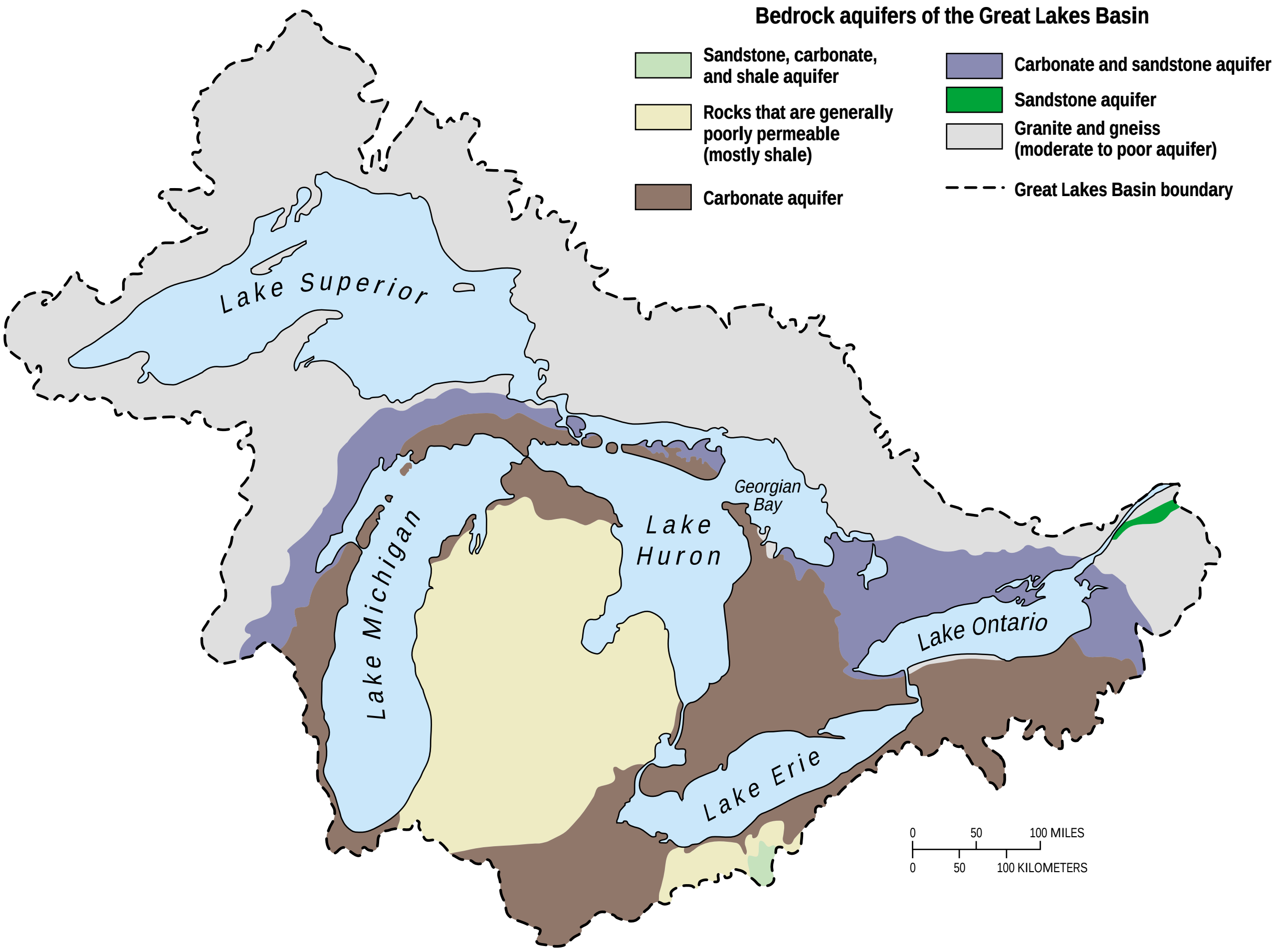
U.S. Department of the Interior
U.S. Geological Survey

The Importance of Ground Water in the Great Lakes Region

Water-Resources Investigations Report 00–4008



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The Importance of Ground Water in the Great Lakes Region

By N.G. Grannemann, R.J. Hunt, J.R. Nicholas, T.E. Reilly, and T.C. Winter

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U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 00–4008

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U.S. DEPARTMENT OF THE INTERIOR
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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
million gallons per day (Mgal/d)	0.04381	cubic meter per second
cubic mile per year (mi^3/yr)	4.16832	cubic kilometers per year

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

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The Importance of Ground Water in the Great Lakes Region

By N.G. Grannemann, R.J. Hunt, J.R. Nicholas, T.E. Reilly, and T.C. Winter

"Governments should immediately take steps to enhance groundwater research in order to better understand the role of groundwater in the Great Lakes Basin."

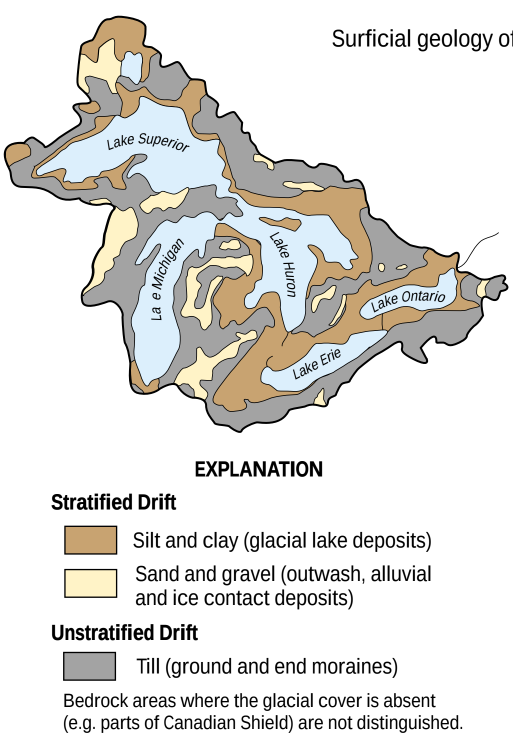
—Interim International Joint Commission (IJC) Report, 1999, Recommendation IV, Page 30

Why do we need to know more about ground-water conditions in the Great Lakes Region?

Ground water is a major natural resource in the Great Lakes Region that helps link the Great Lakes and their watershed. This linkage needs to be more fully understood and quantified before society can address some of the important water-resources issues in the Great Lakes.

The Great Lakes constitute the largest concentration of unfrozen fresh surface water in the western hemisphere—about 5,440 mi^3. Because the quantity of water in the lakes is so large, ground water in the Great Lakes Basin is often overlooked when evaluating the hydrology of the region. Ground water, however, is more important to the hydrology of the Great Lakes and to the health of ecosystems in the watershed than is generally recognized.

Surficial geology of the



from *The Great Lakes: An Environmental Atlas and Resource Book*, 1995

Although more than 1,000 mi^3 of ground water are stored in the basin—a volume of water that is approximately equal to that of Lake Michigan—development of the ground-water resource must be carefully planned. Development of the ground-water resource removes water from storage and alters the paths of ground-water flow. Ground water that normally discharges to streams, lakes, and wetlands can be captured by pumping (the most common form of development), which may deplete or reduce inflows to the Great Lakes.

Ground water is important to ecosystems in the Great Lakes Region because it is, in effect, a large, subsurface reservoir from which water is released slowly to provide a reliable minimum level of water flow to streams, lakes, and wetlands. Ground-water discharge to streams generally provides good quality water that, in turn, promotes habitat for aquatic animals and sustains aquatic plants during periods of low precipitation. Because of the slow movement of ground water, the effects of surface activities on ground-water flow and quality can take years to manifest themselves. As a result, issues relative to ground water are often seemingly less dire than issues related to surface water alone.

Ground water is a major natural resource in the Great Lakes Region that helps link the Great Lakes and their watershed. This linkage needs to be more fully understood and quantified before society can address some of the important water-resources issues in the region.

"The Great Lakes aquatic ecosystem is made up not only of the lakes themselves, but also of the complex network of tributaries and groundwater on which the lakes depend."

—Interim IJC Report, Page 25

What are the major ground-water issues in the Great Lakes Region?

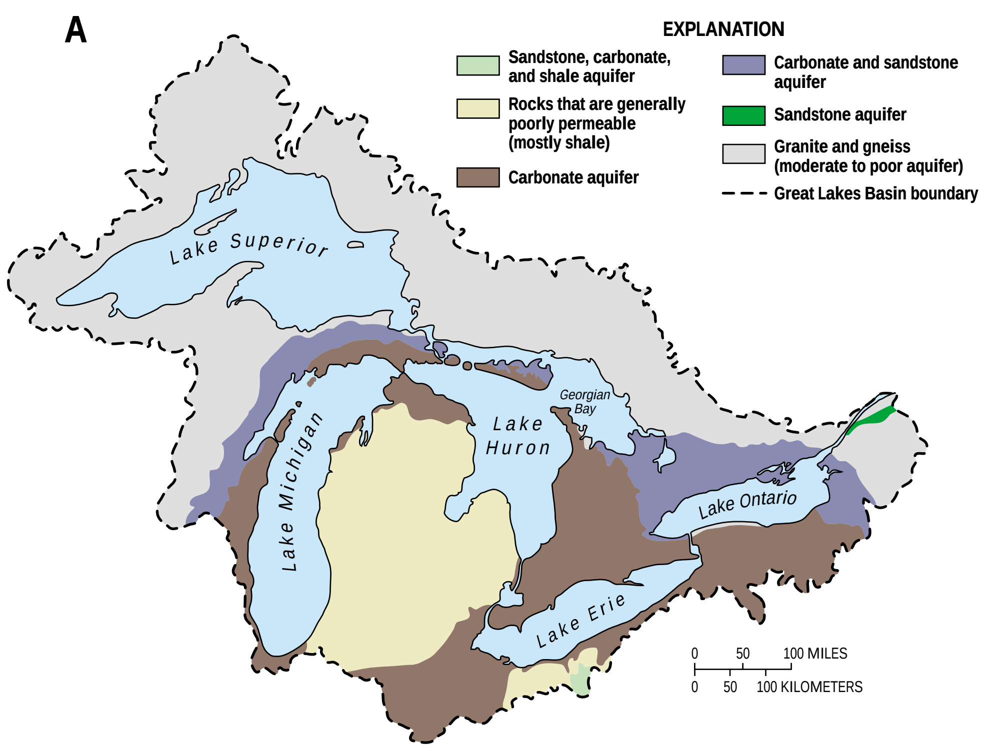
The major ground-water resources issues in the Great Lakes Region revolve around 1) the quantity of ground water, 2) ground-water and surface-water interaction, 3) changes in ground-water quality as development expands, and 4) ecosystem health in relation to quantity and quality of water.

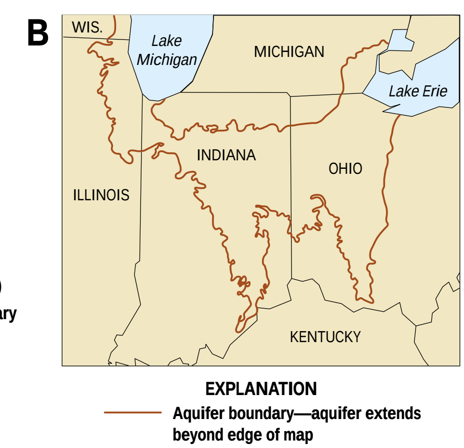
A major attraction of the Great Lakes Region is the abundant water supply on which manufacturing, power generation, transportation, agricultural, and recreational sectors have historically relied. Most large public water supplies are obtained from the lakes themselves, but ground water is the source of drinking water for about 8.2 million people within the watershed. Although most residents of Chicago use water from Lake Michigan, many people in the Chicago suburbs who live outside of the watershed, but are close to it, use ground water as a source of supply. As the suburban areas near the watershed boundary expand, more and more people depend on ground water to supply household water needs. Small manufacturing companies in suburban locations also are increasing their ground-water use. As communities encroach upon agricultural areas, conflicts between agricultural and other ground-water users will increase (Alley and others, 1999). Therefore, ground-water resources need to be characterized according to their occurrence, availability, quality, and use to develop a sustainable supply for all uses.

Pumping ground water can capture water from or intercept flow to streams and alter the area that contributes ground water to the Great Lakes. Thus, ground-water withdrawals can divert ground water that would normally discharge to the Great Lakes system.

> *"Water quantity and water quality are inextricably linked. For most uses, quantity alone does not satisfy the demand."*
>
> *—Interim IJC Report, Page 26*

In addition to water quantity issues in the Great Lakes Region, water quality also can be of concern. As development increases, activities that could threaten the quality of ground water also increase. Human health needs to be safeguarded, as does the health of many other organisms that rely on clean water. Thus, the major ground-water resource issues in the Great Lakes Region revolve around 1) the quantity of ground water, 2) the interaction of ground water and surface water, 3) changes in ground-water quality as development expands, and 4) ecosystem health in relation to quantity and quality of water. In summary, ground water is an essential part of the Great Lakes Region water-supply system. It is a critical resource for maintaining human health and healthy ecosystems.





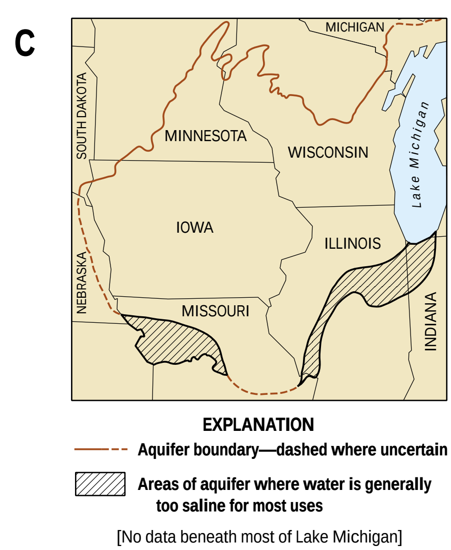


Figure 2. (A) Bedrock aquifers of the Great Lakes Basin (modified from Great Lakes Commission, 1975); (B) Approximate extent of the freshwater bearing carbonate aquifer in Ohio, Indiana, Illinois, and parts of Michigan and Wisconsin (modified from Casey, 1996, figure 14); (C) Approximate extent of the sandstone aquifer west of Lake Michigan (modified from Young, 1992, figure 16).

Geology establishes the framework for aquifers

Ground water is present throughout the Great Lakes Basin, but the quantity that can be withdrawn varies depending on the characteristics of the water-bearing rocks and sediments (aquifers). Unconsolidated material that was deposited at or near the land surface as a result of large-scale glacial ice advances and retreats during the last 2 million years make up the most productive aquifers. These deposits are as much as 1,200 feet thick in parts of Michigan and are several hundred feet thick in buried bedrock valleys in Illinois, Wisconsin, and New York. The deposits are thin or nonexistent in areas where bedrock that was not easily eroded by glacial ice is exposed at land surface. Most glacial deposits are composed of mixtures of sand and gravel, and silt and clay (fig. 1). Sand and gravel deposits (outwash and ice-contact deposits) are the most productive aquifers because they have greater permeability and effective porosity than do the finer grained deposits. Some areas with silt and clay at the surface (till or glacial lake deposits) contain more permeable deposits at depth and are able to yield moderate to large amounts of water to wells. In general, however, the silt and clay deposits are not aquifers.

Bedrock aquifers are generally widespread throughout the region and are more continuous than the aquifers in glacial deposits. Some bedrock aquifers in the region extend far beyond the watershed boundaries. The relations between ground water in these aquifers and water in the Great Lakes is complicated because ground-water divides and watershed boundaries may not coincide. Carbonate rocks (limestone and dolomite) are the most common bedrock aquifers in the region (fig. 2A). Natural processes may increase permeability by dissolving carbonate minerals in these aquifers, but this increased permeability makes the aquifers more vulnerable to contamination. The most extensive carbonate aquifer in the region consists of a series of limestones and dolomites that underlie a large part of the upper Midwest (fig. 2B). Sandstone aquifers are the next most common bedrock aquifer. An extensive sandstone aquifer underlies much of the northern Midwest and even extends under Lake Michigan (fig. 2C). In general, shale, and igneous and metamorphic bedrock have limited water-yielding capacity, and they are not considered regional aquifers.

How does ground water move in the Great Lakes Region?

Aquifers and confining units (relatively impermeable rocks and sediments) make up the ground-water system in the Great Lakes watershed. This system stores water and acts as a conduit for water to move from recharge areas to discharge areas (fig. 3). Recharge takes place between streams in areas that occupy most of the land surface. Ground water moves in both local and regional flow systems.

Most ground water moves in local flow systems

To improve our understanding of the importance of unconsolidated aquifers in the Great Lakes watershed, new geologic maps that show the extent, thickness, and boundaries of these aquifers are needed.

Ground water in local flow systems commonly travels relatively short distances underground before discharging

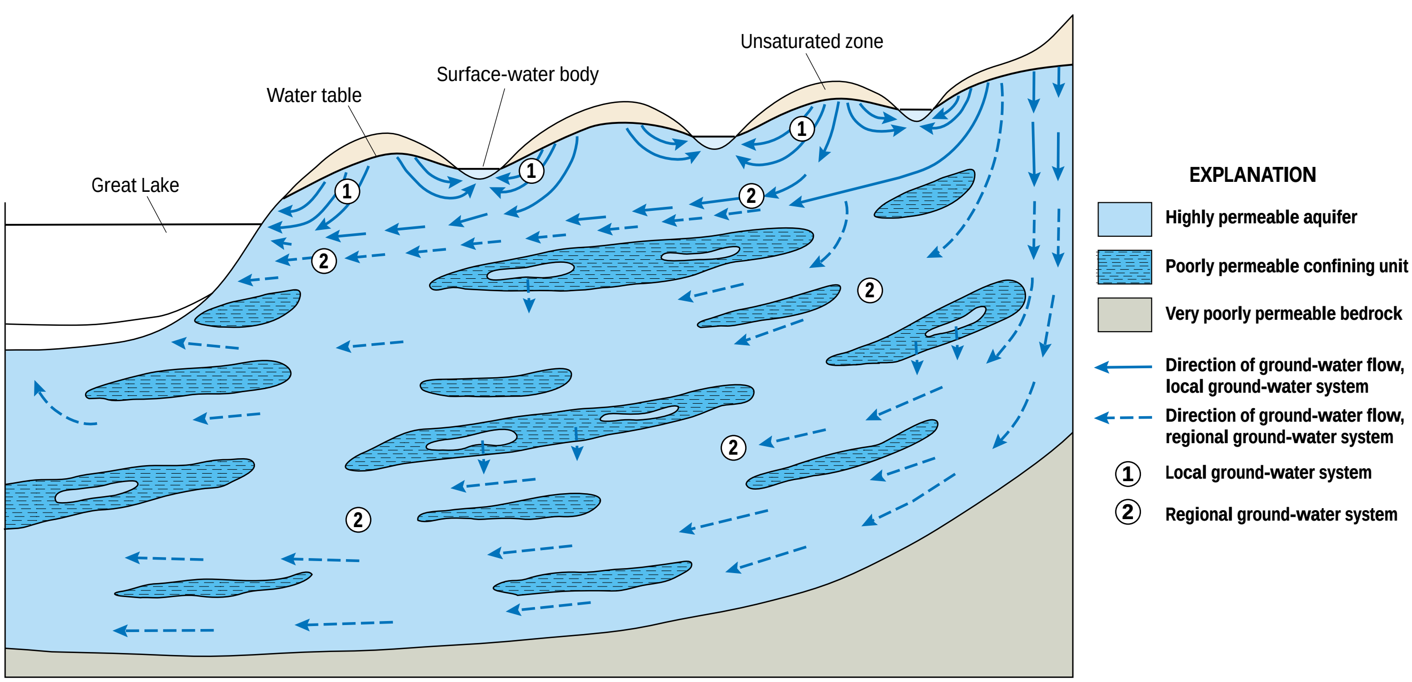


Figure 3. Generalized local and regional ground-water flow systems in the Great Lakes Region.

to a stream, lake, or wetland. The Great Lakes Region has an abundance of small streams, and most ground-water flow takes place in these shallow systems. The amount of ground water moving through these systems is not well quantified, however, because most water-supply studies have focused on deeper regional flow systems. The most productive shallow aquifers are composed of sand and gravel (fig. 1). The extent of these deposits near the land surface is commonly known and illustrated on maps, but the thickness and capability to transmit water often is not well known. To improve our understanding of the importance of ground-water flow in unconsolidated aquifers in the Great Lakes watershed, new geologic maps that show the extent, thickness, and boundaries of these aquifers are needed (Central Great Lakes Geologic Mapping Coalition, 1999).

Most ground water for municipal supply comes from regional ground-water flow systems

More work needs to be done to define and quantify the interactions between regional ground-water flow and ground-water discharge to the Great Lakes.

Regional ground-water flow systems are usually deeper below land surface and have longer flow paths than local flow systems (fig. 3). Confining units that restrict flow of water between the systems commonly separate local from regional flow, but thick, unconfined aquifers may have regional scale ground-water flow. In the Great Lakes Region, regional ground-water flow occurs in both glacial deposits and bedrock aquifers, depending on the hydraulic properties of the aquifers and confining units, and the topographic relief.

Glacial deposits usually consist of a complex assemblage of sediments (fig. 3). In some parts of the region, glacial deposits are as much as 1,200 feet in thickness. As thickness increases, the complexity of the sediment assemblage usually increases. These sediments need to be mapped using established three-dimensional mapping techniques to understand their geological framework (Bhagwat and Berg, 1991). Hydraulic characteristics of the sediments also need to be determined for the aquifers that are increasingly being tapped for water supply. Armed with this hydrogeologic characterization, water managers will be able to make better determinations of sustainable withdrawal rates from the region's aquifers.

The extent, thickness, hydraulic properties, and general directions of flow in the most used bedrock aquifers have been described by regional aquifer studies conducted by the USGS (Sun and others, 1997) and by State and local agencies (Bleuer and others, 1991; Batten and Bradbury, 1996; and Passero and others, 1981). Although these studies provide a baseline of hydrologic and geologic information, more work needs to be done to define and quantify the interactions between regional ground-water flow and ground-water discharge to the Great Lakes. Divides that are transient barriers to ground-water movement are estab-

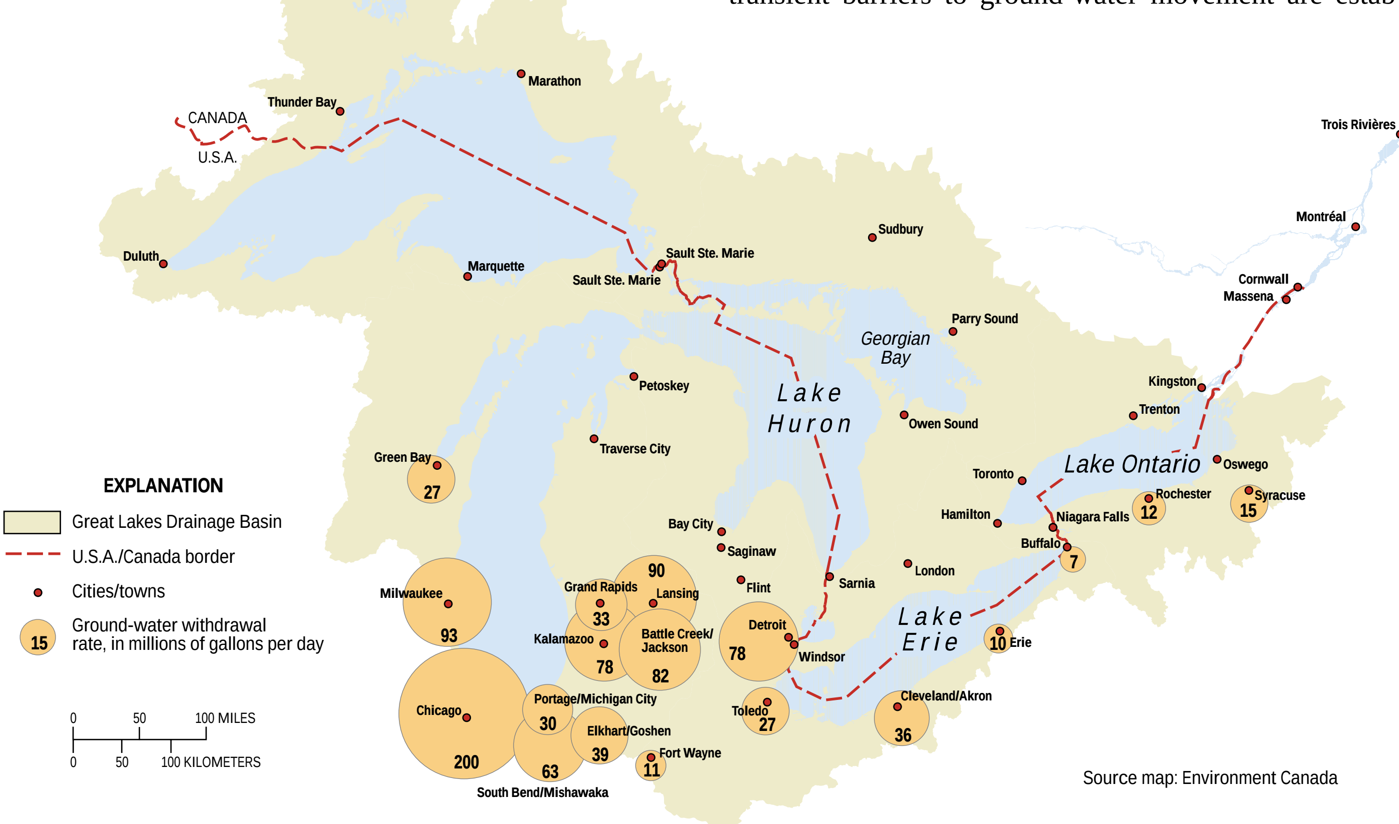


Figure 4. Estimated ground-water withdrawal rates for some major U.S. metropolitan areas (data not available for Canadian areas).

lished by a combination of natural and human-induced stresses on the aquifers. In some areas, bedrock aquifers may discharge large quantities of water to the lakes, but the data needed to quantify the amount of flow have not been collected. In addition, the effects on the Great Lakes of pumping from regional aquifers are unknown. Many ground-water issues take time to be recognized, but, because of the large volumes and resulting long travel times for water in regional flow systems, the time lags expected are usually much longer than for local flow systems. Thus, adverse effects of withdrawals may take years to manifest themselves.

How is ground water replenished?

Ground-water recharge rates estimated in previous studies represent the approximate range of recharge to the water table in the entire Great Lakes Region. A comprehensive study for the entire watershed is needed to more completely determine the importance of ground water in the hydrologic budget of the Great Lakes.

Recharge is the term that is commonly used to describe the process of adding water to the ground-water system. Although it is difficult to directly measure the amount of recharge, it is important to estimate recharge rates to understand the effects of ground water on other hydrologic processes in the basin and to assess how activities at the land surface may change the recharge rates. The amount of recharge can vary considerably throughout the basin depending on soil type, precipitation (rates, types, timing, and amounts), and other factors, including the extent of impervious surfaces (roofed and paved areas) and storm sewers. For example, the amount of water that infiltrates into a sandy soil is usually greater than that into clayey soil. Recharge rates in Michigan's Lower Peninsula range from nearly 0 to about 23 inches per year (Holtschlag, 1997). Ground-water recharge rates estimated in previous studies represent the approximate range of recharge to the water table in the entire Great Lakes Region. A comprehensive study for the entire watershed is needed to more completely determine the importance of ground water in the hydrologic budget of the Great Lakes.

Urban development may reduce recharge amounts because impervious surfaces (such as roads, buildings, and paved areas) often drain to storm sewers, a situation that increases surface runoff and reduces infiltration. These processes may significantly alter ground-water conditions in many urban settings by "short-circuiting" to streams and

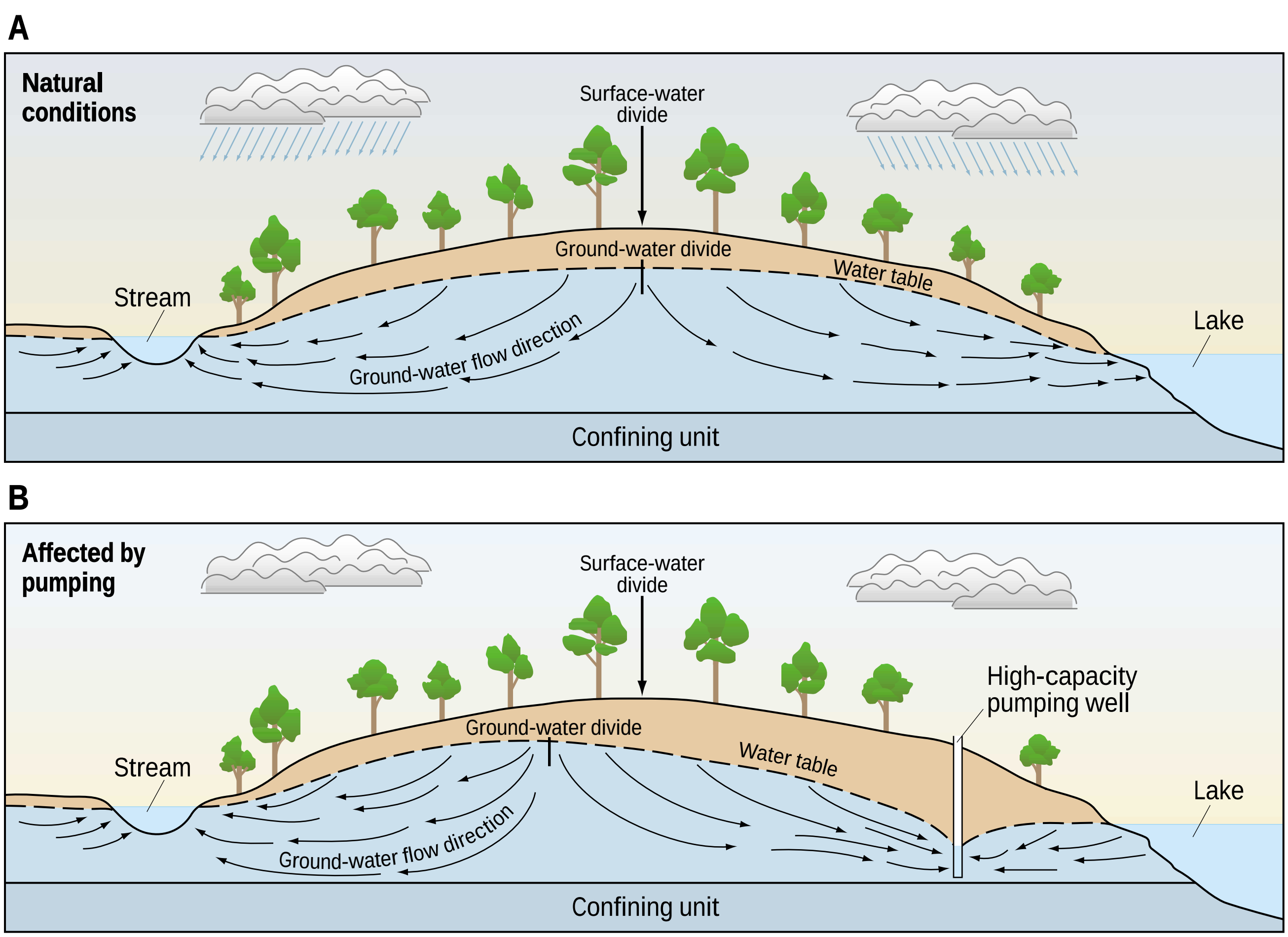
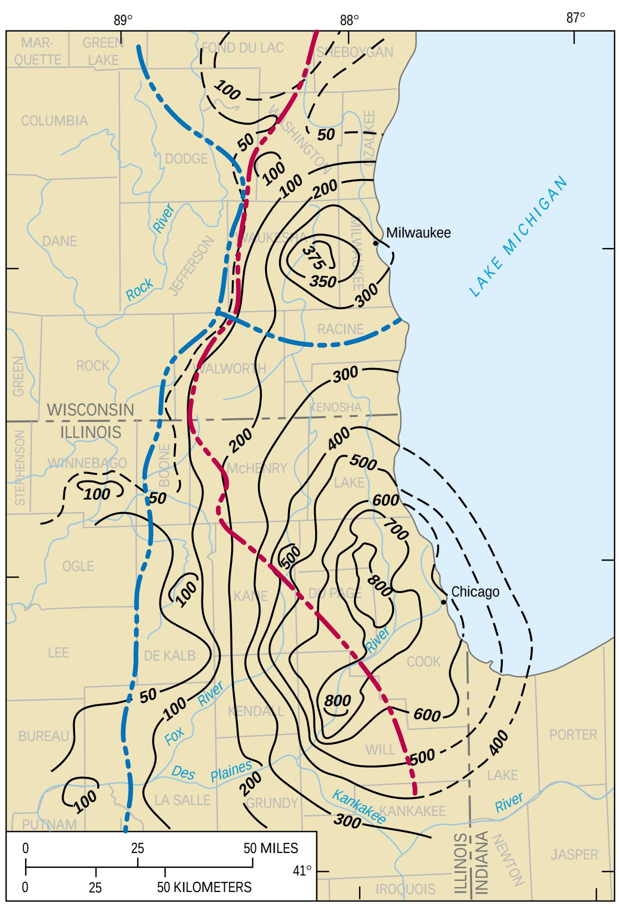


Figure 5. Generalized ground-water flow (A) under natural conditions and (B) affected by pumping (Note that surface- and ground-water divides are coincident in A but not in B).

lakes water that would have infiltrated to the water table. They also may increase flood potential. Currently, only 7 percent of the Great Lakes watershed is classified as urban; therefore, the effects of urbanization on ground-water recharge are likely to be localized and the effects on the watershed as a whole may be minimal. Because urban areas are rapidly expanding, however, it is important to continue to monitor the effects of urbanization on ground-water recharge rates. Other activities associated with urban expansion, such as increased ground-water pumping, along with reduced recharge rates may increase the drawdown of water levels caused by pumping.

Recharge to bedrock aquifers is less well understood than that to unconsolidated aquifers because infiltrating water may need to move through several layers of geologic material before reaching the bedrock aquifer. Direct measurement of recharge rates to bedrock aquifers is difficult. Estimates of these rates have been made in the USGS Regional Aquifer-System Analysis studies (Sun and others, 1997) mostly by simulating regional ground-water flow with digital models. These rates vary considerably from place to place, but generally are much lower than the estimates of recharge to the water table, especially for non-pumping conditions.



Base from U.S. Geological Survey 1:2,000,000 Digital Data
Albers Equal-area Conic projection
Standard parallels 33° and 45°, central meridian –89°

EXPLANATION

—— *700* — — **Line of equal water-level decline, 1864–1980—**Dashed where approximate. Interval, in feet, is variable

Major ground-water divide (1980)

Pre-development ground-water divide (about 1864)

Figure 6. Decline in water levels in the sandstone confined aquifer, Chicago and Milwaukee areas, 1864–1980. (Modified from Avery, 1995.)

How much ground water is pumped in the Great Lakes Region?

Total ground-water withdrawal in the Great Lakes Region is estimated to be about 1,510 Mgal/d or 2,336 ft^3/s (Solley and others, 1998). An additional 200 Mgal/d or 309 ft^3/s is withdrawn from outside the basin but near Lake Michigan in the Chicago area to supply commercial, industrial, domestic, and public-supply customers. For comparison, the average discharge of the St. Clair River at Port Huron is about 120,850 Mgal/d or 187,000 ft^3/s. On a basinwide scale, ground-water withdrawal is a small part of the overall hydrologic budget and only about 5 percent of this water is consumed. The remainder is returned mostly as surface water effluent. Nevertheless, ground water is the source of drinking water for more than 8 million people on the U.S. side of the border in the basin (about one third of the total number of residents) and continues to be a concern in both the U.S. and Canada. The areas where large quantities of ground water are pumped on the U.S. side of the Great Lakes watershed are shown in figure 4. The largest withdrawal takes place in an eight-county area near Chicago, where an unknown amount of the return flow is discharged outside the Great Lakes watershed. At the same time, it should be noted that much of the regional ground-water flow in this area also originates outside of the watershed. An analysis of the amount of ground water pumped from wells in areas just outside the Great Lakes watershed would help identify the magnitude of this diversion.

> *"Issues of diversion and consumptive use of Great Lakes waters (need) to be addressed more comprehensively …"*
>
> *—Interim IJC Report, Page 1*

Some areas where the effects of ground-water pumping have been evaluated

The effects of ground-water withdrawals have been quantified at only a few locations.

Pumping water from aquifers results in lower ground-water levels (fig. 5) and creates a cone of depression around a well. Because water must converge on the well from all directions and because the cross-sectional area through which the flow occurs decreases toward the well, the hy-

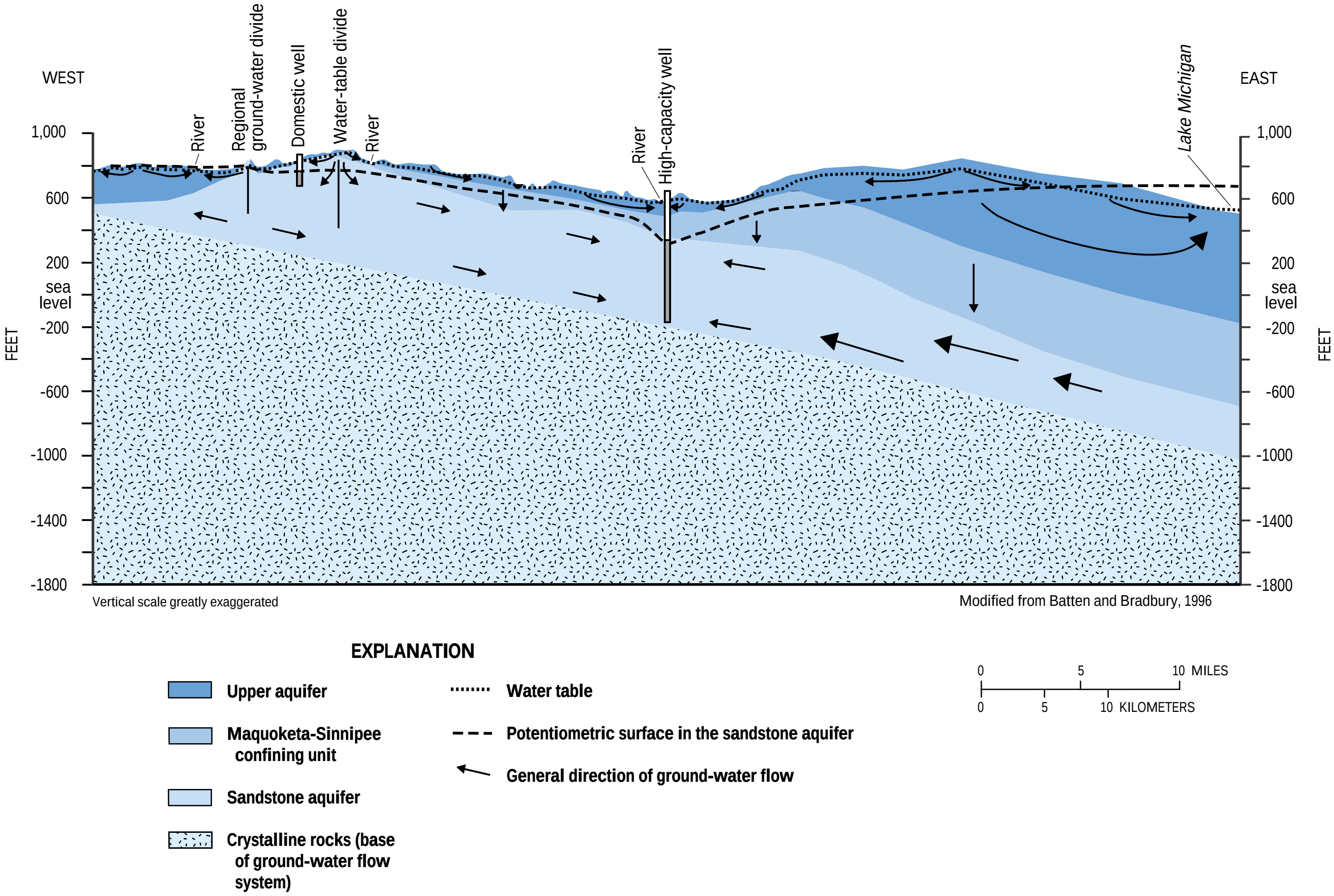


Figure 7. Aquifers, confining unit, and direction of ground-water flow near Green Bay, Wisconsin.

draulic gradient must get steeper toward the well (Heath, 1983). Cones of depression caused by large withdrawals from extensive confined aquifers can affect very large areas (Heath, 1983). Any water withdrawn from the ground-water system will divert part of the water that eventually would have discharged to a stream, lake, or wetland, or been transpired by vegetation. Even ground water withdrawn at some distance from the Great Lakes will reduce flow to the lakes depending on how much of that ground water is returned to streams as wastewater effluent. If the amount of water-level decline is sufficient, ground water that would normally discharge to the Great Lakes may cease and the ground-water divide may be altered (fig. 5). In some cases, water may be drawn from streams or the Great Lakes into the ground-water system. Measurable effects of ground-water withdrawal have been documented at a few locations near the Great Lakes. In order to understand the effect of pumping on the water budget, detailed analyses of ground-water systems near the Great Lakes will be required.

Definition of potentiometric surface: a surface that represents the height above a datum (usually sea level) at which the water level stands in tightly cased wells that penetrate the aquifer. In some wells, the water level rises above the land surface.

Chicago-Milwaukee Area

The effects of ground-water pumping in the Chicago-Milwaukee metropolitan area where, in 1980, about 300 Mgal/d was withdrawn from a very productive sandstone aquifer system (fig. 2C), are documented in Young (1992). Prior to large-scale withdrawal of ground water, recharge and discharge for the aquifer were in balance at about 350 Mgal/d. When wells were first drilled into the sandstone aquifer along Lake Michigan, the initial ground-water level at Milwaukee was reported to be 186 feet above the surface of Lake Michigan; in Chicago, it was reported to be 130 feet above the lake surface. By 1980, large-scale pumping had caused the water levels in wells to decline as much as 375 feet in Milwaukee and 900 feet in Chicago. At some locations, the quality of ground water was altered when water levels were drawn below the layer that confines the aquifer. Ground-water levels below the confining layer will allow parts of the sandstone aquifer to be exposed to oxygen in the air, which can trigger some chemical reactions that do not take place in the absence of oxygen. By 1994, ground-water withdrawals in Chicago for public supply decreased to about 67 Mgal/d and total ground-water withdrawals decreased to about 200 Mgal/d. These withdrawals were concentrated west and southwest of the earlier pumping centers. As a result, ground-water levels in some parts of the Chicago area have risen by as much as 250 feet, although

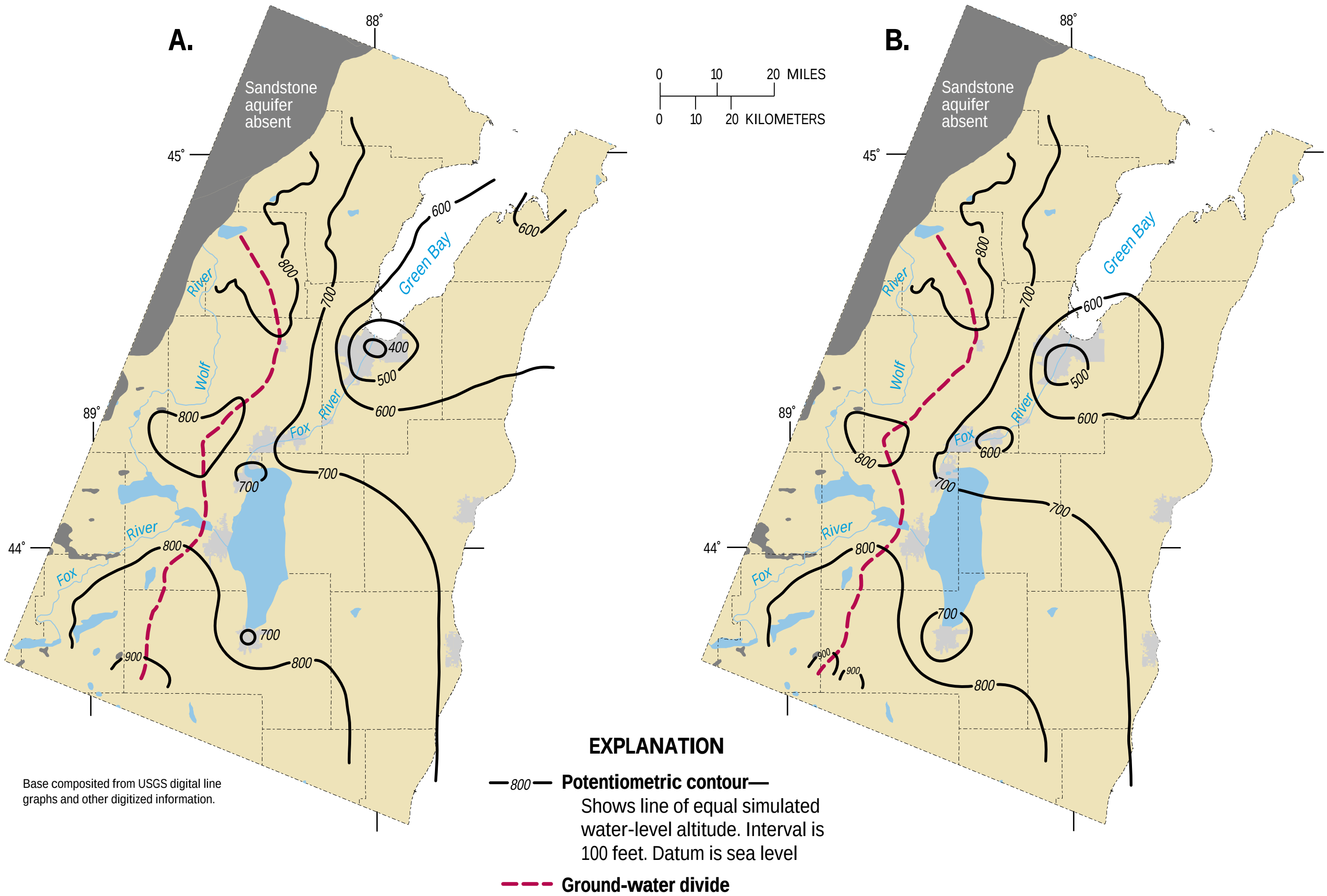


Figure 8. Simulated potentiometric surface in the sandstone aquifer, northeastern Wisconsin, (A) in 1957; and (B) in 1990 (from Conlon, 1998).

levels continue to decline in the southwestern Chicago (Visocky, 1997) and the Milwaukee metropolitan areas.

Computer simulations of the sandstone aquifer system indicate that, for 1980 pumping conditions, depressed water levels in the system have caused additional recharge and have resulted in a reduction of natural discharge (Young, 1992). To keep withdrawals in balance with recharge and discharge, for 1980 pumping rates, water was withdrawn from storage in the aquifer system thus accounting for lower ground-water levels. As a result, in 1980, the ground-water divide in the aquifer system was displaced, in some places, about 50 miles west of its original (pre-pumping) position (fig. 6). The rates of recharge, discharge and removal from storage will vary depending on pumping rates, hydraulic properties of the aquifer and confining units, and sources of water. The hydrologic system is further complicated by the fact that most effluent from ground-water withdrawals in the Chicago area is discharged to the Mississippi River Basin via the Chicago Ship and Sanitary Canal—one of the few places where water is diverted from the Great Lakes Basin. However, the amount of ground-water diverted from the Great Lakes Basin by pumping is unknown because some of the water captured by pumping is recharged to the aquifer or removed from storage in the aquifer west of the surface-water divide. These sources of water need to be more accurately quantified in order to assess whether, on a net basis, water is being diverted from the Great Lakes by ground-water withdrawals.

Green Bay-Fox River Area

The sandstone aquifer also is used as a water-supply source in the Green Bay-Fox River area of Wisconsin. A depiction of the potentiometric surface for the aquifer indicates that water-level declines of as much as 300 feet have occurred (fig. 7). The depressed water levels were deep enough in 1957 (fig. 8A) that the city of Green Bay began pumping water from Lake Michigan to supplement ground-water sources. Withdrawals of ground water were reduced, so that by 1990, ground-water levels had risen by about 100 feet in Green Bay (fig. 8B); levels decreased to the south, however, because of increases in ground-water withdrawals by outlying communities.

Toledo, Ohio Area

The Toledo, Ohio metropolitan area obtains ground water from wells open to the carbonate aquifer and from quarry dewatering near Lake Erie. Pumping has lowered

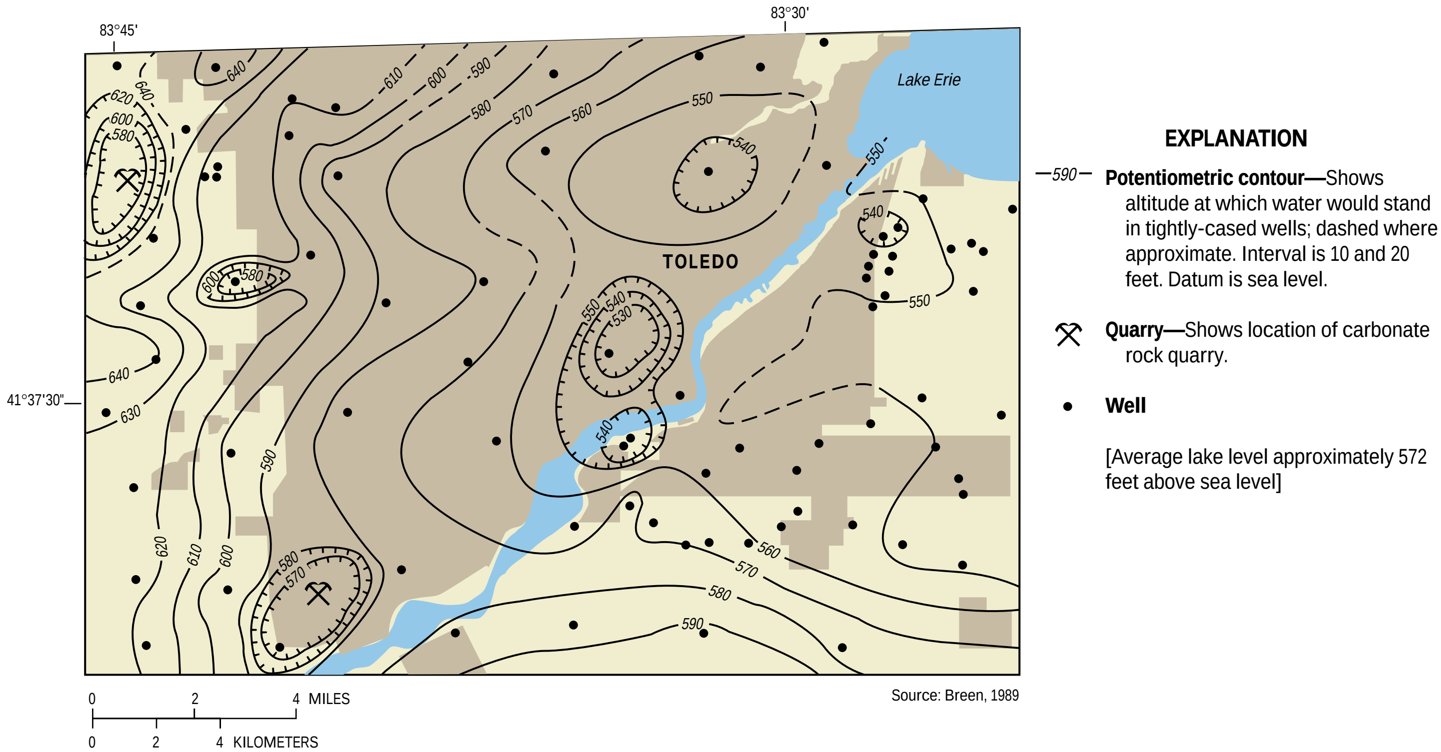


Figure 9. Potentiometric surface for the carbonate aquifer near Toledo, Ohio, July 1986.

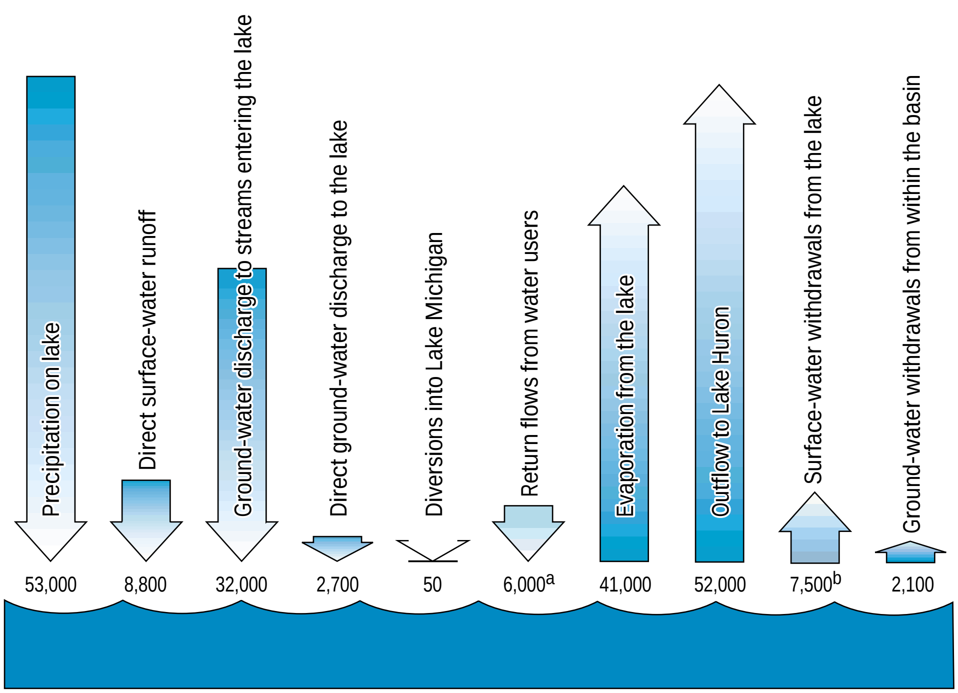


Figure 10. Approximate average water budget for Lake Michigan.

[a] Return flow is reduced by 3,200 ft^3/s that is diverted out of the basin at Chicago, Ill.

[b] Withdrawals for power plant cooling not included

water levels in wells as much as 35 feet below the average level of Lake Erie (fig. 9). In addition, pumping has induced water from Lake Erie into the ground-water system and intercepted water that would have discharged from the ground-water system to Lake Erie (Breen, 1989; Eberts and George, in press; and Eberts, 1999). Although water-level data indicate that these interactions are taking place, the amounts of water being induced from the lake and intercepted by the pumping have not been quantified.

Irrigation throughout the Great Lakes watershed

Irrigation is the largest consumptive use of water in the Great Lakes watershed, and ground-water sources contribute about half of the water used for irrigation. In areas where surface-water sources are not readily available, it is likely that ground water will be the water source if new irrigation systems are installed.

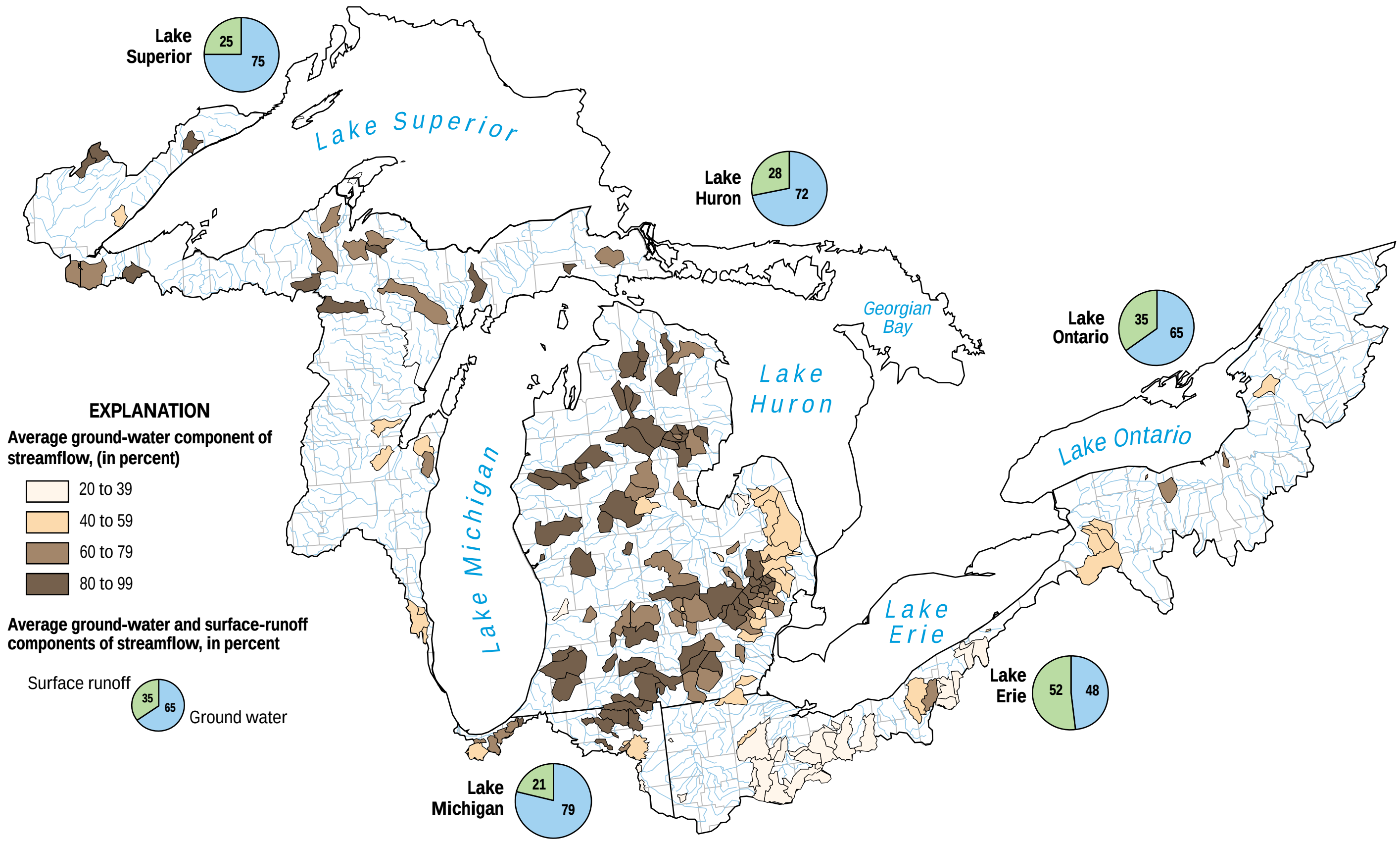


Figure 11. Average ground-water and surface-runoff components of selected watersheds in the U.S. portion of the Great Lakes Basin (from Holtschlag and Nicholas, 1998).

Ground-water and surface-water interactions

"Surface water commonly is hydraulically connected to ground water, but the interactions are difficult to observe and measure and commonly have been ignored in water management considerations and policies. Many natural processes and human activities affect the interactions of ground water and surface water."

—Winter and others, 1998

Streams interact with ground water in three basic ways: they gain water from inflow of ground water through the streambed, they lose water to ground water by outflow through the streambed, and they do both, gaining in some reaches and losing in others (Winter and others, 1998). For ground water to discharge into a stream channel, the altitude of the water table in the vicinity of the stream must be higher than the altitude of the stream-water surface. Conversely, for water in a stream or lake to flow into the ground, the altitude of the water table in the vicinity of the stream must be lower than the altitude of the stream-water surface. The complexity of these interactions may vary from stream to stream as well as over time.

"In recognition of the frequent and pervasive interaction between groundwater and surface water and the virtual impossibility of distinguishing between them in some instances, the governments of Canada and the United States should apply the precautionary principle with respect to removals and consumptive use of groundwater in the Basin."

—Interim IJC Report Recommendation V

Ground-water flow into the Great Lakes

"Groundwater is important to the Great Lakes ecosystem…"

—Interim IJC Report, Page 5

An approximate water budget for Lake Michigan helps place the role of ground water in perspective. This water budget quantifies the flow of water into and out of Lake Michigan (fig. 10). Inflow of water to Lake Michigan consists of precipitation on the lake (about 53,000 ft^3/s); direct surface runoff into the lake (about 8,800 ft^3/s); indirect ground-water discharge to the lake (about 32,000 ft^3/s); direct ground-water discharge to the lake (about 2,700 ft^3/s); diversions into the lake (about 50 ft^3/s); and return flows into the lake from water users (about 6,000 ft^3/s). Outflow of water from Lake Michigan consists of evaporation from the lake surface (about 41,000 ft^3/s); outflow from Lake Michigan to Lake Huron (about 52,000 ft^3/s); surface-water withdrawals from the lake (about 7,500 ft^3/s); and ground-water withdrawals in the watershed (about 2,100 ft^3/s) (Croley and Hunter, 1994; written commun., Great Lakes Commission; Holtschlag and Nicholas, 1998; and Grannemann and Weaver, 1999). Although small in comparison to the amount of water in storage in the Great Lakes, ground water directly and indirectly contributes about 80 percent of the water flowing from the watershed into Lake Michigan. On the basis of these data, it is evident that ground water is an important component of the hydrologic budget for the Great Lakes Region.

A relatively small amount of ground water flows directly to the Great Lakes

The Great Lakes are in topographically low settings that, under natural flow conditions, causes them to function as discharge areas or "sinks" for the ground-water-flow system. Most ground water that discharges directly into the lakes is believed to take place near the shore (Grannemann and Weaver, 1999). Of all the Great Lakes, Lake Michigan has the largest amount of direct ground-water discharge (2,700 ft^3/s) because it has more sand and gravel aquifers near the shore than any of the other Great Lakes (Grannemann and Weaver, 1999). Although this is a relatively low inflow compared to the total streamflow into the lake from land areas (41,200 ft^3/s) (Croley and Hunter, 1994), it is nearly equal to the amount of water diverted from Lake Michigan through the Chicago Ship and Sanitary Canal (Oberg and Schmidt, 1996).

Ground water keeps streams flowing during periods of low surface runoff

In most instances, the flow of a stream includes both a surface-water runoff component and a ground-water inflow component. The fraction of total streamflow that originated from ground water must be known to analyze and understand the interaction between surface water and ground water in the stream. Holtschlag and Nicholas (1998) used a method called "hydrograph separation" to estimate the amount of ground water in the total streamflow that discharges to the Great Lakes. They call this quantity of water "indirect ground-water discharge" to the lakes. Prior to this study, indirect ground-water discharge was not explicitly considered in estimates of Great Lakes Basin water supply. Instead, it was incorporated into the streamflow component of the supply. Surface runoff is a short-term component of flow that results from precipitation moving overland to a stream without percolating into an aquifer. Ground-water discharge is a long-term, persistent component that results from that part of precipitation that infiltrates into the soil, percolates into an aquifer, and then flows to a stream.

Although Holtschlag and Nicholas (1998) used data from 195 streamgaging stations in the watershed for their analysis, the combined drainage areas to these stations covered only 13.6 percent of the total drainage area of the Great Lakes Basin. These results were extended to the entire basin by assuming that the average ground-water component of streamflow estimated for the ungaged streams is about the same as that estimated for gaged streams in the basin. Using this approach Holtschlag and Nicholas estimated that the average ground-water component of streamflow ranges from 48 percent for Lake Erie to 79 percent for Lake Michigan (fig. 11).

Ground water, wetlands, and stream ecology

Ground water and wetlands

> *"Similar to streams and lakes, wetlands can receive ground-water inflow, recharge ground water, or do both."*
>
> *—Winter and others, 1998*

Wetlands, once perceived as worthless land, are now recognized as a necessary component of a vital landscape (Hunt, 1996). They are often considered the "kidneys of the landscape" because of their role in mitigating and filtering the effects of human activity on water resources in the watershed. Wetland functions have been shown to include storm and floodwater retention, shoreline protection, and water-quality improvement. Wetlands also provide wildlife habitat. More than one-third of endangered species in the United States are associated with wetlands even though wetlands comprise less than five percent of the landscape. Vast areas of wetland acreage —more than 50 percent in the United States, and more than 95 percent in some states that border the Great Lakes—have been destroyed, modified, or converted to other uses since presettlement time. Although the effects of these losses are beginning to be understood, more study is needed to improve our knowledge about the role of these important wetland systems.

Wetland hydrology is widely recognized as the primary effect on wetland ecology, development, and persistence. An understanding of the hydrology is essential to identify and quantify wetland functions and processes. For example, ground-water flow has been shown to be important for the physical and chemical environment of other aquatic systems because the amount of dissolved solids carried by ground water is typically much higher than that carried by surface water. Thus, ground water can have a profound effect on the acid susceptibility and nutrient status of the wetland (Hunt and others, 1997). It is widely recognized that linkages between water-budget components and wetlands are not well known, due, in large part, to poor understanding of how ground water flows into and out of wetlands.

While problems associated with ignoring ground water in water-budget analyses are well known (Winter, 1981), traditional hydrologic analyses have had limited success in showing the linkage of ground water to physical and chemical hydrology of wetlands. Previous work on ground water in wetlands has often relied on methods used in aquifer-scale studies, such as widely spaced sample intervals and aquifer tests. Recently, non-traditional investigations of wetlands have shown substantial complexity within wetland hydrologic systems (Harvey and Nuttle, 1995; Hunt and others, 1996). Moreover, this research is showing that ground water has profound effects on the physical and chemical environment of a wetland (Hunt and others, 1999).

Ground water provides refuge for aquatic organisms

Ground-water discharge to streams may help provide important habitat for aquatic organisms, including fish. In addition, because ground-water temperatures are nearly constant throughout the year, stream reaches with relatively large amounts of ground-water discharge can provide refuge to organisms from heat in summer and from cold in winter. For example, some stream reaches in the region remain unfrozen even though air temperatures are well below 32° Fahrenheit. Other possible benefits to the survival of aquatic organisms related to ground-water discharge to streams include increasing concentrations of dissolved oxygen; adding small amounts of nutrients that are essential to the health of organisms; providing cold pockets of water in summer; and maintaining streamflow during dry periods.

Summary and conclusions

Ground water is a major natural resource in the Great Lakes Region because it indirectly contributes more than 50 percent of the stream discharge to the Great Lakes. In addition, ground water is the source of drinking water for millions of people in the region, is an important source of supply for agriculture and many industries, and provides a relatively uniform supply of water in some ecologically sensitive areas to sustain plant and animal species. Therefore, to improve our understanding of water-resources issues in the Great Lakes Region, it is important to have a better understanding of the role that ground water plays in the overall hydrologic system of the lakes.

The main ground-water resources issues in the Great Lakes Region are related to the amount of ground water, the interaction of ground water and surface water, changes in ground-water quality as development expands, and ecosystem health related to quantity and quality of water.

• Issues related to the amount of ground water

Although the amount of water in the Great Lakes Region is vast, issues related to relatively small quantities of water are being raised more and more often. For example, even though the amount of ground water pumped in the region is small compared to the total amount of water present, ground water is an important source of public-water supply as well as an important source of supply for industrial, agricultural, and domestic needs. Less clearly understood, however, is the relation between the amount of streamflow discharging to the Great Lakes and the large portion of that flow that originates as ground water. The implications of this understanding for water- and land-use practices and, in turn, their effects on water quantity and quality, have not been fully incorporated into a policy framework. To help include information about the implications of the role that ground water plays in addressing regional water issues, a comprehensive analysis of indirect ground-water discharge to the Great Lakes is needed.

Direct ground-water discharge to the Great Lakes is not a large factor in water-budget analyses for the Great Lakes. Locally, however, direct ground-water discharge to the Great Lakes may be important, even though the rates and places of discharge are not well known. A long-term evaluation of direct ground-water discharge to the Great Lakes would help place this hydrologic process in proper perspective. Near-shore areas with high rates of direct ground-water discharge may provide valuable habitat for aquatic organisms.

• Issues related to the interaction of ground water and surface water

Withdrawal of ground water removes that water from the watershed when it is consumptively used or when the return flow is discharged to another drainage basin. Under these circumstances, pumping ground water constitutes a diversion of Great Lakes water. Alternatively, ground-water withdrawal could have the opposite effect of diverting ground-water flow into the watershed by altering the ground-water divides. In particular, as withdrawals associated with urban expansion increase, more accurate data on the amount and effects of ground-water use need to be collected. Data on the amounts of ground water pumped both within the watershed and outside, but near the watershed boundaries needs to be collected and evaluated for potential diversion of water to or from the Great Lakes. It is currently thought that both irrigation and ground-water withdrawals near the watershed boundaries constitute relatively small amounts of water; however, both rapidly changing farming practices and rapidly expanding urban communities could alter these amounts in a relatively short timeframe, especially during drought periods. At present, the effects of ground-water withdrawals have been quantified in detail at only a few urban locations.

In addition to quantifying the amount of water pumped out of aquifers, it is also important to improve our knowledge of the amount of water that is recharging them. Ground-water recharge rates estimated in earlier studies cover only a small part of the Great Lakes Region. A comprehensive study of ground-water recharge rates for the entire watershed is needed to more completely determine the role of ground water in the hydrologic budget of the Great Lakes.

- **Issues related to changes in ground-water quality as development expands**

Ground-water quality is as important as quantity for most water uses. As ground-water development proceeds, the possibility of altering the quality of ground water increases. The quality of ground water can be altered when water levels are drawn below the layer that confines the aquifer or by inducing water of lesser quality into an aquifer. Many local studies of these problems have been conducted, but few regional-scale analyses of changes in ground-water quality as a result of ground-water development have been done.

- **Issues related to ecosystem health and quantity and quality of ground water**

Ground water is essential to maintain wetlands and to provide healthy habitat for other aquatic systems. Wetland hydrology is widely recognized as the primary influence on wetland ecology, development, and persistence, and information about hydrology is essential to understanding and quantifying wetland functions and processes. Studies of the role of ground water in selected wetlands in a range of physiographic settings throughout the Great Lakes watershed are needed to more fully understand the role of wetlands in the Great Lakes Region.

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