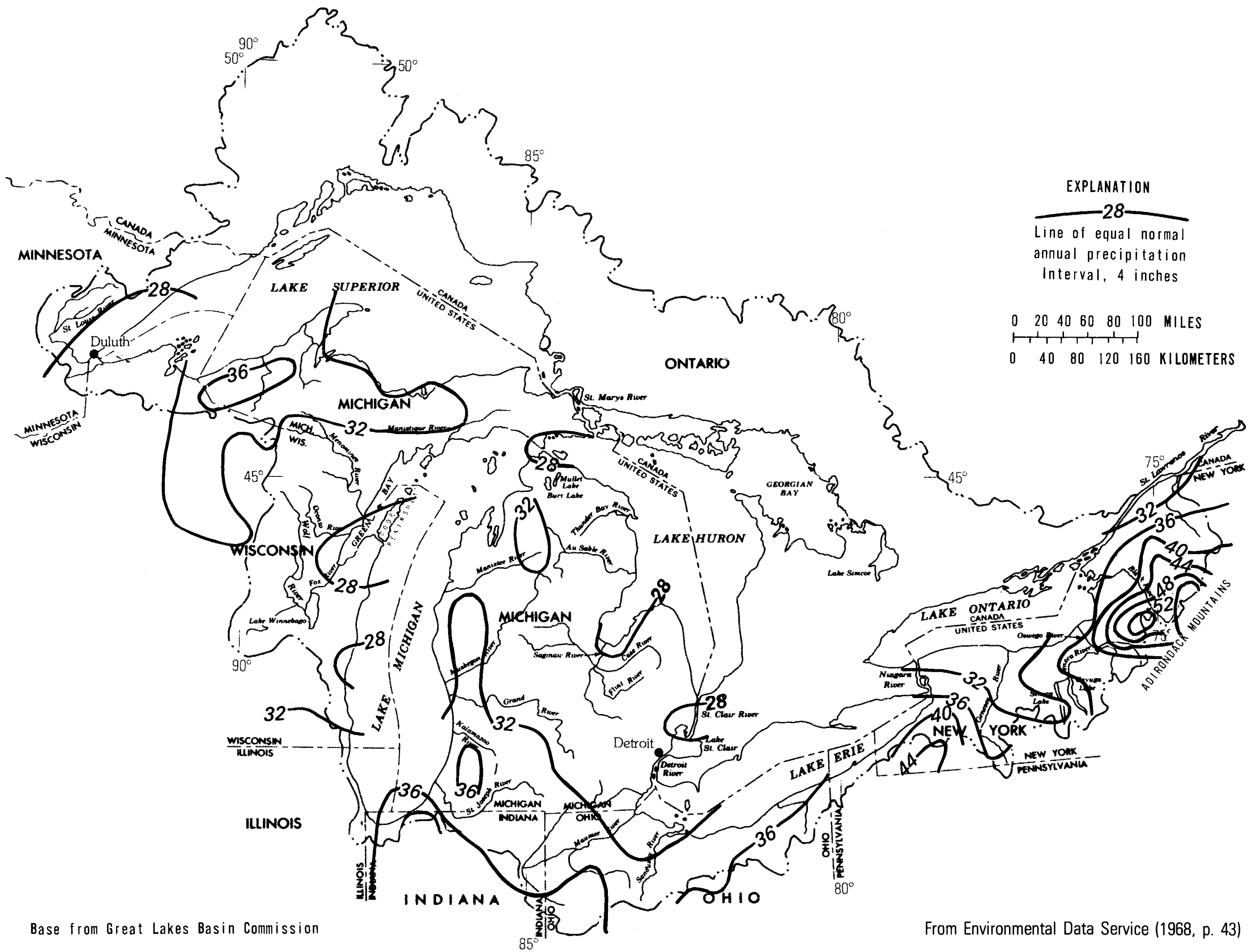
Because of its large water areas, the region has a more moderate climate than regions of similar latitude to the west. In January, normal daily average temperatures range from 10° F (−12° C) in Minnesota to 28° F (−2° C) in Ohio. In August they range from 65° F (18° C) in Minnesota to 73° F (23° C) in Ohio (Environmental Data Service, 1968).

Precipitation is affected by the Great Lakes and by the highlands along the eastern border of the region. Normal annual precipitation ranges from 28 in in the Duluth area, along part of western Lake Michigan and Lake Huron, and in the Detroit area, to more than 52 in in the Adirondacks (fig. 2).

TABLE 1.—*Water resources of the Great Lakes Region*

Lake basin	Average annual precipitation on basin,[1] 1900–69 (inches)	Average runoff into lake,[2] 1935–64 (ft^3/s)	Volume of water in lake[3] (billion ft^3)	Average outflow of lake through natural channel,[4] 1860–1970 (ft^3/s)	Estimated volume of ground water containing less than 3,000 mg/L dissolved solids available from storage[5] (billion ft^3)
Superior	29.56	50,300	431,400	75,000	3,500
Michigan	31.16	37,400	173,500	52,000	14,900
Huron	31.26	51,300	124,800	187,300	4,800
Erie	33.79	24,500	17,200	201,900	8,200
Ontario	34.18	28,100	57,800	239,200	3,600
Region	31.46	141,600	804,700	---	35,000

[1] Data from Leonard and Raoul, 1975, p. 36.
[2] Data from Leonard and Raoul, 1975, p. 37.
[3] Data from Leonard and Raoul, 1975, p. 7.
[4] Data from Leonard and Raoul, 1975, p. 13.
[5] Data from Norris and Fidler, unpub. rept., 1975.



Base from Great Lakes Basin Commission

From Environmental Data Service (1968, p. 43)

FIGURE 2.—Normal annual precipitation, 1931–60.

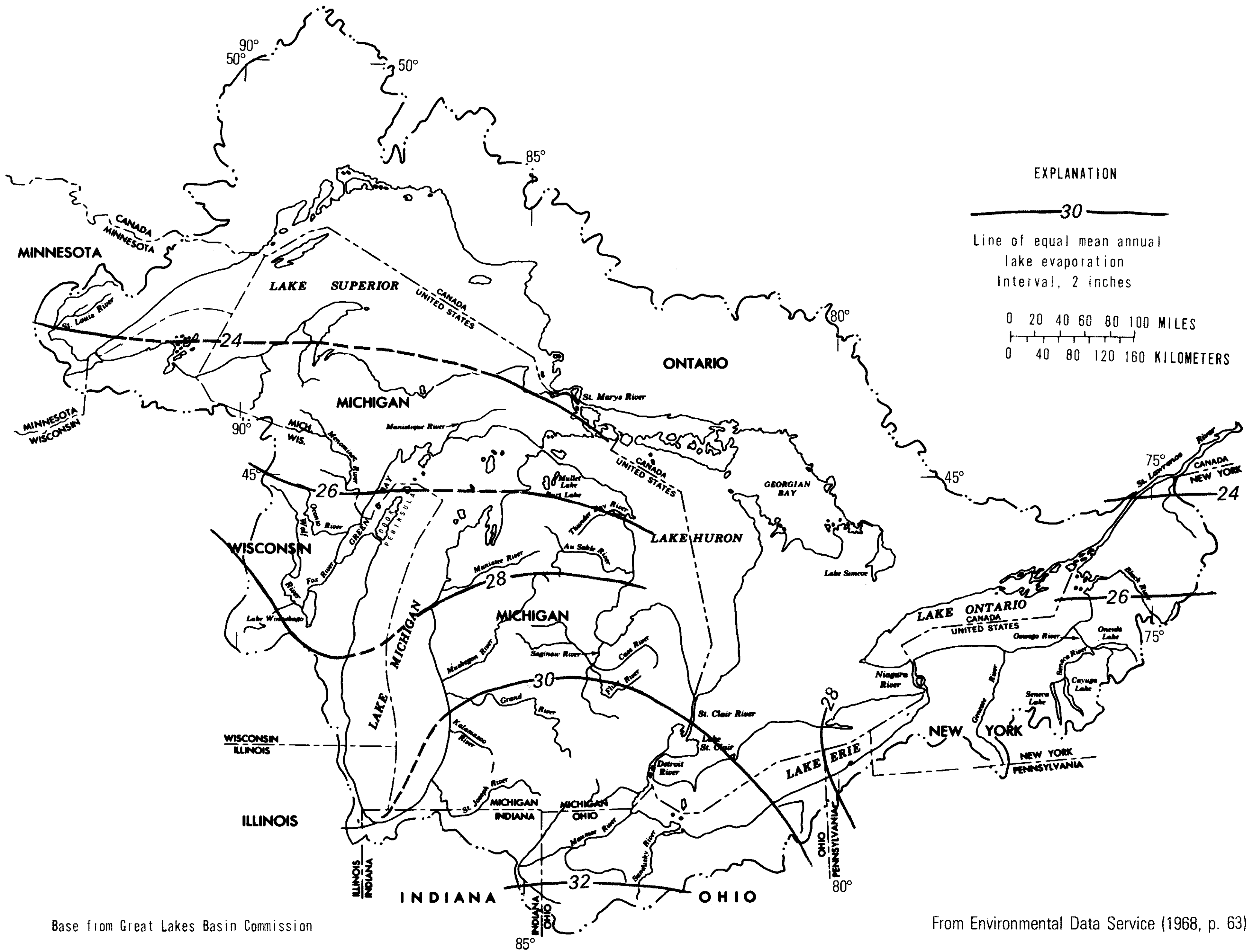


FIGURE 3.—Mean annual lake evaporation, 1946–55.

Annual precipitation as a whole averages 31 in. Areas downwind (east) of the lakes generally receive more precipitation than areas upwind. The Adirondacks rise from the lake plains of the eastern border of the region and deflect moisture-laden air upward, so that the Lake Ontario basin receives the most precipitation. Precipitation is fairly evenly distributed throughout the year. February generally has the least (1.78 in) and September the most (3.24 in) (Leonard and Raoul, 1975).

Nearly two-thirds of the precipitation returns to the atmosphere through evaporation and transpiration. As shown in figure 3, mean annual lake evaporation ranges from 24 to 32 in, being greatest along the southernmost edge of the region. About 80 percent of the evaporation occurs between May and October (Environmental Data Service, 1968).

SURFACE WATER

Average annual runoff in the Great Lakes Region is 11.6 in, ranging from 9 to 38 in (Great Lakes Basin Commission, 1975a, p. 25). This wide range is due to differences in geology, surficial features, and land use as well as to differences in precipitation. The Great Lakes form the major drainage system; average flow out of Lake Ontario is more than 239,000 ft^3/s (table 1). Developed storage on streams and lakes provides a sustained water-supply yield of more than 18 billion gallons per day (Great Lakes Basin Commission, 1975b).

Although flood flows get more publicity than low flows because of the damage and suffering they can cause, low flows of streams are more important than floods in terms of water supply, waste assimilation, and fish and wildlife. Floods are a function of precipitation, soil-moisture conditions, snow cover, topographic relief, and other physical features, whereas low flows are a function primarily of ground-water contribution to streamflow. When surface runoff ends, flow in streams is maintained by ground-water discharge. Where streams are fed by extensive aquifers, flow will be maintained even during prolonged periods of no rain; but where streams are adjacent to small aquifers or deposits having low permeability, such as till and lake sediments, flow will decrease fairly rapidly, and may even cease.

The ground-water contribution to streamflow can be estimated from flow-duration curves, which are cumulative frequency curves showing the percentage of time specified discharges are equaled or exceeded. Waller and Allen (1975, p. 8) determined that flow at 70-percent duration represents a conservative value for average ground-water discharge in the Great Lakes basin.

Runoff at 70-percent duration ranges from 0.01 $(ft^3/s)/mi^2$ in streams in parts of the eastern Lake Ontario basin to 0.90 $(ft^3/s)/mi^2$ in the Mannistee River in Michigan and the Black River in New York. Runoff of many of the streams is in the range from 0.20 to 0.40 $(ft^3/s)/mi^2$ (Waller and Allen, 1975).

GROUND WATER

The occurrence of ground water in the region is described in detail in the ground-water appendix to the Great Lakes Basin Framework Study (Waller and Allen, 1975). Therefore, only a brief summary is presented in this report.

Ground water is unevenly distributed across the Great Lakes Region. Land-surface features, precipitation, surface and subsurface drainage, and the hydrologic properties of the underlying rocks combine to determine the availability of ground water in any area. The hydrologic property of the rocks is probably the most important factor in the Great Lakes Region. Unconsolidated outwash sand and gravel deposits are highly permeable and represent the best aquifers in the region. The most productive aquifers are in the valleys of major streams. These aquifers can be recharged by induced infiltration of streamflow, and the sand and gravel act as natural filters to remove many impurities.

In areas of the Great Lakes Region where the unconsolidated deposits are poorly permeable, thin, or absent, ground-water sources are limited to the consolidated (bedrock) aquifers. Supplies from these aquifers are generally adequate and dependable, except locally where shale or crystalline rocks crop out. Fortunately, these areas are few and scattered.

Waller and Allen (1975, p. v) state:

> Carbonate (limestone and dolomite) aquifers constitute the most common bedrock aquifers in the Basin. They occur along the northern and western shore of Lake Michigan, from Illinois to Cleveland, and along the southern shore of Lake Ontario. The carbonates are most productive, with well yields as much as 1,000 gpm, where they extrude or are overlain by unconsolidated deposits. Solution processes have developed good permeability in these areas. Sandstone aquifers are the next most common bedrock aquifers. A thick sequence of productive sandstone units (well yields as much as 1,300 gpm) is present along the western and northern part of the Lake Michigan basin. Such productive units with well yields as much as 500 gpm are also present in parts of Michigan and in Ohio, Pennsylvania, and New York. As aquifers, shale beds are the least productive sedimentary unit. Shales are abundant in the southern part of the Great Lakes Basin from Indiana to the Adirondack Mountains.

Crystalline rocks constitute the bedrock west of Lake Superior and in the Adirondacks region. Wells in these rocks provide adequate yields for domestic and rural supplies and, in exceptional areas, for small commercial and industrial supplies. Water is obtained from fractures and from the upper, weathered part of the rocks.

Yields of as much as 5,000 gal/min are obtainable from wells in some thick deposits of highly permeable sand and gravel, and yields in excess of 500 gal/min have been reported from bedrock in some areas. On the other hand, yields of 5 gal/min may be difficult to obtain in some areas underlain by till or crystalline bedrock. Table 2 summarizes the occurrence of ground water in the Great Lakes Region. Figure 4 shows the distribution of the bedrock units in the region and figures 5–9 show the availability of ground water in unconsolidated deposits in each Great Lake basin.

Well yields and water quality vary across the region, even within the same aquifer system, and a detailed study of the water resources is needed before heavy development can be planned in any area. An important aquifer in one area may yield only small amounts of water elsewhere or water that is too saline for most uses. For example, the Cambrian-Ordovician aquifer system is an important source of water for the Chicago area. However, in northern Indiana the water is so saline that the system is relegated to deep-well waste disposal. In the Lake Superior basin, the Silurian aquifer system yields 50 to 100 gal/min to wells, whereas in parts of the Lake Michigan basin the system yields as much as 1,000 gal/min. In general, the highest yields are obtained from fractured rock aquifers or those that contain solution channels.

The long-term water-yielding potential of an aquifer is dependent on the availability of recharge. In the Great Lakes Region most recharge from snowmelt and rainfall occurs as water infiltrates the soil and percolates to the water table. However, highest well yields are generally obtained from aquifers

TABLE 2.—*Occurrence of ground water in the Great Lakes Region*

[Data from Waller and Allen, 1975]

Aquifer system	Yields of highest-capacity wells (gal/min)	Principal water-bearing units	Areas of greatest potential
		Unconsolidated deposits	
Glacial lake deposits	10–20	Sandy zones within the silt and clay.	
Outwash sand and gravel	50–5,000	Highest yields are obtained in areas with good sources of recharge.	Indiana—South Bend area. Michigan—Jackson, Kalamazoo, area; Au Sable, Manitee, and Muskegon River valley. New York—Genesee River basin. Ohio—northeastern. Pennsylvania.
Till	10–20	Sand and gravel lenses	
		Bedrock	
Pennsylvanian	50–700	Sandstone and shale. Brine and sulfates frequently encountered in lower part.	Southern Michigan.
Mississippian	50–1,800	Sandstone and shale. May contain oil, gas, and brine.	Southern Michigan, northeastern Ohio, Pennsylvania.
Devonian	50–700	Mostly carbonate rocks with some sandstone. May contain oil, gas, and brine.	Ohio, southern Michigan, northeastern Indiana.
Devonian-Silurian	50–500	Carbonate rocks	North Michigan.
Silurian	50–1,000	Mostly carbonate rocks. Water is saline in places.	Eastern Wisconsin, Illinois, northeastern Indiana, northwestern Ohio.
Ordovician	50–500	Carbonate rocks and sandstone. Saline water at depth.	Western New York.
Cambrian-Ordovician	50–1,300	Carbonate rocks and sandstone. Saline water at depth.	Illinois, eastern Wisconsin.
Cambrian	50–500	Sandstone. Saline water at depth.	Illinois.
Cambrian-Precambrian	50–500	Sandstone	North Michigan.
Precambrian	100–250	Sandstone and crystalline rocks	Minnesota—Mesabi Range.

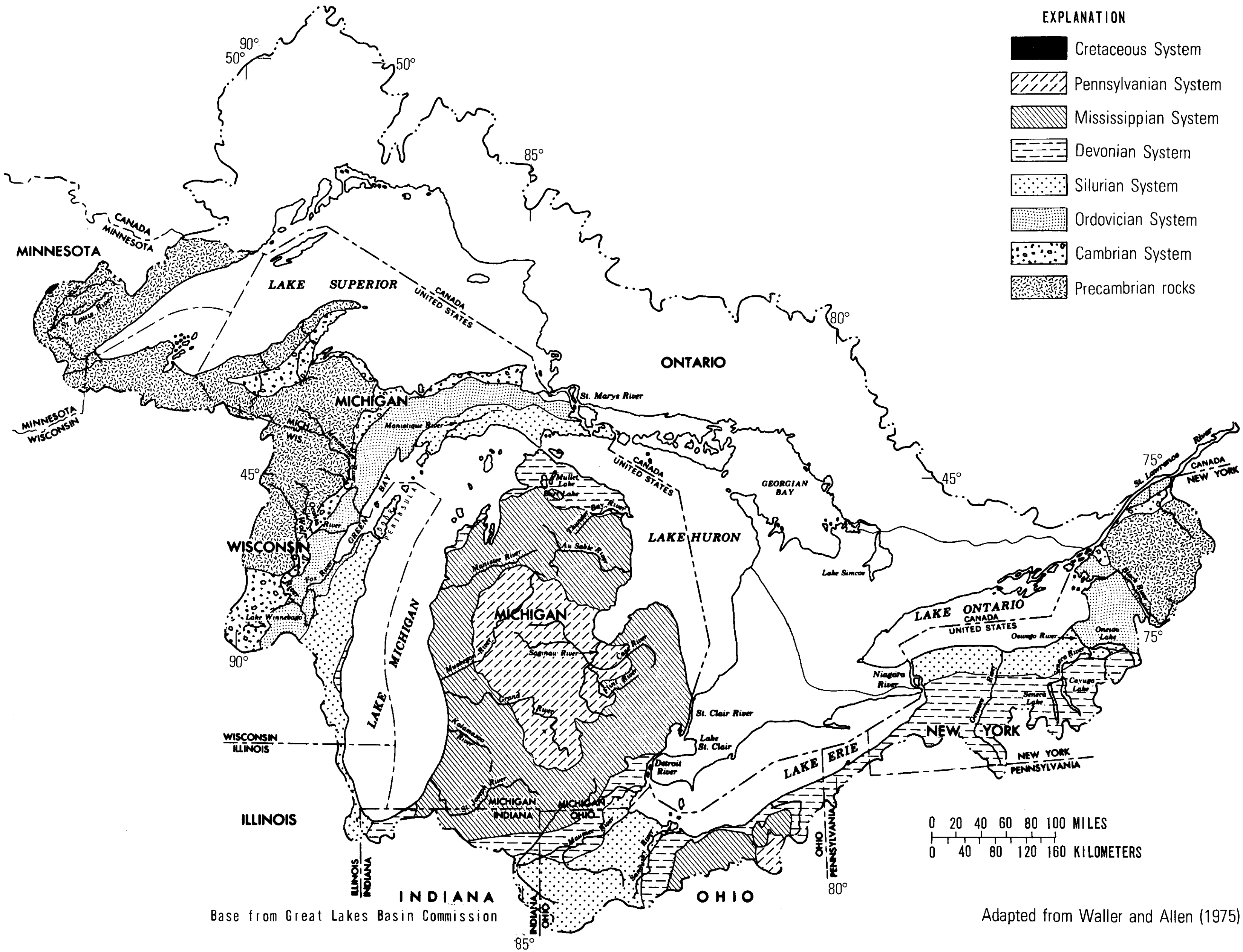


FIGURE 4.—Bedrock geology of the Great Lakes Region.

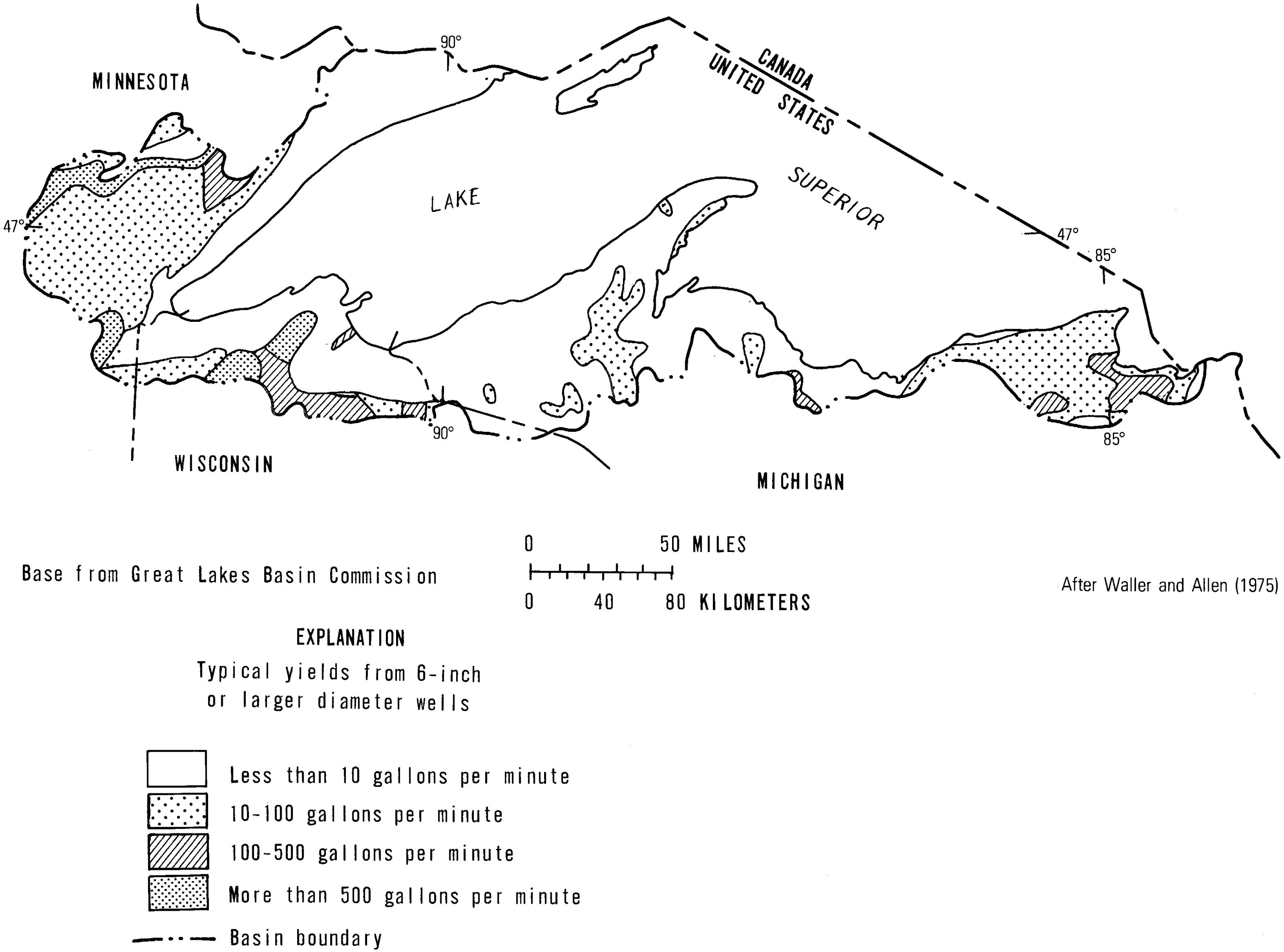


FIGURE 5.—Availability of ground water in unconsolidated deposits in the United States part of **the Lake Superior basin.**

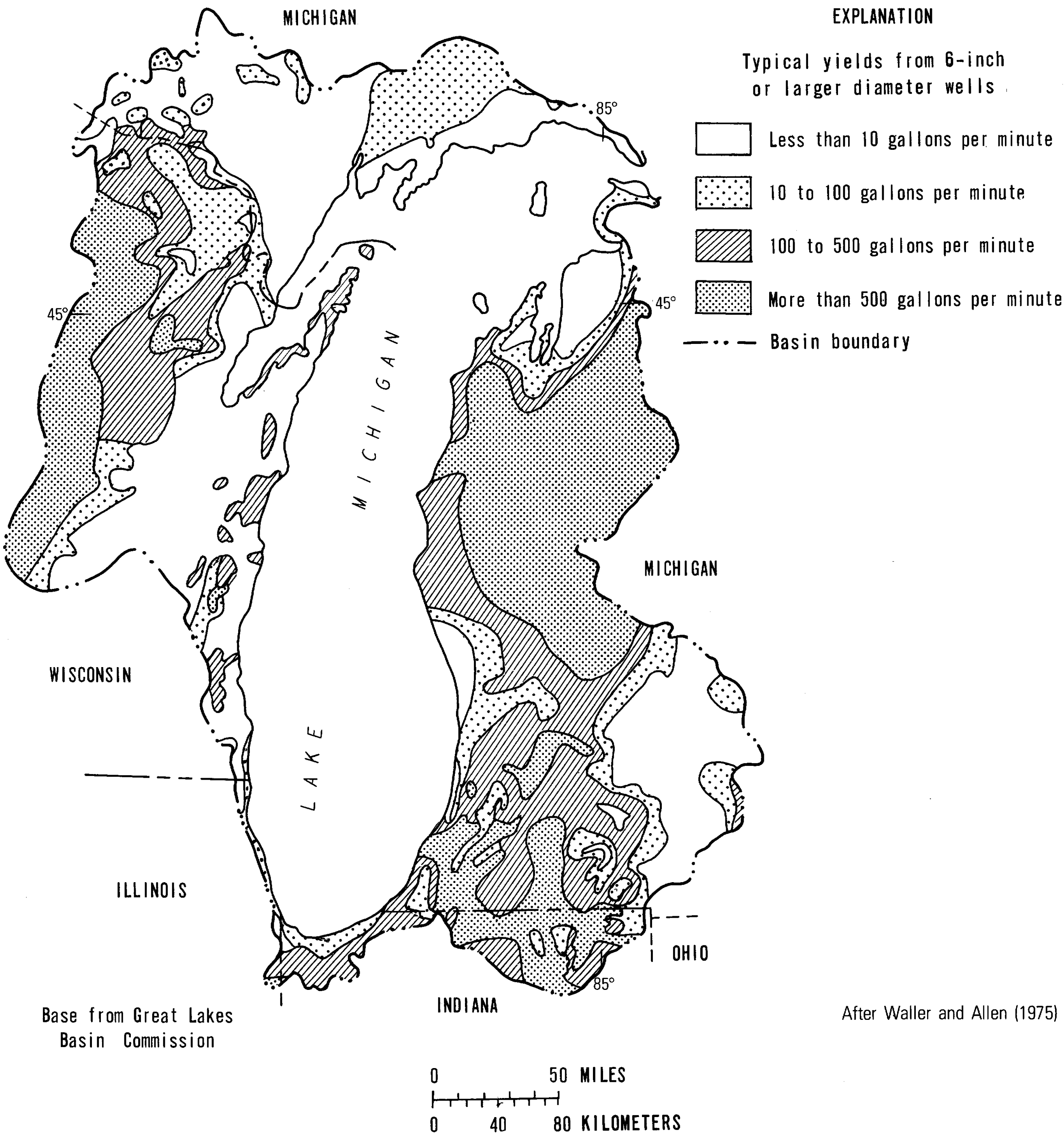


FIGURE 6.—Availability of ground water in unconsolidated deposits in the United States part of the Lake Michigan basin.

that are in direct hydraulic continuity with lakes or streams. Under such conditions, heavy pumping can induce recharge from these water bodies. This will, of course, result in reduced streamflow or lower lake levels.

Natural ground-water discharge maintains streamflow during dry periods and helps to maintain lake levels and wetlands. This discharge varies seasonally. At least 30 percent of the time, during low flow, nearly all water in streams comes from ground-water discharge. This amounts to nearly 26 billion gallons per day for the region (Great Lakes Basin Commission, 1975b). At higher streamflows

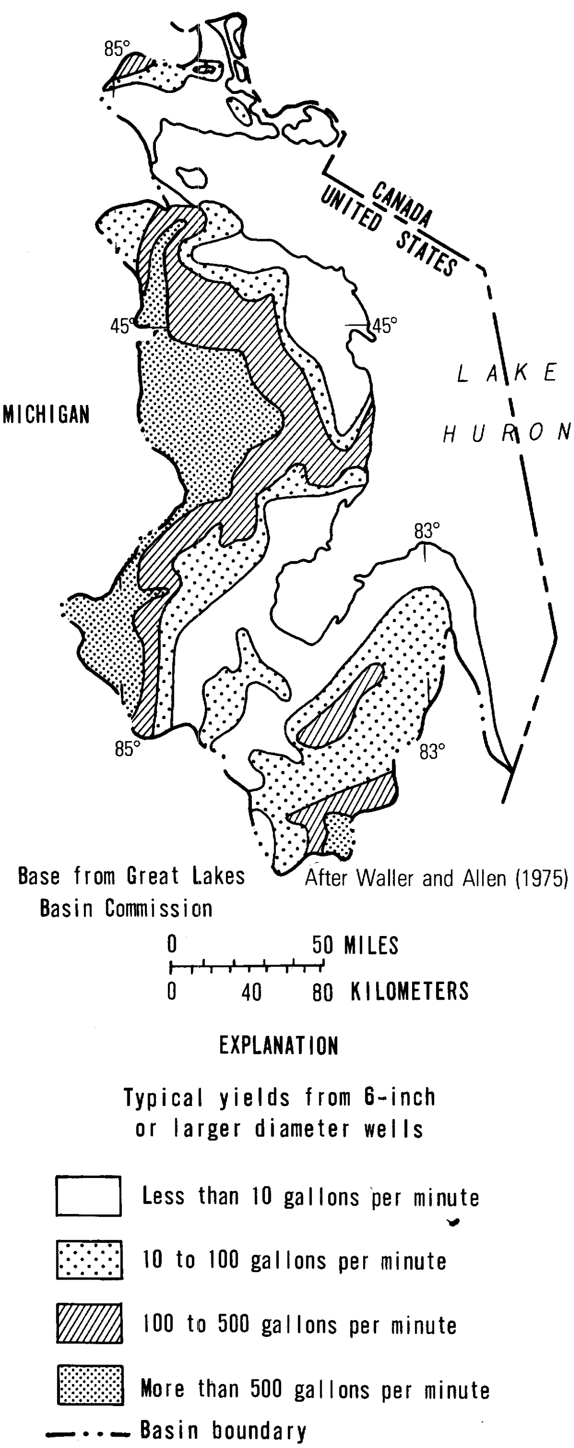


Figure 7.—Availability of ground water in unconsolidated deposits in the United States part of the Lake Huron basin.

the ground-water discharge may be greater, but data are not readily available to determine amounts.

Ground-water divides are generally assumed to coincide with surface-water divides. However, this is not always so in the Great Lakes Region. Near Chicago the Great Lakes drainage area is only a mile or so wide, but the bedrock aquifers extend several tens of miles beyond. Heavy pumping from these aquifers in the Chicago area has lowered the pressure in the aquifers, causing water to flow into the area from outside the Great Lakes Region.

ECONOMIC SETTING

DEVELOPMENT

The Great Lakes Region, which constitutes only 4 percent of the Nation's land area, contained slightly more than 14 percent of the population, or 29,322,300 people, in 1970. Of these, 85 percent were concentrated in the Lake Michigan and Lake Erie basins and only 2 percent in the Lake Superior basin.

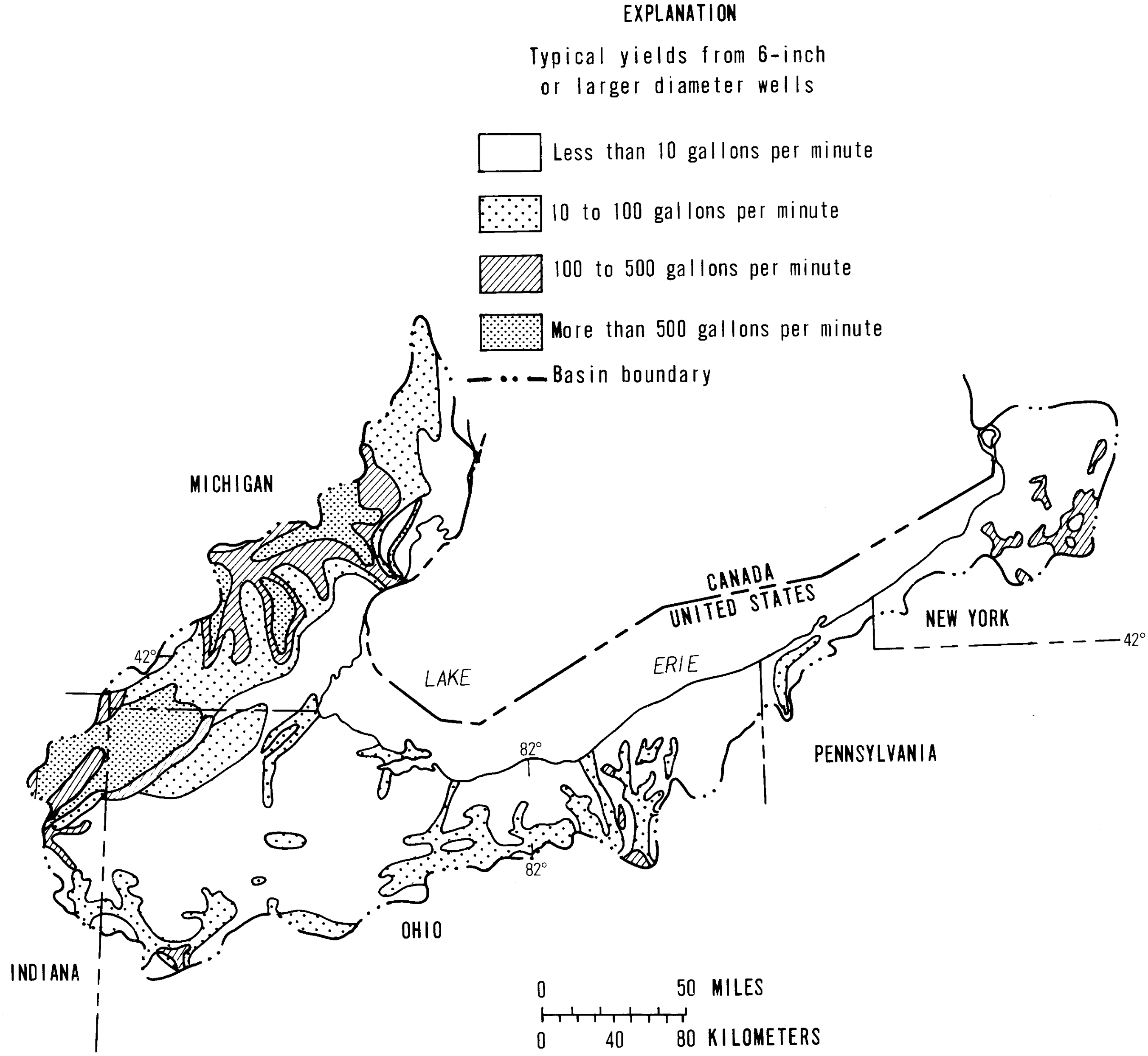
Major industries include steel production (47 percent of the Nation's total in 1970), petroleum refining, and manufacturing of chemicals, paper, and food products. Urban and industrial areas occupy 8.4 percent of the land.

More than 38 percent of the land is devoted to agriculture, which ranks behind the metal, food, and chemical industries in number of employees. Major crops include corn, wheat, oats, soybeans, and hay. Locally important crops include vegetables, grapes, fruit, and dairy products.

Nearly 50 percent of the land is forested. Recreational use of the land is increasing rapidly, particularly in northern Wisconsin, northern Michigan, and parts of New York. Mining, especially production of sand and gravel, crushed stone, iron ore, and portland cement, is important in some areas. Significant quantities of petroleum are pumped in scattered fields in the region.

WATER USE

The magnitude of water use in the Great Lakes Region is a function of economic development. Heaviest use is in the urban and industrial areas; lightest use is in the forested areas. Steel production, petroleum, refining, and manufacturing of chemicals, paper, and food products account for about 80 percent of the region's industrial water requirements, as well as most water-quality problems (Great Lakes Basin Commission, 1975d, p. 4–5). Locally, mining and ore processing require large amounts of water. With the large quantities of water readily available and most of the major urban areas located on their shores, the Great Lakes are the major source of water. Water use in the region in 1970 is summarized in table 3.



Base from Great Lakes Basin Commission

After Waller and Allen (1975)

FIGURE 8.—Availability of ground water in unconsolidated deposits in the United States part of the Lake Erie basin.

TABLE 3.—*Water use in the Great Lakes Region, 1970, in millions of gallons per day*

[Partial figures may not add to totals because of independent rounding]

Use	Total	Source [1]	
		Surface water	Ground water
Public supply	4,400	3,700	700
Self-supplied industrial	[2] 35,000	34,300	340 fresh 400 saline
Rural domestic	280	7	270
Livestock	90	24	62
Irrigation	90	53	37
	39,900	38,100	1,800

[1] Data from Murray and Reeves, 1972.
[2] Includes thermoelectric power use.

ROLE OF GROUND WATER IN THE WATER-RELATED PROBLEMS OF THE REGION

The main objective of this report is to discuss water-related problems and concerns of the Great Lakes Region, how ground water relates to them, and the role ground water can play in meeting or helping to alleviate them. In discussions with water officials and investigators of the region, the author asked what they felt were their major water-related problems. Table 4 summarizes their replies and also

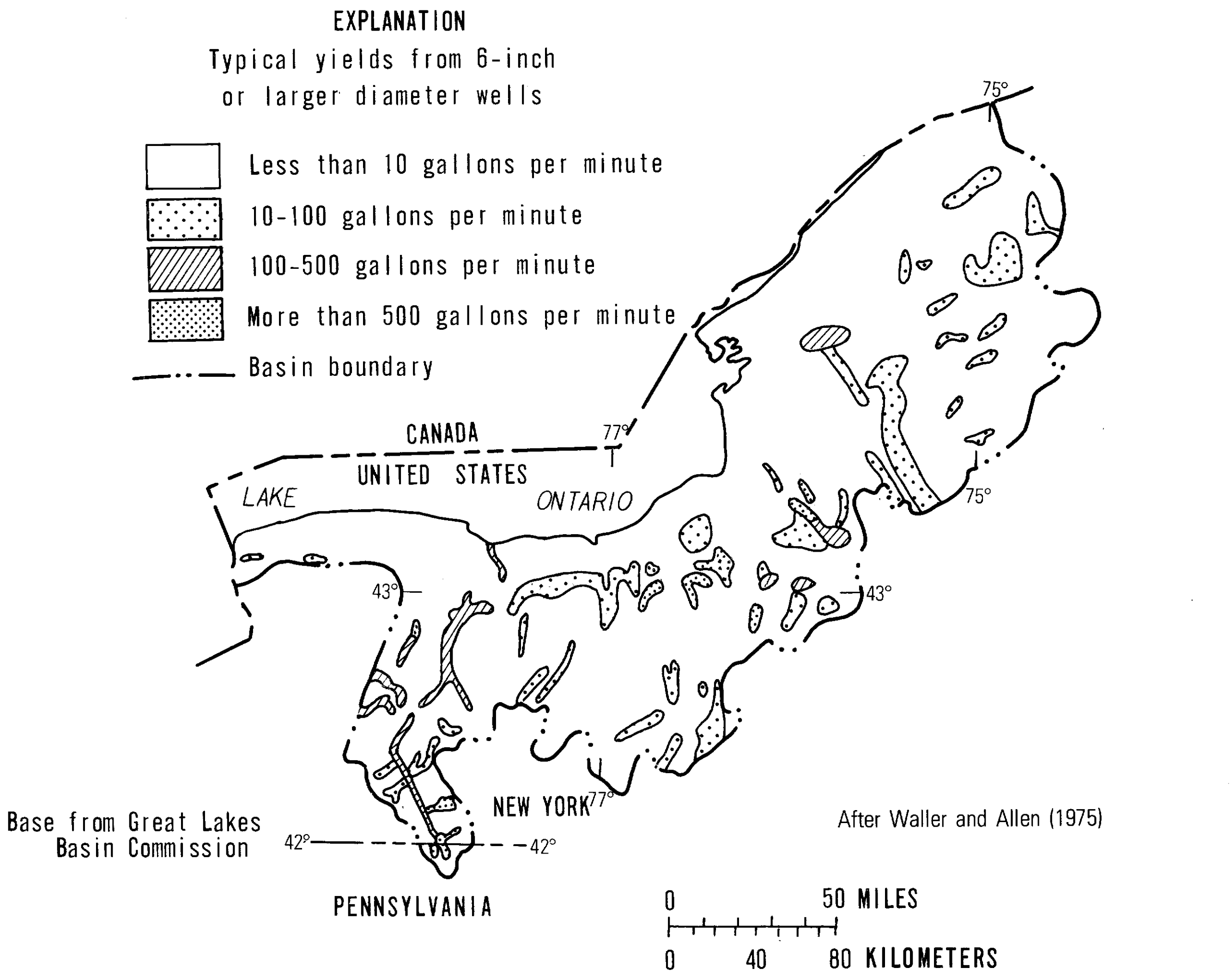


FIGURE 9.—Availability of ground water in unconsolidated deposits in the United States part of the Lake Ontario basin.

summarizes problems identified in reports prepared by various water-resource agencies. The concerns most frequently mentioned relate to management, lack of data, water quality, waste disposal, and water supply. Other, in general lesser concerns include flooding, erosion, wetlands, and low streamflow. Management and lack of data are covered under separate major headings, "Managing ground-water resources" and "Future Considerations," respectively. All the other concerns are discussed in the sections that immediately follow.

WATER QUALITY

NATURAL QUALITY

Natural quality of ground water in the Great Lakes Region is variable, though generally acceptable for most uses. Ground water is hard (more than 120 mg/L) (milligrams per liter) in most of the region, and iron concentrations greater than 0.3 mg/L are common, particularly in water from the sandstone aquifer in Wisconsin and Illinois and from the glacial deposits. High sulfate concentrations (more than 100 mg/L) are found in water from some of the unconsolidated aquifers, particularly in New York, Ohio, Indiana, and Michigan, and in water from Silurian and older bedrock aquifers throughout the region. In general, the water becomes more highly mineralized with depth.

Because ground-water discharge maintains dry-weather flow in the streams and helps to maintain the levels of most lakes and ponds, the chemical quality of these surface bodies of water during dry weather reflects the quality of water in adjacent shallow aquifers. During periods of high flow and in areas affected by pumping, water may move from the streams into the adjacent aquifers.

Ground water usually has a more constant quality than does surface water. During periods of low streamflow, when the quality of surface water may

TABLE 4.—*Water-related concerns*

Agency or investigator	Erosion	Flooding	Lack of data	Low streamflow	Management	Recreation	Waste disposal	
							Deep well	Landfills
Illinois								
Illinois Water Survey	--	X	--	--	X	--	--	--
Northeastern Illinois Planning Commission	--	X	--	--	--	X	--	--
Metropolitan Sanitary District, Chicago	--	X	--	--	--	--	--	--
Indiana								
U.S. Geological Survey	X	--	X	--	X	--	--	X
Northwestern Indiana Regional Planning Commission	--	X	--	--	X	--	--	--
Michiana Area Council of Governments	X	--	X	--	X	--	--	--
Michigan								
U.S. Geological Survey	--	--	--	X	X	X	--	--
Michigan Geological Survey	--	--	X	--	X	--	--	X
Soil Conservation Service	X	X	--	--	--	X	--	--
Michigan Department of Natural Resources	--	X	X	--	X	--	--	X
Michigan Bureau of Water Management	--	--	--	--	--	--	--	--
Dr. C. R. Humphreys (Mich. State Univ.)	--	X	X	--	X	X	X	X
Minnesota								
U.S. Geological Survey	X	X	X	X	X	X	--	--
Minnesota Department of Natural Resources	X	--	X	--	X	--	--	X
Arrowhead Regional Development Commission	--	--	X	X	--	--	--	--
New York								
U.S. Geological Survey	--	--	--	--	X	--	--	--
New York State Geological Survey	--	--	--	--	X	--	X	X
New York State Department of Public Service	--	--	--	X	--	--	X	--
New York State Department of Environmental Conservation	--	--	--	X	--	--	X	--
Central New York Regional Planning and Development Board	--	--	X	--	X	--	--	X
Genesee/Finger Lakes Regional Planning Board	--	X	X	X	X	--	X	X
Erie and Niagara Counties Regional Planning Board	--	--	--	--	X	--	--	X
Corps of Engineers, Buffalo District	--	--	X	X	--	--	--	X
Black River Basin Regional Water Resources Planning Board	--	X	--	X	--	X	--	--
Ohio								
U.S. Geological Survey	--	--	--	--	X	--	--	--
Ohio Environmental Protection Agency	--	--	--	--	--	--	X	X
Ohio Department of Natural Resources	X	X	X	X	X	X	X	X
Pennsylvania								
U.S. Geological Survey	X	--	X	--	--	--	X	X
Erie County Department of Health	--	--	--	X	--	--	--	--
Wisconsin								
U.S. Geological Survey	X	X	X	X	--	--	--	--
Wisconsin Geological Survey	X	--	X	--	X	--	--	X
Wisconsin Department of Natural Resources	X	X	X	X	X	X	--	X
Dr. David Stevenson (Univ. of Wisconsin)	X	--	X	X	X	--	X	X
Southeast Wisconsin Regional Planning Commission	X	X	--	X	X	--	--	X
Bay-Lake Regional Planning Commission	X	X	--	--	X	X	--	--
East-Central Wisconsin Regional Planning Commission	X	X	--	--	X	X	--	X
North-Central Wisconsin Regional Planning Commission	--	--	--	--	--	X	--	X
Entire Basin								
Great Lakes Basin Commission	X	X	X	X	X	X	X	X
National Oceanic and Atmospheric Administration	X	X	X	--	--	--	--	--
W. J. Drescher, U.S. Geological Survey	X	--	--	--	X	--	X	X

not meet water-quality standards, it may be feasible to utilize ground water to improve the quality of the streams. (See section on "Low Flow.") Ground water also can be used to improve water quality in small ponds. (See section on "Wetlands and Lakes.")

MINERALIZED GROUND WATER

The term "mineralized water" means different things to different people. This report follows the classification of Krieger, Hatchett, and Poole (1957, p. 5):

Terminology	Dissolved solids (mg/L)
Slightly saline	1,000–3,000
Moderately saline	3,000–10,000
Very saline	10,000–35,000
Brine (sea water)	More than 35,000

The U.S. Public Health Service (1962) recommends that water containing more than 1,000 mg/L of dissolved solids not be used for interstate commerce.

of the Great Lakes Region

Waste disposal—Continued			Water quality						Water supply				Wetlands
Spreading	Effluents	Septic tanks	Hardness	Iron	Salinity	Sulfate	Industrial operations	Road deicing	Domestic	Industrial	Irrigation	Municipal	
						Illinois—Continued							
--	--	--	--	--	--	--	--	--	--	--	--	X	X
--	X	X	--	--	--	--	--	--	--	--	--	X	--
--	X	--	--	--	--	--	--	--	--	--	--	X	--
						Indiana—Continued							
--	X	X	X	X	X	X	--	X	--	--	--	X	X
--	--	--	--	--	--	--	--	--	--	--	--	--	--
--	X	--	--	--	--	--	--	--	--	--	--	X	--
						Michigan—Continued							
X	X	X	--	--	X	--	--	X	--	(1)	X	X	--
--	X	--	--	--	--	--	X	--	--	--	X	--	--
--	--	--	--	--	--	--	--	X	--	--	X	--	--
X	--	X	--	--	--	--	X	X	--	--	--	X	--
--	--	--	--	--	--	--	--	--	--	--	--	X	--
--	--	--	--	--	X	--	--	--	--	--	--	X	--
						Minnesota—Continued							
X	X	--	--	--	X	--	(1)	--	X	(1)	X	X	--
--	--	--	--	--	--	--	--	--	--	X	--	X	--
--	--	--	--	--	--	--	--	--	--	(1)	--	X	--
						New York—Continued							
--	--	--	--	--	--	--	--	--	--	--	--	--	--
--	--	--	--	--	--	--	--	--	--	(2)	--	--	--
--	--	--	--	--	--	--	X	--	--	(2)	--	--	--
--	--	--	--	--	X	--	--	--	--	--	X	--	--
--	--	--	--	--	X	--	--	X	--	--	--	--	X
--	--	X	X	--	--	X	--	X	--	X	X	X	X
--	--	--	X	--	--	X	--	--	--	--	--	--	--
--	--	--	--	--	--	--	--	--	--	--	--	--	--
--	--	--	--	--	--	X	--	--	--	X	X	X	X
						Ohio—Continued							
--	--	--	--	--	--	--	--	--	--	--	--	--	--
--	--	X	--	--	--	--	X	X	--	--	--	--	--
--	X	--	X	--	--	--	--	--	--	--	X	X	--
						Pennsylvania—Continued							
--	--	X	--	--	X	--	X	--	--	--	--	X	--
--	X	--	--	X	--	--	--	--	X	--	X	X	--
						Wisconsin—Continued							
--	X	X	X	X	X	X	--	X	X	X	X	X	X
X	X	X	X	X	--	X	X	X	X	X	X	X	X
--	X	X	X	X	--	X	X	--	X	X	X	X	X
--	X	X	--	--	--	--	--	--	--	--	--	--	--
--	X	X	--	--	X	--	X	--	--	--	--	X	--
--	X	X	--	--	--	X	X	--	--	X	--	X	X
--	--	X	--	--	--	--	X	--	--	--	--	--	--
--	--	X	--	--	--	--	X	--	--	--	--	--	--
						Entire Basin—Continued							
--	X	X	X	X	X	X	X	X	--	X	X	X	X
--	--	--	--	--	--	--	--	--	--	--	--	--	--
--	--	--	--	--	--	--	--	--	--	X	--	X	X

[1] Mining.
[2] Power.

However, people can become accustomed to water with a higher dissolved-solids concentration, and water containing as much as 3,000 mg/L can be used for a domestic supply, where less mineralized water is not available.

Slightly saline water occurs at depths less than 500 ft below land surface throughout much of the region (fig. 10). In parts of eastern Michigan and Pennsylvania, saline water is at depths less than 100 ft below land surface. Most mineralized water at shallow depths is due to natural migration upward and outward from deeper bedrock formations and to leakage through uncased or improperly constructed wells.

Mineralized ground water is generally considered a nuisance in most of the Great Lakes Region. However, it does have considerable economic potential. In areas where supplies of potable ground water are scant, such as in parts of eastern Michigan and central New York, mineralized ground water is a

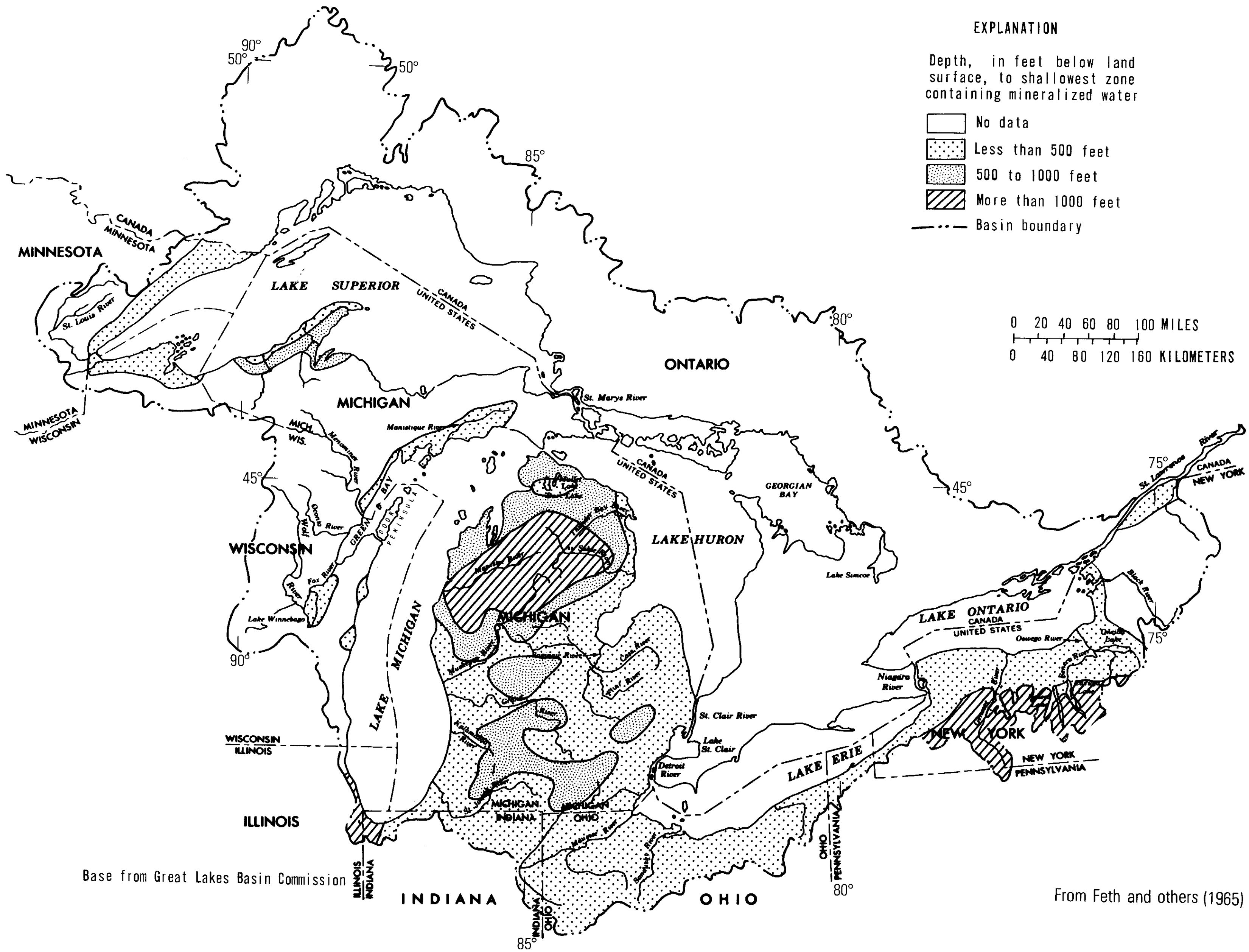


FIGURE 10.—Areas where dissolved-solids concentration of ground water exceeds 1,000 mg/L.

potential source of water supply. Advances in desalination processes are making saline water economically competitive with other alternatives, such as reservoirs and pipelines. Industry can use mineralized water for cooling and for processing, where the water does not become part of the finished product.

A concept that is attracting increasing interest is the use of saline aquifers to store freshwater or natural gas. Kimbler, Kazmann, and Whitehead (1975), working with hydrologic models (physical and mathematical) of unconsolidated aquifers, found that a zone of stagnation can be created within a saline aquifer to reduce mixing of injected fresh and host saline waters. They report that the percentage of the freshwater recovered uncontaminated with saline water improves with each cycle of injection and recovery. Storing freshwater in a saline aquifer would be particularly attractive in heavily populated areas, where all feasible surface reservoir sites have been developed or where land is too expensive for surface reservoirs.

Because most investigations so far have been confined to aquifers having intergranular permeability and porosity, storage of freshwater in a saline aquifer may have only slight application in the Great Lakes Region, where most saline aquifers are in fractured bedrock. Additional studies, however, may show that the principles described by Kimbler, Kazmann, and Whitehead (1975, p. 73–74) can be modified to apply to these aquifers.

Saline aquifers are also used for disposal of liquid wastes. Caution is necessary, however, for much still needs to be learned about the processes and risks involved. Disposal of liquid wastes is discussed in more detail in the next section.

POLLUTION

Ground water can become polluted in many ways. Some pollution is related to development of the resource, as when heavy pumping induces flow into an aquifer from an adjacent saline water aquifer; some is related to waste disposal, as when leachate enters an aquifer from a landfill; and some is related to other activities of man, such as oil and gas production. The major sources of ground-water pollution in the Great Lakes Region are listed in table 5.

Waste disposal and the effects it may have on water quality is a major concern in the region. Under the Federal Water Pollution Control Act Amendments of 1972, the States are mandated to eliminate stream pollution. Implementation of this law could place additional stress on the ground-water system through an increase in use of landfills and deep disposal wells and through the surface spreading of liquid-waste effluents.

TABLE 5.—*Major sources of ground-water pollution in the Great Lakes Region*

Source of pollution	Primary pollutants
Waste disposal	
Septic tanks and cesspools	Bacteria, nitrate, detergent, chloride.
Landfills and dumps	Heavy metals, PCB's (polychlorinated biphenyls), chloride, phenols, nutrients.
Spreading of water-treatment and waste-treatment effluents.	Chloride, nutrients, heavy metals.
Holding ponds	Variety of industrial wastes such as phenols, PCB's, heavy metals.
Disposal wells	Radioactive wastes, industrial chemicals.
Industrial operations	
Oil and gas recovery	Chloride, petroleum products.
Salt mining	Chloride.
Accidental spills, leakage	Petroleum products, industrial chemicals.
Road deicing	Chloride.
Agricultural activities	
Feedlots	Bacteria, nutrients.
Use of fertilizers	Nutrients.
Use of pesticides	Various hydrocarbon compounds.
Management problems	
Overdevelopment of aquifer	Chloride.
Abandoned wells, leaky casings, improperly cased wells.	Chloride, nitrate.

SEPTIC TANKS

The most widespread means of waste disposal in the region is through septic tanks. Unfortunately, soils in much of the region are not suitable for this type of disposal. Septic tanks do not function well where the water table is near land surface, where the soil is clayey, or where the soil cover is thin. These conditions, singly or in combination, are common throughout much of the Great Lakes Region. Numerous septic tanks clustered together under these conditions, as in summer-home developments, can cause pollution.

Vogt (1972) and Pettyjohn (1972) describe two areas where ground water has become polluted from septic-tank wastes. In both areas only a few feet of soil overlies a highly permeable limestone, which is the source of household water for the areas. At Posen, Mich. (Vogt, 1972), septic-tank effluent carrying hepatitis virus was discharged into the soil zone. Percolating water from melting snow and spring rains carried the effluent and virus into the ground-water reservoir, spreading the virus to nearby wells and causing an epidemic of infectious hepatitis.

Residents of Bellevue, in north-central Ohio, used septic tanks that discharged into a thin soil zone overlying a very permeable limestone aquifer. They also drilled waste-disposal wells into the limestone (Pettyjohn, 1972). The result was a plume of polluted ground water extending 15 mi to Lake Erie through a highly productive aquifer (well yields greater than 500 gal/min).

Wisconsin's Door Peninsula is another area where pollution of ground water is widespread owing to the disposal of septic-tank effluent and agricultural, industrial, and municipal wastes into a thin soil zone (Sherrill, 1975). The wastes percolate through the soil, enter a cavernous limestone aquifer, and then spread rapidly through the aquifer. Thus, the shallow ground water is polluted, and the State now requires at least 100 ft of casing in new wells. This pollution could increase and spread laterally and vertically unless other means of waste disposal are used.

Increased eutrophication of many lakes in the region is, in part, a result of ground-water pollution from septic wastes. Nutrients in septic-tank effluents are transported by ground water and discharged into lakes. Conditions conductive to eutrophication are particularly prevalent in lakes of northern Wisconsin and northern Michigan, where lake shores are occupied by year-round communities and subdivisions.

LANDFILLS

Although not as numerous or widespread as septic tanks, landfills are another potential source of ground-water pollution. For example, three landfills in northern Ohio have polluted a shallow aquifer, which is the source of water for nearby residents (David Johe, Ohio Environmental Protection Agency, oral commun., 1975). Johe reports that two of the landfills have been closed but that polluted water will continue to enter the aquifer for years, and new sources of household water will have to be found. Because ground water moves so slowly and diffusion rates are so low, polluted ground water may not be noticed for many years. Other landfills in the Great Lakes Region are probably polluting ground-water bodies.

A waste-disposal site is usually considered suitable if the surface will remain unsaturated. In humid areas, such as the Great Lakes Region, sites where excavation will not intersect the zone of saturation are difficult to find. For this reason, many landfills are located in materials of low permeability, such as till. Generally, test drilling is necessary to identify the materials at the potential landfill site, which can be expensive. For preliminary evaluation of a site, data from nearby water wells can be used to estimate the characteristics of the subsurface materials and the depth to water.

WASTEWATER EFFLUENTS

Disposal of effluents from water-treatment and sewage-treatment plants is of increasing concern as more wastes are generated. Statutes restrict the discharge of effluent to streams. Early results from an effluent-disposal project near Muskegon, Mich., indicate that spray-irrigation of liquid wastes may be practical. Effluent from Muskegon and from a nearby paper company are being used to spray irrigate about 6,000 acres of principally very sandy soil. Irrigation water that percolates through the upper few feet of soil is collected in perforated tile drains and discharged into nearby streams. Thus far the return water has been of acceptable quality. If return water of good quality can be maintained, spray irrigation may not only provide a means of waste disposal but also may become a source of recharge to the local aquifer.

DEEP-WELL DISPOSAL

Deep-well disposal of liquid wastes, although not new, has received increasing interest in recent years (Cook, 1972; Braunstein, 1973). This approach has an out-of-sight, out-of-mind appeal and is sometimes the easiest method of disposal, but it may be impractical or unwise in many areas. The effects of injecting wastes into deep aquifers are complex and varied. Injection is not a means of permanent disposal but, rather, a means of storage (Piper, 1969, p. 6), and the wastes could become a problem in the future. Most of the wastes are injected into aquifers containing highly saline water. Although the saline water has no use at present, it may be of beneficial use in the future.

The Great Lakes Basin Commission reports 86 waste-disposal wells in the region (Eugene A. Jarecki, oral commun., 1975). The U.S. Environmental Protection Agency (1974) published records of 33 operating wells and 19 inactive wells in the region in 1973. Of those in use, 21 are in Michigan, 8 in northwestern Indiana, 3 in northwestern Ohio, and 1 in New York. One well in Michigan injects wastes into Mississippian sandstone at a depth of 1,030 ft. The Cambrian Mount Simon Sandstone receives wastes from 3 wells in Michigan, 3 in Ohio, and 6 in Indiana. Well depths range from 2,160 ft in Indiana to 4,608 ft in Michigan. The rest of the wells inject waste into Devonian limestone, dolomite, and sandstone. Well depths range from 255 ft in Indiana to 4,986 ft in Michigan. Most of the wastes are from steel mills (spent pickling liquor), chemical and drug manufacturing, and brine processing but also include wastes from oil refining and from a laundromat. Rates of injection range from about 1 gal/min to 556 gal/min.

Because of the wide variation in geologic and hydrologic settings and in the volume and nature of wastes, adoption of uniform nationwide standards and criteria for deep-well disposal is not fully practical. At present (1976), Minnesota and Wisconsin do not allow deep-well disposal of liquid wastes. Where such disposal is considered in the other States in the Great Lakes Region, careful studies help to determine the physical and chemical nature of the wastes, compatibility of the wastes with fluids in the injection zone, and possible reactions between the wastes and the rock materials constituting the aquifers. Stringent well-construction standards and careful monitoring of the injection process would help to protect potable ground-water.

OTHER SOURCES OF POLLUTION

In addition to waste disposal, other activities cause ground-water pollution in the region. Improperly cased wells, improperly plugged abandoned wells, or unplugged abandoned wells with deteriorated casings have allowed water of poor quality to move into aquifers that contained good water. Accidental spills, leaky storage tanks, and broken pipelines have allowed petroleum products to contaminate ground water. The effects of these and similar activities are usually local, but they are very long lasting.

One widespread source of ground-water pollution that is increasingly recognized is the salt used in deicing roads. The salt not only imparts a bitter taste to the water but also may be hazardous to persons on a low-sodium diet.

WATER SUPPLY

Considering the amount of water available in the Great Lakes Region, the idea of water-supply problems may seem anomalous. Nevertheless, the problems are real. Although many supply problems relate to water quality, as previously discussed, some areas face a potential shortage of water. In other areas, water-supply problems are the result of local overdevelopment.

The water-supply situation in the Great Lakes Region is summarized in the following table (Great Lakes Basin Commission, 1975b, p. 30):

	1970 (Mgal/d)	2020 (Mgal/d)
Public supply:		
Use	4,400	9,200
1970 capacity/2020 needs	7,400	1,800
Industrial supply:		
Use	[1] 10,600	12,800
1970 capacity/2020 needs	10,600	2,200
Rural supply:		
Use	470	740
1970 capacity/2020 needs	470	270

[1] Does not include thermoelectric power use.

The entry "1970 capacity" is the developed capacity to supply water as of 1970. The entry "2020 needs" refers to the additional capacity that must be developed to meet the demands anticipated by the year 2020. This capacity could involve developing additional water supplies, increasing the capacity of water-treatment plants, installing new distribution lines, or other similar measures.

Many people are aware of some of the advantages and disadvantages of ground water as a source of supply because many of them obtain water from their own wells or from municipally owned wells. Nevertheless, a brief discussion seems indicated. Ground water generally costs less to develop than an equal amount of surface water. Howard (1974) reported that costs for developing a ground-water supply range from $100 to $300 per gallon per minute, whereas the costs for developing a surface-water supply ranges from $1,100 to $1,500 per gallon per minute. A ground-water supply can be developed gradually as demand warrants, whereas an intake structure or reservoir for a surface-water supply must be designed and constructed to meet not only present demands but also anticipated future demands. Properly managed, a ground-water supply does not lose its capacity or deteriorate, nor does it require a large land area. A surface-water reservoir, on the other hand, is subject to loss of capacity from siltation, eutrophication, pollution from water-based recreation, and deterioration of the physical facilities.

Ground water usually has a narrow temperature range, little or no sediment or turbidity, is relatively free from nuclear fallout, and usually is not polluted by bacteria or viruses. (A study of public water supplies in New York has shown that ground water there is free from organic pollution (U.S. Geol.

Survey, 1974). There were no traces of PCB's, pesticides, or organic mercury in any samples of ground-water supplies.) In addition, ground-water loss through evaporation is minimal, and ground water is widely available throughout the region, at least in moderate quantities.

On the other hand, ground water is generally more mineralized than surface water and, once polluted, is very difficult, if not economically impossible, to clean up. Where a ground-water source is heavily developed, water levels are lowered in nearby wells, pumping costs are increased, and streamflow may be decreased as a result of induced flow into the ground-water system. If water of poor quality is present in an adjacent aquifer, heavy pumping may induce this water to flow into the developed aquifer. In parts of the Great Lakes Region, available quantities of ground water are insufficient to support large-scale development.

PUBLIC SUPPLIES

Most large metropolitan areas in the Great Lakes region obtain water from surface reservoirs, streams, or one of the Great Lakes. Smaller communities generally obtain their supply from ground water. In general, in spite of local problems, ample water is available to meet current municipal demands.

Water for public supplies in 1970 was withdrawn at a rate of about 4,400 Mgal/d (Great Lakes Basin Commission, 1975b, p. 30), of which 3,400 Mgal/d, or 77 percent, came from the Great Lakes; 390 Mgal/d, or 9 percent, from inland lakes and streams; and 560 Mgal/d, or 13 percent, from ground-water bodies. Developed water-supply capacity was 7,400 Mgal/d. The Great Lakes Basin Commission estimates that by the year 2020 nearly 9,200 Mgal/d will be needed to meet public-supply demands—an increase of 1,800 Mgal/d over present developed capacity.

The city of Chicago obtains most of its water from Lake Michigan. Many of the surrounding communities and industries, however, obtain water from deep bedrock aquifers. This deep aquifer system is fairly uniform throughout the area, and well yields and water quality are predictable. Pumping has lowered water levels several hundred feet at major pumping centers. Pumping has been heavy also in the Milwaukee area, and the drawdown cones of the Chicago and Milwaukee areas have begun to overlap. Further development of the deep aquifer system would probably accelerate the decline in water levels and may induce water of poor quality to move updip into the area from the east.

Less is known about the hydrology of the shallow aquifers in the Chicago area because they have not been developed as much as the deep aquifers. Increased development of the shallow aquifers could relieve some of the stress on the deep aquifer system. Digital models of the aquifer systems have been made by the Illinois Water Survey for the Chicago area and by the U.S. Geological Survey for the Milwaukee area. These models will enable planners to manage the development and use of the aquifers more effectively.

Prior to 1957, the city of Green Bay, along with neighboring communities and industries, obtained its water supply from a sandstone aquifer. By 1957 the water level in wells tapping the aquifer had declined more than 200 ft in downtown Green Bay (Knowles, 1964), and the city had to seek another source of supply. Other sources in the immediate area—Green Bay, Fox River, and Lake Winnebago—are polluted. Thus, the city turned to Lake Michigan for its supply and since 1957 has obtained water from the Lake by pipeline across the Door Peninsula. When Green Bay discontinued pumping from the sandstone aquifer, water levels recovered rapidly. However, subsequent development of the aquifer has caused the water levels to decline severely again.

Although the sandstone aquifer is heavily used, it has potential for additional development, but careful planning would be necessary to prevent interference between wells and consequent local depletion of supplies. Local officials are concerned that concentrated heavy pumping will cause water of poor quality from the south to move into the aquifer.

As glaciers moved across the Great Lakes Region, many valleys were filled with debris. These buried valleys that contain extensive deposits of saturated sand and gravel are a potential source of public-water supply.

Fort Wayne, Ind., obtains its water supply from the St. Joseph River. The U.S. Geological Survey, in cooperation with the Indiana Department of Natural Resources and the city of Fort Wayne, is making a study of the availability of ground water for future supply. Preliminary results indicate that a buried valley to the northwest may be able to supply sufficient water to the city for many years.

Buried valleys are also potential sources of water for communities in the Erie, Pa., area and parts of northeastern Ohio. These valleys have not been systematically studied, so little is known about their hydrologic character. The U.S. Geological Survey, in cooperation with the Pennsylvania Geological Survey, is starting a study of Erie County that will include investigation of the ground-water potential of some of these valleys.

For cities near one of the Great Lakes, the conjunctive use of ground water and surface water may have advantages. Ground water could be used during summer and fall, when it is cooler than lake water. The lake water could be used during winter and spring while the aquifers are recharged. Mixing water from both sources could reduce treatment costs. Alternatively, areas near the lake could be supplied with lake water while inland areas are supplied with ground water. This could reduce pumping and transmission costs.

INDUSTRIAL SUPPLIES

The Great Lakes Region is heavily industrialized, and industrialization is expected to increase during the next few decades. In addition to manufacturing, other large industrial uses of water include power generation, sand and gravel production, and ore processing. Self-supplied industrial use of water in 1970 was 10,600 Mgal/d. This is expected to increase to nearly 12,800 Mgal/d by the year 2020 (Great Lakes Basin Commission, 1975b, p. 30).

Many industries in the region purchase water from municipalities; many others, however, provide their own supply. Industries tend to cluster together, usually in or near large cities. Their closeness can lead to overdevelopment of the water sources and to deterioration of water quality. Nearly everywhere that municipalities in the region are faced with a water-supply problem, industries also have a problem.

Although outside the Great Lakes Region, the Mill Creek valley in southwestern Ohio is a good example of what industries can do by cooperating in developing their water supplies. The Mill Creek valley is part of the greater Cincinnati industrial area. Industrial development started in the late 1800's and increased steadily, with both World Wars providing impetus for rapid growth. Ground-water withdrawals rose comparably, and, by the late 1940's, water levels were extremely low and well yields sharply reduced. In an effort to improve the situation, 11 industries formed the Southwestern Ohio Water Company. They developed a ground-water system in an adjacent valley and piped the water into their industrial complex. As a result, withdrawals from the aquifer in Mill Creek valley declined, and water levels and yields recovered. However, increased industrial development brought the threat of further problems, and the water users requested a study of the feasibility of artificial recharge to the aquifer. This study (Fidler, 1970), made in cooperation with the Ohio Department of Natural Resources, Division of Water, concluded that artificial recharge through injection wells would reverse the declining water levels.

Formation of a cooperative to import water may not be feasible everywhere in the Great Lakes Region. Nevertheless, it shows what cooperation and ingenuity can do to meet a water-supply problem.

IRRIGATION

Irrigation of crops does not yet play a major role in the Great Lakes Region. Out of a total of 11,972,000 potentially irrigable acres, 196,800 acres were irrigated in 1968 (Great Lakes Basin Commission, 1975c, p. 8–9). More than half the irrigation is in Michigan. Irrigated acreage is estimated to increase to more than 520,000 acres by 2020. Agricultural irrigation in the region required 106,700 acre-ft in 1968 and probably will require more than 480,000 acre-ft in 2020. Similar amounts were used and will be used to irrigate golf courses.

In recent years, agriculture has depended on improved hybrid crops and fertilizers to increase production. A plateau may have been reached in their effectiveness, however, and farmers may be turning more to irrigation to ensure high productivity. If so, demand for water will increase.

Even in the humid climate of the Great Lakes Region, soil moisture can limit crop growth. Studies of the relation of evapotranspiration to climate show that yield-depressing droughts are common, even though average precipitation during the growing season may exceed the amount needed by the crop (Richards and Richards, 1957, p. 49).

A steady, dependable source of good-quality water is needed for irrigation, which means that most of the increased demand will be supplied by ground water. This water may come directly from wells, from ponds excavated into the water table, or by pumping from wells into a holding pond and then distributing the water as needed. This last method will permit irrigation in areas where high yielding wells are not feasible.

LOW FLOW

Low flow (dry-weather flow or base flow) in streams consists of ground-water discharge into the streams. In the Great Lakes Region, low flows are greatest per unit area in streams that drain highly permeable aquifers. In streams that drain poorly permeable aquifers, flow will decrease fairly rapidly after rains and may even cease altogether between rains. Flow-duration curves for two streams in Ohio are shown in figure 11. The data were adjusted to the 1931–60 period (Cross, 1968). Curve A is for the Ottawa River at Allentown, Ohio. The river drains an area of fairly coarse-grained glacial materials that readily yield ground water to maintain streamflow. The stream also receives discharge from the underlying carbonate-rock aquifer. Curve B is for the Ashtabula River near Ashtabula, Ohio. The river drains fine-grained glacial and lake deposits, which do not yield much ground water to maintain streamflow. Using figure 11, one can calculate that, at the 95 percentile, the Ottawa River will have a flow of 11 ft^3/s, whereas the Ashtabula will have a flow of 0.1 ft^3/s.

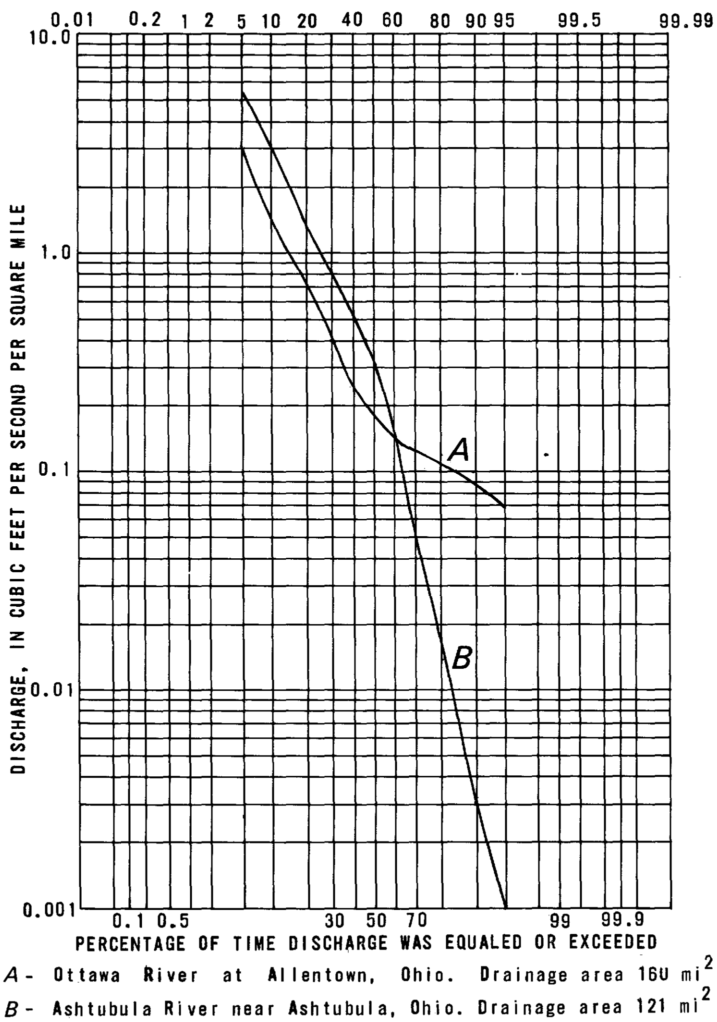


FIGURE 11.—Flow-duration curves for two streams in Ohio, 1931–60.

Augmentation of low flow has been considered for some streams, usually to maintain the quality of the water. Implementation of the Federal Water Pollution Control Act Amendments of 1972 should lessen the need for augmentation to control water quality. However, nonpoint sources of pollution will continue to affect the quality of many streams. Other reasons for low-flow augmentation include maintaining streamflow as a source of water for industries and municipalities, maintaining fish and wildlife habitats, and recreation.

Many of the small communities along the Great Lakes obtain their water supply from small streams that drain directly into the Lakes. During dry periods, flow in many of these streams is insufficient to meet needs of the communities. Even on larger streams, a combination of low flow and heavy development can cause water shortages. In addition to maintaining sufficient flow to avoid damage to fish and wildlife habitats, low-flow augmentation can be used to improve water-quality (temperature, dissolved oxygen) conditions in trout streams (Novitski, 1973).

Most low-flow augmentation is done with water from reservoirs. In some areas, ground water is an alternative source. Where the aquifer is separated from a stream by a less permeable zone, pumping ground water into a stream for flow augmentation may be especially practical. Even where the aquifer is in good hydraulic connection with the stream, proper well location can prevent adverse effects of pumping on streamflow during the critical low-flow period. Most periods of critical low flow, when augmentation would be needed, last only a few days. By locating the well(s) several hundred to a few thousand feet (depending on hydrologic character of the aquifer) from the stream, the effects of diverting ground-water flow will not reach the stream until the critical period is over. By then, pumping will have stopped, and the water table can recover.

WETLANDS AND LAKES

The relationship between ground water and wetlands is frequently misunderstood. Many people think of wetlands as areas of ground-water recharge, whereas most wetlands are maintained because they are areas of ground-water discharge. Similarly, ground-water discharge maintains the water level in most of the smaller lakes and ponds in the region. Permanently draining a wetland, pond, or lake would decrease the availability of ground water in the area because it would lower the water table.

Wetlands, lakes, and ponds do recharge aquifers during floods, when the water level in the wetlands and lakes is higher than in adjacent aquifers. However, the recharged water generally quickly dissipates once flood levels recede, as water flows from the aquifers back into the wetlands and lakes. This same process along streams is termed "bank storage."

In some places, ground water can be used to maintain the water level artificially in a wetlands or a small lake or to create a new wetlands or lake. If the aquifer is not hydraulically connected with the lake or wetlands, water could be pumped from the aquifer to maintain levels (fig. 12*A*). However, if the aquifer is hydraulically connected with the lake (fig. 12*B*), pumping from a well near the lake could cycle the water from the lake to the aquifer and back to the lake.

During recent years, the Detroit municipal water system, which obtains water from Lake Huron, has enlarged its service area to include about 2,000 mi^2 in southeastern Michigan, including Pontiac and Flint. Much of this area formerly used ground-water supplies but switched to the Detroit system as water levels declined and pumping costs increased. Ground-water levels have now recovered, and, in some areas, wells are flowing. This ground water could be diverted or pumped to create recreational ponds or lakes.

Water quality is becoming a problem in many lakes in the region, particularly because of high nutrient concentration. Ground water, particularly that from deep aquifers, generally contains a much smaller nutrient load than surface water. It may be feasible to remove much of the nutrients in small, highly eutrophic lakes by draining and refilling the lakes, either by natural ground-water discharge or by pumping from a deep aquifer. Born and others (1973) described an attempt to rehabilitate Snake Lake, in northern Wisconsin. The lake, which covers 12.3 acres, had received direct discharge of municipal waste for more than 20 years, destroying the lake's recreational and esthetic value. The lake was drained and then allowed to refill from natural ground-water discharge and from precipitation. Although dissolved-oxygen-depletion problems continued, there was a substantial initial reduction in nutrient concentrations, as well as a reduction in chloride concentration, conductance, and water color. The subsequent return of these constituents to near predraining levels is attributed to their release from bottom sediments. If the nutrient-rich bottom sediments had been leached or removed before the lake was refilled, the reduction in nutrients, chloride, and other mineral concentrations, would probably have been permanent. Other beneficial effects were the elimination of a heavy growth of duckweed and a deepening of part of the littoral zone through sediment compaction.

EROSION

The role of ground water in shoreline erosion is not generally recognized. The action of ground water may not be as spectacular as that of a stream cutting into its banks or waves beating on a cliff. Nevertheless, ground water can erode. Where the water table in a bluff is above the level of the lake or stream, perhaps a perched water table held up by a clay layer in unconsolidated deposits, the water loosens the deposits, allowing them to slump down to the shore and be carried away by wave action. Even a small trickle of water seeping out of a hillside can gradually wash away the deposits over which it flows (fig. 13).

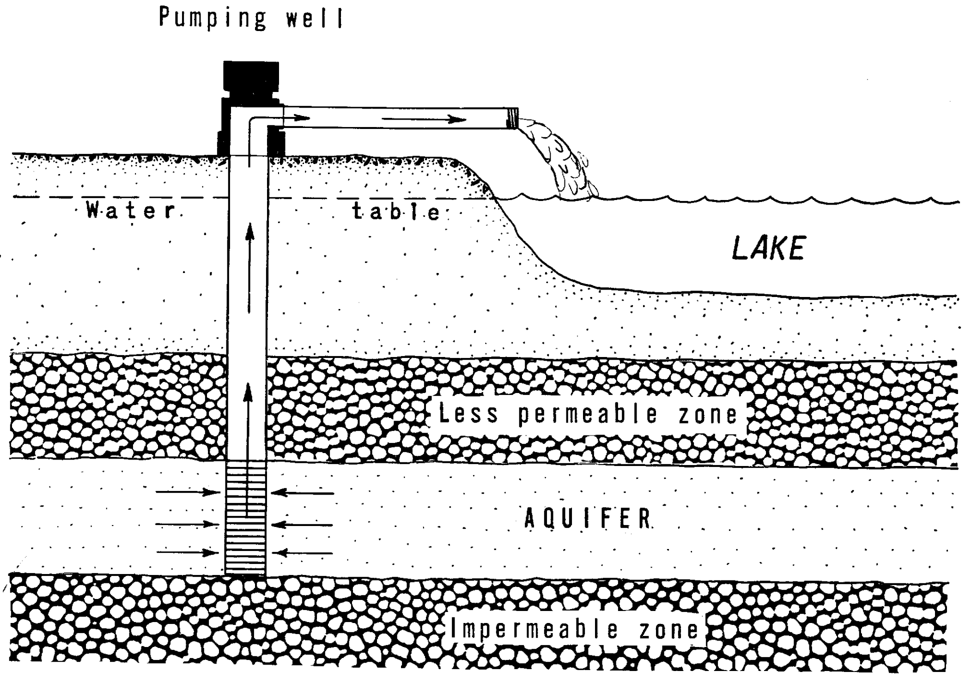
In some areas this erosion may be reduced or stopped by dewatering the bluff along the shore. Depending on local conditions, this might be done by several large capacity wells or by a line of drive-point wells. The pumped water could be used for local public-supply, industrial, or irrigation needs.

FLOODING

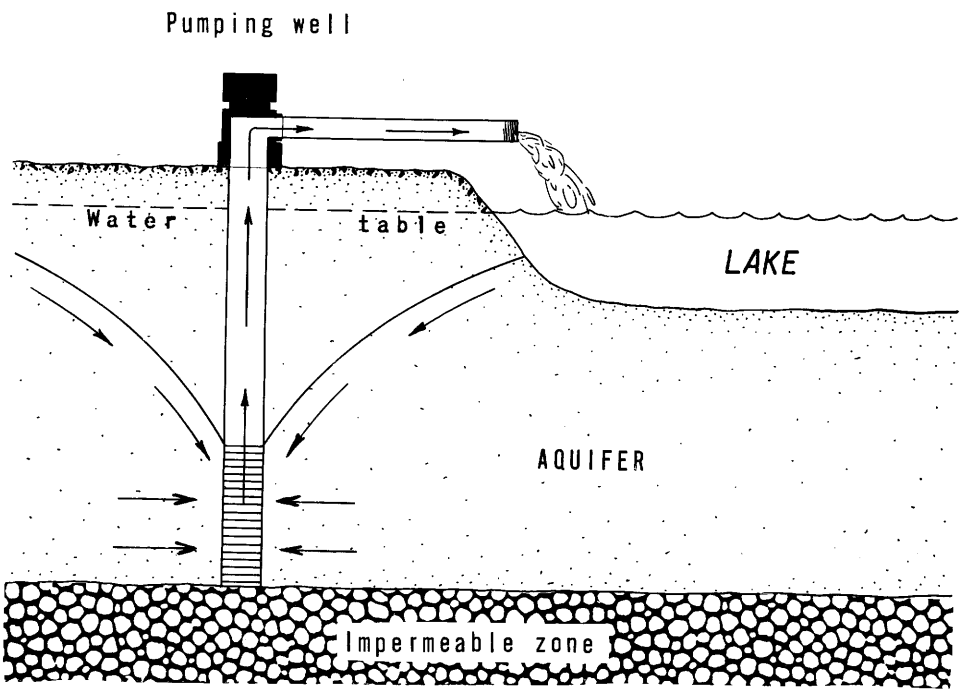
The ground-water system can be used to alleviate flooding. Where conditions permit, flood peaks could be reduced by diverting some or all the flow into recharge areas, such as abandoned sand and gravel pits or specially prepared areas. Waller and Ayer (1975, p. 163–164) have suggested that floodflows in the Black River basin in western New York be diverted into ditches running across the top of sand deltas at the base of the Adirondacks. The water would either recharge the aquifers or go into temporary storage that would later supply baseflow to the numerous streams that rise in the deltas.

MANAGING GROUND-WATER RESOURCES

Effective and efficient management of ground-water resources requires a knowledge of ground-water hydrology and the local hydrologic system and cooperation of all involved in water use. It includes planning the development of the resource, managing withdrawals, monitoring the results of development, and modifying pumping schedules and



A



B

FIGURE 12.—Feasible (*A*) and infeasible (*B*) conditions for pumping ground water to maintain lake levels.

FIGURE 13.—Erosion from ground-water discharge along Lake Michigan in Indiana.

additional development on the basis of past experience and analytical studies. Ground-water management combined with surface-water management enables the two sources to be treated as a single resource.

The discussions in the preceding sections of this paper indicate the probability of water-related problems even in an area of abundant water such as the Great Lakes Region. Recognizing the need for a reference on management principles, the American Society of Civil Engineers has published a manual on ground-water management (Coe and others, 1972). The manual discusses in detail the concepts that are only briefly mentioned here and contains an extensive bibliography of pertinent reports.

COORDINATING DEVELOPMENT

The first step in managing ground-water resources is to coordinate the development of supplies by using knowledge of the hydrologic system. This requires a good data base, including information on recharge rates, boundary conditions, water quality, and geology. A good development plan would have wells spaced to minimize boundary and well-interference effects without overly increasing the costs of transmission lines. It could also include conjunctive use of surface water, where feasible. For example, coordinated development in the area along the Mesabi Iron Range, particularly around Hibbing and Virginia, Minn., could be of great benefit to both municipal and industrial water users. The surface-water potential in the area is only fair, and ground water, which is used for most industrial and municipal supplies, may not be sufficient for future demands.

Mining companies in the area have been using 1,200 to 6,000 gal of water/ton of ore processed, mostly from surface sources. At the same time, much of the large quantities of ground water being pumped to dewater deep mines is discharged to nearby streams (Cotter and others, 1965; Winter, 1973). Through coordination, the pumped ground water could be made available to nearby municipalities or used for ore processing, leaving the surface water for municipal use. The suggestion has been made that it might be possible to pipe in water, either from Lake Superior or from a distant well field, to meet future needs. If all those who would benefit from such a plan would finance it jointly, the cost would be minimal for any single entity.

Perhaps the most important factor in ground-water management is mutual planning and development by municipalities and industries. Several areas in the Great Lakes Region are faced with water-supply problems because cooperation and coordination has been inadequate. The Lansing, Mich., area is an example.

The city of Lansing installed its first well in 1885 in unconsolidated deposits along the Grand River. In 1974, the city pumped 8,054 million gal from about 125 wells tapping both unconsolidated glacial deposits and the Saginaw Formation. Four other water-supply systems in the area pumped 4,438 million gal from about 50 wells (fig. 14). Additional quantities were pumped by several large industrial wells in the area. This heavy development of ground water has produced a cone of depression under at least 100 mi^2 of the Lansing area. Near the center of the cone, water levels have declined as much as 160 ft (F. R. Twenter, written commun., 1976). As a result, many privately owned wells have gone dry.

The principal aquifer underlying the Lansing area is the Pennsylvanian Saginaw Formation, but large supplies of water also can be obtained from the overlying Pennsylvanian Grand River Formation and

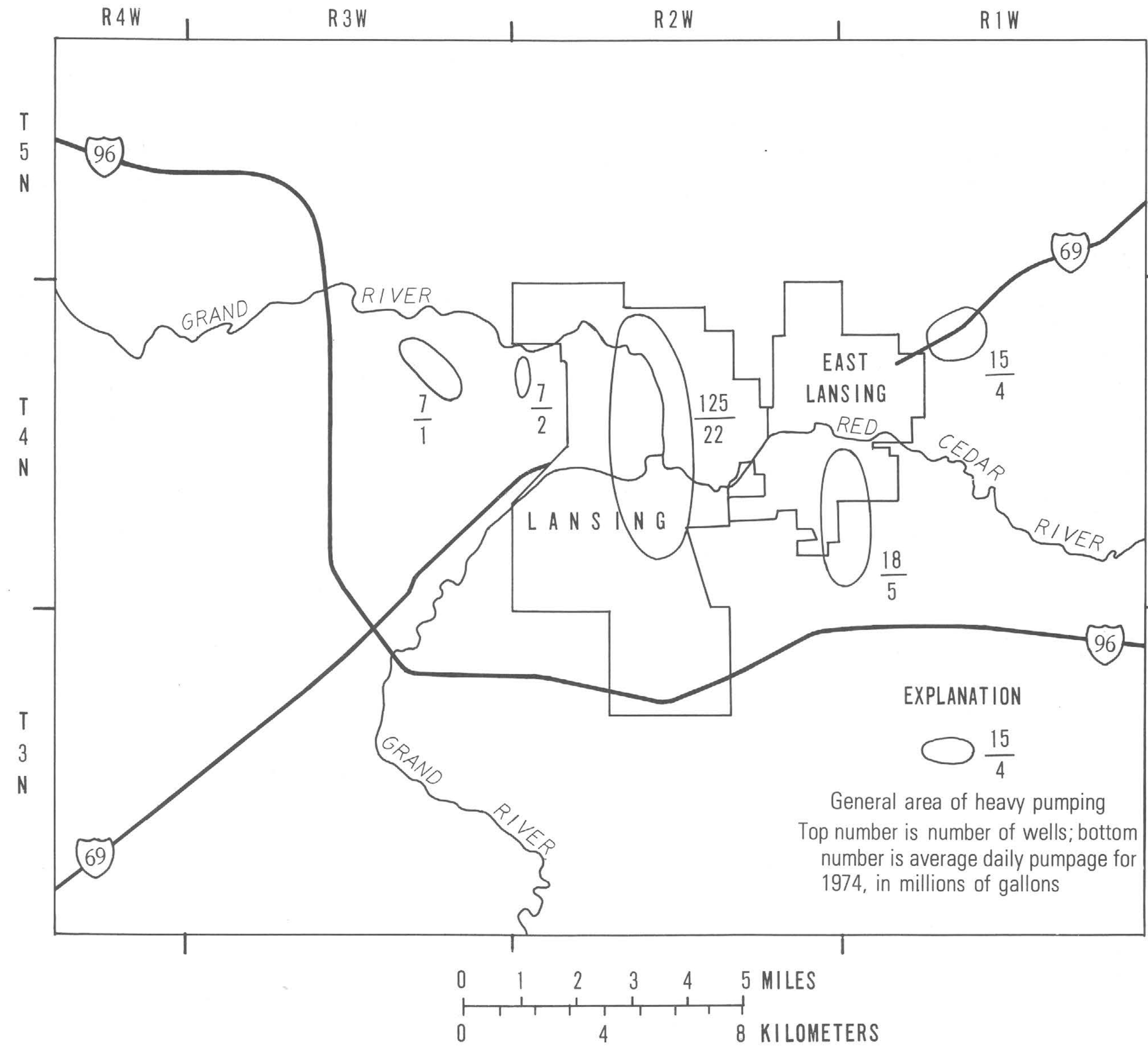


FIGURE 14.—Ground-water development in the Lansing, Mich., area.

some of the glacial deposits. Vanlier and others (1973) used an analog model to evaluate the hydrologic systems of the area. They discussed several different water-supply developments that included conjunctive use of ground water and surface water, increasing recharge to the aquifer, and additional development of the aquifer. They concluded that an intensive management program, with the cooperation of all the large water users in the area, would assure ample water to meet the needs of the area for many decades.

Recharge to the aquifers is an important consideration of water management. It is not possible to pump water from an aquifer without decreasing natural discharge, increasing natural recharge, removing water from storage, or some combination of these. In general, ground-water development is designed to take advantage of opportunities to increase recharge. In many places, wells can be located so that pumping will induce recharge from a nearby river.

Artificial recharge through wells may not be economically feasible in most of the Great Lakes Region. Augmentation of natural recharge by water spreading or diverting flow into gravel pits would probably be more effective.

MONITORING THE USE OF GROUND WATER

Managing ground-water resources does not end when the wells are put into service. Most ground-water development is planned using inadequate data. Although models of hydrologic systems are excellent tools for developing water resources, models are no better than the data used to construct them. Continued data collection during project operation, therefore, can be used for refining models. These data include, as a minimum, water-level measurements in observation wells and records of pumpage. If the aquifer is unconfined and is hydraulically connected to a river, flow upstream and downstream could be monitored. Predictions of well yields, water-level declines, and streamflow changes can be used to adjust pumping rates of wells and to locate additional wells for optimum development.

Water samples collected periodically from the pumping wells can be analyzed for chemical and bacteriological quality. Protecting the quality of the ground water might also involve monitoring land-use changes. As pumping increases, changes in the flow pattern of ground water can be determined. Landfills, sewage lagoons, storage pits, and similar sites in areas that are contributing to the ground-water supply constitute potential sources of pollution.

LEGAL CONSIDERATIONS

All the States in the Great Lakes Region have comprehensive laws and regulations to control the development and to protect the quality of their surface-water bodies. However, they do not have similar comprehensive laws and regulations for ground-water bodies.

Two common-law rules are applied to ground-water use in the Great Lakes Region: the rule of absolute ownership (English rule) and the rule of reasonable use (American rule). Under absolute ownership, the land owner can use all the ground water he can find; he is not liable, even if he drains his neighbor's supply. Only Wisconsin, among the Great Lakes States, follows this rule. The other States follow the reasonable-use rule, which allows a landowner to withdraw ground water, even by inducing flow from neighboring land, as long as the use of the water is reasonable. Nonexercise of the rights to use ground water does not result in forfeiture of those rights under either rule.

The Great Lakes Basin Commission (1975e) has summarized the State laws regarding ground-water resources. Within the Great Lakes Region, all the States except Ohio and New York require water-well drillers to obtain a license. The primary purpose of licensing are: (1) insures that the persons drilling a well are competent, (2) facilitates data collection, and (3) places control of drilling in a responsible agency. All the States except New York require that records be filed with the State on completion of a water well.

Michigan, Ohio, and Wisconsin have established standards for methods of constructing water wells and the materials used. Indiana, Michigan, and New York require a permit before a public-supply well can be installed. To protect ground-water resources from pollution or to protect scant supplies, Illinois, Indiana, and Minnesota can designate restrictive-use areas, specifying allowable pumping capacities under various geologic and hydrologic conditions. Wisconsin can do the same in areas where high-capacity wells (70 gal/min) can be developed. Michigan may specify the volume of water that may be used or allowed to flow in areas where a nuisance occurs owing to waste or unreasonable use. Indiana and Minnesota have statutes to conserve artesian pressure.

Illinois, Indiana, Minnesota, Ohio, and Pennsylvania control drilling, where wells penetrate several aquifers, in order to prevent interchange of fluids between the aquifers. Michigan has similar controls that apply to oil, gas, and brine wells but not to wells for private water supply. All the States except New York and Ohio require that abandoned wells and test holes be filled, capped, and(or) plugged, and New York and Ohio require these measures for oil and gas wells.

Regulation of waste disposal is also important in protecting ground-water resources. All the States in the Great Lakes Region require a license to operate a solid-waste disposal site and have adopted regulations governing the location of such sites. Michigan, Pennsylvania, and Wisconsin have regulations governing the size of lots in unsewered subdivisions. Indiana requires a minimum lot size of 15,000 ft^2 where 5 or more unsewered lots are developed along a public freshwater lake.

The National Water Commission (1973, p. 61–63) recommended enactment of laws outlining the establishment of water-management agencies that would have the power to manage surface water and ground water conjunctively, coordinate withdrawals from either or both sources, control the rate of depletion in an aquifer, and use artificial recharge to replenish aquifers. The commission does not believe that Federal regulation of ground water is desirable, but would let the States decide whether or not to regulate it.

In the framework study, the Great Lakes Basin Commission (1975e, p. ix) recognized nine legislative controls of ground water.

1. Regulation to control well spacing and withdrawal rates.
2. Plugging, filling, and capping of abandoned wells.
3. Determine rights of municipalities to withdraw water from land outside their limits.
4. Develop stricter laws to prevent ground-water pollution, and foster research and recordkeeping.
5. Require State certification of waste-treatment operators who are discharging wastes into ground-water bodies.
6. Regulation of solid-waste disposal sites to prevent pollution of ground water.
7. Regulation of abandoned mines.
8. Regulation of waste-disposal wells.
9. Establish ground-water rights.

Water-resources legislation need not be restrictive. As pointed out by Thomas (1961, p. 6), permissive legislation can encourage organization of public districts having the common interest of economic and effective development and use of water in a specified area. Laws recognizing potentialities as well as limitations of water resources can help rather than hinder development.

Because there are so many variations geographically, hydrologically, and temporally in water resources in the Great Lakes Region and even within a State, water laws, ideally, should be flexible enough to accommodate most any change. Thomas (1961, p. 6) suggested that one method to achieve flexibility is for such laws:

> to enunciate only the basic principles in statutes, to confer broad powers upon the administrator responsible for working out detailed solutions to specific problems, and to provide for prompt and effective action by the courts on appeals from the administrators' decisions.

In this manner, fundamental decisions on development and use of water resources would be made by those most knowledgeable of the local situation, subject to broad guidelines from the State.

FUTURE CONSIDERATIONS

Proper management of ground water and legislation to control its development and to protect its quality depend on a thorough knowledge of the ground-water system. Reports on ground-water resources are available for about 80 percent of the Great Lakes Region, but most are reconnaissance in scope. Michigan, in particular, is lacking in detailed ground-water studies. Waller and Allen (1975) include an extensive bibliography in their report on ground water in the Great Lakes Basin.

Many planners in the Region consider available ground-water data inadequate. The inadequacy is of several forms. In some areas, little or no basic ground-water data are available; in others, data are available but not in a form that planners can use. Elsewhere, available data are scant or not detailed for thorough planning. Several planners mentioned the need for a central clearing house for geologic and hydrologic data, perhaps on a statewide basis.

Many of the areas that have little or no basic data are also areas of little or no development. In such areas, wells are few and old, and little is known about them. The ground-water system in these areas, however, can be envisioned by interpolating from well records and geologic data in similar areas. As interest in these undeveloped areas increases, hydrologic studies would help evaluate the potential for ground-water development.

Data are generally available, but not in a usable form, in areas where most wells are stock and domestic wells. Numerous well records are available from drillers, State agencies, and the Geological Survey. Many of these records have been published as parts of reconnaissance reports. Of particular use are data organized to show areas of recharge, depth to water table, amount of water available, and rate of ground-water discharge into streams. This type of information can be interpreted by experienced ground-water hydrologists.

In areas of extensive ground-water development, or in areas having such a potential, some of which have been discussed earlier, quantitative ground-water studies would encourage fullest use of the resource. Digital or electric-analog models of the hydrologic system can be used as predictive tools to determine the best places for large withdrawals of ground water, the amount of water that can be safely pumped, and the long-term effects of pumping on water levels and streamflow.

Another concern to planners is the effect of urbanization on the local total hydrologic system. How much does paving increase runoff and decrease recharge? What is the effect on low flows? How is the quality of both surface water and ground water affected? Studies that answer these questions are useful to planners. Planners also seek information on the effects of filling in wetlands and the movement of pollutants in ground water. Few studies relating to the above have been made in the Great Lakes Region. Detailed ground-water studies have been made for some of the metropolitan areas, as previously mentioned (Chicago, Green Bay, Lansing and Milwaukee), and other studies will be made. Most of the studies, however, although suitable for initial planning, are not sufficiently detailed for designing.

Some planners were not fully aware of the studies that had been done in their area and indicated a need for both greater publicity and a clearing house on a local or State level where they could get information on geology, soils, water resources, and hydrology. The U.S. Geological Survey District offices in each State are usually informed on the availability of these types of data and serve as public-information offices. The State water-resources agencies are other sources of information.

The Geological Survey's NAWDEX (National Water Data Exchange) and RALI (Resources and Land Information) systems are clearing houses at the national level for sources of water and land data. The Survey's WATSTORE (Water Data Storage and Retrieval) system provides up-to-date basic water data collected by the Survey.

SUMMARY

Ground water available from storage in the Great Lakes Region is estimated to be 35,000 billion ft^3. Ground-water discharge to streams and lakes in the region is estimated to be 26 billion gallons per day. Despite this abundance of ground water, only 1.8 billion gallons per day was used in the region in 1970. This is about 11.6 percent of the total water used, excluding thermoelectric power use.

Ground water is available throughout the Great Lakes Region. However, the amount available locally varies widely. The most productive aquifers, those along the valleys of major streams, yield as much as 5,000 gal/min. Yields in excess of 1,000 gal/min have been obtained from the bedrock in some areas. Because well yields vary across the region, even within the same aquifer system, a detailed study of the hydrologic system is desirable before heavy development is started or continued.

In addition to being a potential source of water to meet increasing municipal and industrial demands, ground water can be used to augment low streamflow, to dilute water of poorer quality, and to maintain lake levels and wetlands, among other uses. In places, floodflows may be diminished by diverting them over areas where some of the water can infiltrate the ground and recharge the local aquifer.

Mineralized ground water has an economic potential for the region. Improved desalination processes make moderately saline (less than 10,000 mg/L dissolved solids) ground water a viable alternative source of water. Saline aquifers also could be used to store freshwater or natural gas, and the more highly saline aquifers have been used for liquid waste disposal.

Effective utilization of ground water depends on good management. This includes planning the development of the resource, monitoring pumping and modifying future development, and protecting ground water from pollution. Legislation that recognizes the variability and potential of ground water as well as its limitations can help in effective management.

Nature has endowed the Great Lakes Region with an abundance of water. Ground water, although only a small part of the total, is playing an increasingly important role in the Region's growth. Wise management of this resource will assure its orderly development and undiminished quality.

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