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National Water Availability and Use Program

Lake-Level Variability and Water Availability in the Great Lakes

Circular 1311

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

Front-cover photo: Drowned-river-mouth wetland in Pigeon River near Port Sheldon, Michigan, in late summer 2000; photo shows mostly annual emergent plants along the shore that grew from the seed bank in exposed shoreline sediments after Lake Michigan water levels dropped more than 1.5 feet from what they were in 1998. (Photo by Douglas Wilcox, U.S. Geological Survey)

Above: Same area in spring 1999, before growth of the emergent plants. (Photo by Douglas Wilcox, U.S. Geological Survey)

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Conversion Factors, Datum, and Abbreviations

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
cubic mile (mi^3)	4.168	cubic kilometer (km^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Great Lakes water levels are referenced to the International Great Lakes Datum of 1985 (IGLD 1985).

Lake-Level Variability and Water Availability in the Great Lakes

By Douglas A. Wilcox[1], Todd A. Thompson[2], Robert K. Booth[3], and J.R. Nicholas[1]

Introduction

Key components of water availability in a **hydrologic system**[4] are the amount of water in storage and the variability of that amount. In the Great Lakes Basin, a vast amount of water is stored in the lakes themselves. Because of the lakes' size, small changes in water levels cause huge changes in the amount of water in storage. Approximately 5,439 mi^3 of water, measured at **chart datum**, is stored in the Great Lakes. A change of 1 ft in water level over the total Great Lakes surface area of 94,250 mi^2 means a change of 18 mi^3 of water in storage. Changes in lake level over time also play an important role in human activities and in coastal processes and nearshore ecosystems, including development and maintenance of beaches, dunes, and wetlands.

The purpose of this report is to present recorded and reconstructed (pre-historical) changes in water levels in the Great Lakes, relate them to climate changes of the past, and highlight major water-availability implications for storage, coastal ecosystems, and human activities. Reconstructed water-level changes have not been completed for all Great Lakes; consequently, this report presents these changes primarily for Lakes Michigan and Huron, with some reference to Lake Superior also.

A wealth of scientific and popular literature summarizes physical and hydrologic characteristics of the Great Lakes Basin. Basic physical data are summarized by the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data ("Coordinating Committee" hereafter; 1977); the Coordinating Committee is a binational group of scientists and engineers that works on behalf of the International Joint Commission (IJC). Long-term Great Lakes hydrologic data are summarized by Croley and others (2001). The IJC, in "Protection of the Waters of the Great Lakes" (2000), summarizes the natural hydrologic system and how humans have changed it. A more popular treatment of Great Lakes water levels is that of the U.S. Army Corps of Engineers and the Great Lakes Commission (1999). Much of the information contained in the above literature is brought together in "Toward a Water Resources Management Decision Support System" (Great Lakes Commission, 2003) and "Uncertainty in the Great Lakes Water Balance" (Neff and Nicholas, 2005). This circular borrows heavily from these latter two publications in the sections that describe physical setting, hydrologic setting, water balance, and recorded water-level history.

Physical Setting

The Great Lakes-St. Lawrence River System comprises (1) Lakes Superior, Michigan, Huron, Erie, and Ontario, (2) their connecting channels, the St. Marys River, the St. Clair River, Lake St. Clair, the Detroit River, and the Niagara River, and (3) the St. Lawrence River, which carries the waters of the Great Lakes to the Atlantic Ocean (fig. 1). The system also includes several manmade canals and control structures that either interconnect Great Lakes or connect the Great Lakes to other river systems.

The Great Lakes Basin, including the international section of the St. Lawrence River above Cornwall, Ontario, and Massena, New York, covers about 295,000 mi^2 (Neff and Nicholas, 2005). It includes parts of eight states and one province: Minnesota, Wisconsin, Illinois, Indiana, Michigan, Ohio, Pennsylvania, New York, and Ontario. About 59 percent of the basin is in the United States, and about 41 percent is in Canada. The basin is about 700 mi long from north to south and about 900 mi long from the west to the outlet of Lake Ontario at Cornwall and Massena in the east. The St. Lawrence River below Cornwall and Massena is about 540 mi long and flows through the provinces of Ontario and Quebec.

The **surficial geology** and topography of the Great Lakes Basin are highly varied. Metamorphic and igneous rocks of Precambrian age surround most of Lake Superior and northern Lake Huron in what is known as the Superior Upland physiographic region (Fenneman, 1946). This area is very rocky and rugged and has little or no overburden. Most of the remainder of the basin is in the Central Lowland physiographic region (Fenneman, 1946), an area underlain by sedimentary rocks of Cambrian through Cretaceous age (Rickard and Fisher,

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[1] U.S. Geological Survey.

[2] Indiana Geological Survey.

[3] Lehigh University.

[4] Terms listed in the glossary at the back of the report are in bold type where first used in the text.

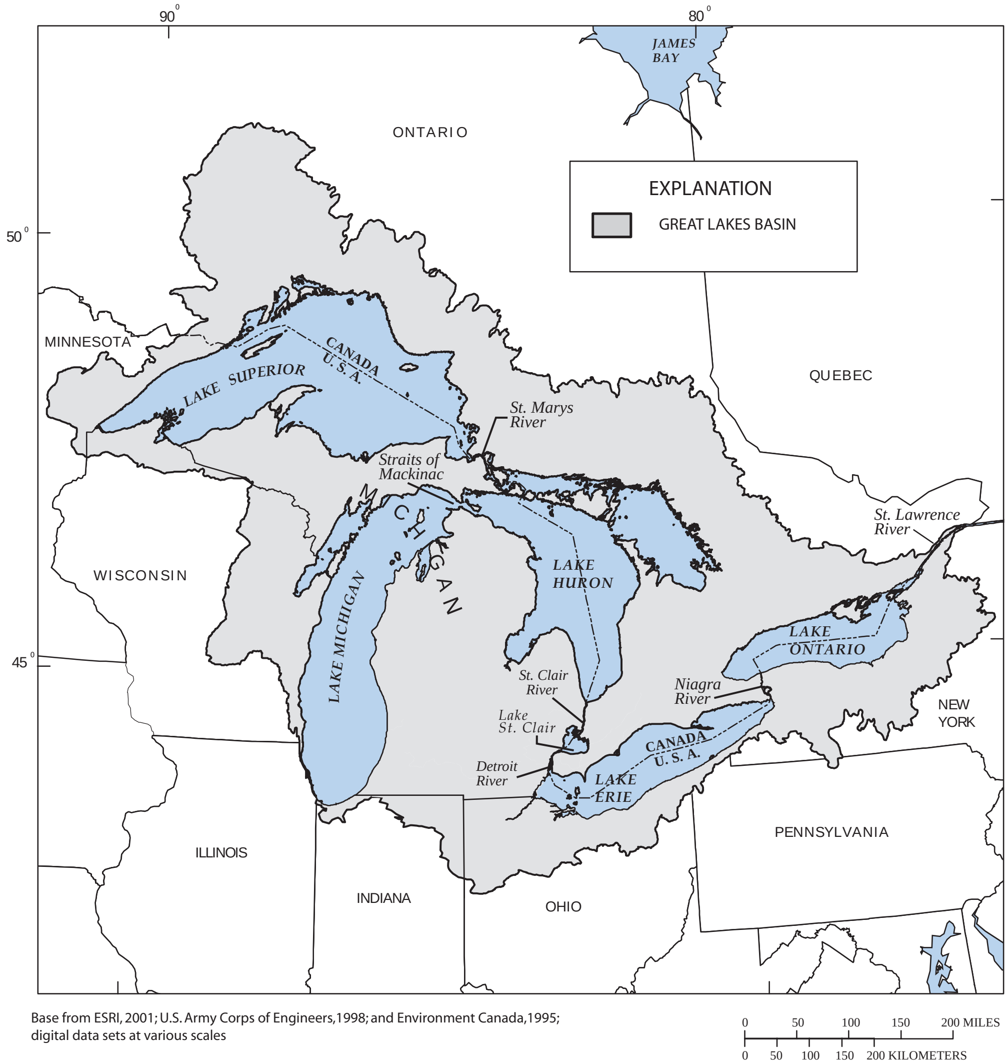
1970; Shaver, 1985) that are covered mostly by unconsolidated deposits from glaciers and glacial meltwater. Thickness of the glacial deposits ranges from 0 to more than 1,000 ft. The topography in the Central Lowland is generally flat and rolling.

About 52 percent of the basin is forested, 35 percent is in agricultural uses, 7 percent is urban or suburban, and 6 percent is in other uses. The population of the basin is about 33 million. Major commerce and industries in the basin include manufacturing, tourism, and agriculture, at about $308 billion, $82 billion, and $48 billion per year, respectively (Great Lakes Commission, 2003).

Hydrologic Setting

The hydrologic system of the Great Lakes is complex. The Lake Superior Basin is at the upstream end of the Great Lakes-St. Lawrence River System (fig. 1). Lake Superior discharges into Lake Huron by way of the St. Marys River, which has a long-term average flow of 75,000 ft^3/s (Neff and Nicholas, 2005). Lakes Huron and Michigan are usually considered as one lake hydraulically because of their wide connection at the Straits of Mackinac. Lake Huron is connected to Lake Erie by the St. Clair River, Lake St. Clair, and the Detroit River. Lake Erie discharges to Lake Ontario by way of the Niagara River. There are also several flow reroutings in the Niagara area, including the Welland Canal, the New York State Barge Canal, and hydropower facilities (Neff and Nicholas, 2005). Lake Ontario discharges to the St. Lawrence River, which has a long-term average discharge of about 238,000 ft^3/s at Cornwall and Massena.

The climate of the Great Lakes Basin varies widely because of the basin's long north-south extent and the effects of the Great Lakes on nearshore temperatures and precipitation. For instance, the mean January temperature ranges from -2°F in the north to 28°F in the south, and the mean July temperature ranges from 64°F in the north to 74°F in the south.



Base from ESRI, 2001; U.S. Army Corps of Engineers,1998; and Environment Canada,1995; digital data sets at various scales

Figure 1. Map of the Great Lakes showing the extent of the drainage basin (from Neff and Nicholas, 2005).

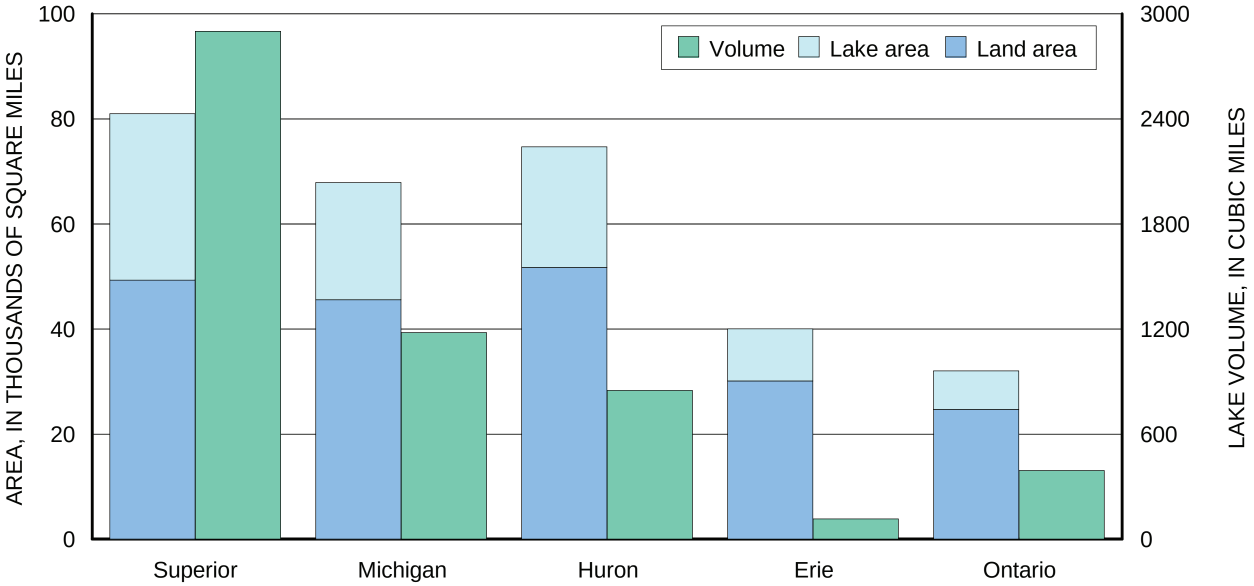


Figure 2. Volume and land and lake area for each of the Great Lakes (modified from Great Lakes Commission, 2003).

Precipitation is distributed relatively uniformly throughout the year but variably west to east across the basin, ranging from a mean annual precipitation of 28 in. north of Lake Superior to 52 in. east of Lake Ontario. Mean annual snowfall is much more variable because of temperature differences from north to south and the snowbelt areas near the east side of Great Lakes. For instance, in the southern areas of the basin, annual snowfall is about 20 in., whereas in snowbelt areas downwind of Lakes Superior and Ontario, snowfall can average 140 in. and sometimes exceed 350 in. annually. Wind is also an important component of the Great Lakes climate. During all seasons, the predominant wind directions have a westerly component. In fall and winter, very strong winds are common in nearshore areas because of temperature differences between the lakes and the air moving over them.

The Great Lakes and their connecting channels cover approximately 32 percent of the entire Great Lakes-St. Lawrence River Basin above Cornwall and Massena (Coordinating Committee, 1977). Figure 2 shows the volume of each of the Great Lakes, as well as the areas of the land and lake components of their individual basins. For example, the total area of the Lake Superior Basin is 81,000 mi^2. The surface area of Lake Superior itself is 31,700 mi^2, or 39 percent of its entire basin area. In contrast, the surface area of Lake Ontario, 7,340 mi^2, is only 23 percent of the entire basin area. The proportion of a lake's basin area that is lake surface area directly affects the amount and timing of water that is received by a lake as precipitation directly on the lake surface and as runoff from its basin tributary streams, as well as the amount of water lost through evaporation from the lake surface.

Lake Erie is the shallowest of the Great Lakes, with an average depth of only 62 ft, followed by Lakes Huron (195 ft), Michigan (279 ft), Ontario (283 ft), and Superior (483 ft). Although Lake Ontario is on average deeper than Lake Michigan, Lake Michigan has a maximum depth of 925 ft that is about 125 ft deeper than the deepest part of Lake Ontario. The maximum depth for Lake Michigan, however, is still 400 ft shallower than Lake Superior's maximum depth of 1,332 ft.

Water Balance

The **water balance** of the Great Lakes includes flows into and out of the lakes and change in storage in the lakes. Change in storage is discussed in a later section of this report. Flows into and out of the Great Lakes include tributary streamflow (also referred to as basin runoff), ground-water inflow, precipitation on the lake surface, evaporation from the lake surface, connecting-channel flows, **diversions**, and **consumptive uses**. Consumptive uses are a very small proportion of the total flows (Great Lakes Commission, 2003) and are not discussed further in this report.

Streamflow is a large part of each Great Lake's inflow, but the percentage varies from one lake to another (fig. 3). Excluding inflows from connecting channels, which are discussed separately, streamflow is 47 percent of the inflow to Lake Michigan-Huron and 68 percent of the inflow to Lake Ontario. This variability is related mostly to the amount of a lake's basin that is land surface as compared to the amount that is lake surface.

The amount of **ground water** that discharges directly into the Great Lakes and connecting channels is considered small relative to other flows into the Great Lakes and is not measured. For these reasons, direct ground-water discharge is typically ignored in water-balance computations and discussions of flows into and out of the Great Lakes. A summary of the available literature on this topic is included in Grannemann and Weaver (1999) and Neff and Killian (2003). Locally, however, ground-water discharge to the Great Lakes may be important to aquatic ecosystems because it can provide a fairly constant supply of water and allow wetlands to remain wet even during warm, dry climatic periods (Burkett and others, 2005). Ground water also discharges to the Great Lakes and connecting channels indirectly by way of tributary streams (Holtschlag and Nicholas, 1998). Estimates for ground-water flow-system boundaries, based on regional ground-water divides, are given by Sheets and Simonson (2006).

Precipitation directly on the Great Lakes is a large part of each Great Lake's inflow (fig. 3). The percentage varies from one lake to another, depending mostly on the area of the lake surface as compared to the area of the land surface draining to the lake. For instance, precipitation directly on Lake Ontario is only about 32 percent of the total inflow, excluding connecting-channel flows, because Lake Ontario has a small lake surface relative to its drainage area.

Evaporation from the surface of the Great Lakes is a large part of each Great Lake's outflow (fig. 4). Again, the percentage varies from one lake to another, depending mostly on the area of the lake surface as compared to the area of the land surface draining to the lake. Much of the seasonal decline of the lakes each fall and early winter is due to the increase in evaporation off their surfaces, which results when cool, dry air passes over the relatively warm water of the lakes.

Connecting-channel flows are a large part of each Great Lake's outflow and inflows of all but Lake Superior (fig. 5). The percentage of the water balance tied to the connecting channels generally increases downstream.

Diversions are a small part of Great Lakes flows. Some diversions are interbasin; that is, they transfer water either into or out of the Great Lakes Basin. Other diversions are intrabasin and transfer water from one Great Lake to another Great Lake. Overall, interbasin diversion into the lakes is greater than interbasin diversion out.

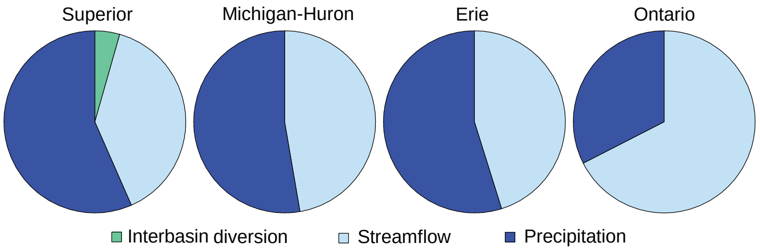


Figure 3. Water inflow to the lakes (modified from Great Lakes Commission, 2003).

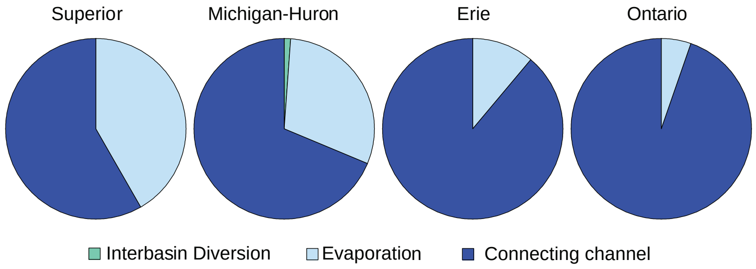


Figure 4. Water outflow from the lakes (modified from Great Lakes Commission, 2003).

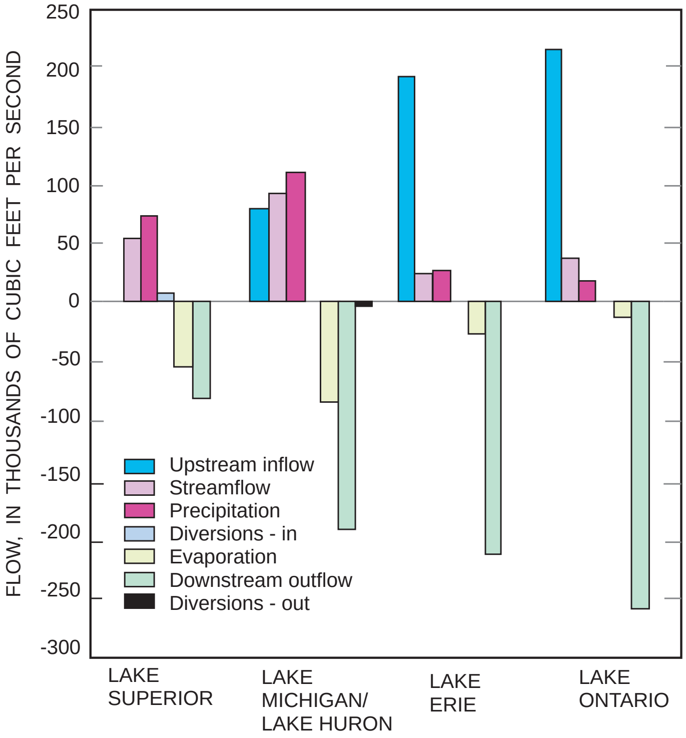


Figure 5. Water balance for the Great Lakes, including types of input to and output from the lakes (from Neff and Nicholas, 2005).

Water Availability

Although the quantities of water in a hydrologic system can be measured, computed, or estimated in a straightforward manner, water availability cannot. Like water sustainability, water availability is an elusive concept (Alley and others, 1999). Water availability relates to both human uses and natural uses. The balancing of how water is portioned among human and natural uses is done by society at large, not by scientists. Therefore, in this report, water availability includes a recognition of the fact that water must be available for human and natural uses, but the balancing of how much should be set aside for which use is not discussed.

The remainder of this report places the variability of Great Lakes water levels within the context of water availability. "Great Lakes Water Levels" and the two subsections on recorded and reconstructed water-level history explain the variability in water available to humans and ecosystems. "Relation to Climate" explains why the changes occur. "Relation to Storage" converts lake levels to volumes of water available and describes the differences in volume between high and low lake levels. Finally, "Relation to Coastal Ecosystems" and "Relation to Human Activities" describe the importance of the variability in both lake levels and water available for human purposes.

Great Lakes Water Levels

Changes in Great Lakes water levels represent a change in water availability or the volume of water stored. Water-level changes are the result of several natural factors and also are influenced by human activities. These factors and activities operate on timescales that range from hours to millennia. The primary natural factors affecting lake levels are the amount of inflow received by each lake, the outflow characteristics of the outlet channels, and **crustal movement**. Influential human factors include diversions into or out of the basin, dredging of outlet channels, and the regulation of outflows.

Short-term water-level changes, lasting hours to days, result from storm surges and **seiches**. Although these changes can be large, they do not represent a change in storage in the lake because water is simply moved from one part of the lake to another.

Seasonal (one-year) fluctuations of the Great Lakes levels reflect the annual hydrologic cycle, which is characterized by higher water levels during the spring and early summer and lower water levels during the remainder of the year. The highest lake level usually occurs in June on Lakes Ontario and Erie, in July on Lake Michigan-Huron, and in August on Lake Superior. The lowest lake level usually occurs in December on Lake Ontario, in February on Lakes Erie and Michigan-Huron, and in March on Lake Superior. Based on the monthly average water levels, the magnitudes of unregulated seasonal fluctuations are relatively small, averaging about 1.3 ft on Lakes Superior and Michigan-Huron, about 1.6 ft on Lake Erie, and about 2.0 ft on Lake Ontario (Great Lakes Commission, 2003). Regulation of water levels also affects seasonal variability on Lakes Superior and Ontario.

Fluctuations over the longer term (multiyear, decadal, and longer) are recognizable in the historical gage dataset and are preserved in geologic features and deposits throughout the Great Lakes Basin. These fluctuations represent basinwide climate changes that influence overall water storage. Combining historical data and geologic data with climate **proxy records** expands our understanding of the physical limits and timing of lake-level change in response to climatic influences.

Recorded Water-Level History

Great Lakes and connecting-channel water levels are measured for many reasons. Instantaneous, daily, monthly, and long-term average water levels are used to help meet regulatory requirements, assist with commercial and recreational navigation, operate hydroelectric power stations, predict future water levels, and calculate changes in storage in each Great Lake. Although water-level recording began in the 1840s, systematic records from all lakes began in 1860. The current network of multiple gages on each lake has been in operation since 1918. Great Lakes water-level data are referenced to the International Great Lakes Datum of 1985 (IGLD 1985), which ties to sea level at Rimouski, Quebec, near the mouth of the St. Lawrence River. Water levels are measured by Fisheries and Oceans Canada and by the National Ocean Service in the United States. Periodically, binationally agreed-upon water levels are produced by the Coordinating Committee on behalf of the International Joint Commission. Information regarding how to find and obtain lake-level data is available in Neff and Killian (2003).

Dredging, control structures, locks, dams, hydroelectric facilities, canals, and diversions have altered the hydrology of the Great Lakes-St. Lawrence River System. Dredging and control structures have had the largest impacts. For instance, dredging of the St. Clair River from 1880 to 1965 permanently lowered Lake Michigan-Huron by about 16 in. Control structures at the outlets of Lake Superior and Lake Ontario keep the levels of these lakes regulated within a range that is smaller than the range of levels that would occur under natural outflow conditions.

Recorded lake-level histories for each lake show some similarities (fig. 6). Periods of higher lake levels generally occurred in the late 1800s, the late 1920s, the mid-1950s, and from the early 1970s to mid-1980s. Pronounced low lake levels occurred in the mid-1920s, the mid-1930s, and the mid-1960s and returned again in 1999. Because Lake Superior water levels have been regulated since about 1914 and levels of Lake Ontario have been regulated since about 1960, lake-level patterns on those lakes since regulation began do not reflect all the natural variability that would have occurred without regulation. For example, unregulated Lakes Michigan-Huron and Erie had extremely high water-level peaks in 1929, 1952, 1973, 1986, and 1997, as well as extreme lows bottoming out in 1926, 1934, 1964, and 2003. Some of those extreme levels, especially the lows, were muted in Lakes Superior and Ontario after regulation began.

Lake Michigan-Huron has a wide range of water-level fluctuations in recorded history (6.6 ft), with a maximum of 582.6 ft (IGLD 1985) in June 1886 and a minimum of 576.0 ft in March-April 1964 (fig. 6). The mean annual variability from wintertime low to summertime high is 1.0 ft (578.5 to 579.5 ft), as determined using data from 1918 to present. Lake Erie also has a wide range of recorded lake levels (6.2 ft), with a maximum of 574.3 ft in June 1986 and a minimum of 568.1 ft in February 1936. The mean annual variability is 1.1 ft (570.8 to 571.9 ft). Prior to regulation, Lake Ontario levels ranged from a maximum of 248.6 ft in June 1952 to a minimum of 242.0 ft in November 1934, a total of 6.6 ft. Over the past three decades of regulation, that range has been reduced to 4.3 ft. If not regulated, projected lake levels would have reached 249.6 ft in July 1986 and 244.1 ft in February 2000, a range of 5.5 ft (IJC Lake Ontario-St. Lawrence River Reference Study data). As currently regulated, the mean annual variability is 1.7 ft (244.4 to 246.1 ft). Lake Superior water levels have been regulated through much of the period of record. Preregulation data span only 55 years, and the 3.6-ft range from 603.2 ft (August 1876) to 599.6 ft (February 1866) does not differ greatly from the postregulation 4.0-ft range of 603.4 ft (October–November 1985) to 599.4 ft (April 1926). As regulated, the mean annual variability is 1.0 ft (601.3 to 602.3 ft).

Reconstructed Water-Level History

The Great Lakes are rimmed by coastal features and associated sedimentary deposits, some as old as 14,000 years and some that are developing today. Many of these features are formed by and respond to changes in lake level (Thompson and others, 2004). Most depend on having sufficient sediment supply to create them and a location to preserve them. Such features and deposits include **wave-cut terraces**, **mainland-attached beaches**, **barrier beaches, spits,** dunes, deltas, and riverine, **palustrine**, and lacustrine sediments. Because many of these relict coastal deposits formed in response to either short-term or long-term fluctuations in lake level, they can be used to reconstruct lake-level changes that preceded instrument measurement of water levels that began in the mid-1800s.

Of particular importance in the reconstruction of past lake levels are beach ridges. These shore-parallel ridges of sand commonly occur in embayments along the lakes, forming a washboard pattern, or **strandplain**, inland from the shore (fig. 7). Although beach ridges on ocean coasts may be formed by storms, beach ridges along the Great Lakes are primarily a product of fluctuations in lake level and are believed to form in the final stages of a long-term lake-level rise to a **highstand** (Thompson and Baedke, 1995). Internally, beach ridges contain sedimentary deposits that accumulated through **eolian** and nearshore processes. Deposits that accumulate along the beach face (**swash zone**) are very narrowly distributed in beach ridges, and the base of these swash-zone deposits is at or very near lake level (Baedke and others, 2004). The basal swash-zone deposits are much coarser than underlying or overlying sediments, and their elevation can be used to determine the elevation of the lake when each beach ridge formed.

By radiocarbon-dating the base of the wetlands deposits between the ridges or by dating the sand grains in the ridges themselves using a technique called optically stimulated luminescence, the age of the ridge can be determined (Thompson and Baedke, 1997; Argyilan and others, 2005). By combining the elevation and age data from numerous beach ridges at any strandplain, a graph of lake-level change—a **hydrograph**—for the strandplain can be produced. The hydrograph records only the time period in which the strandplain was forming beach ridges, and strandplains having many ridges generally preserve the longest lake-level history.

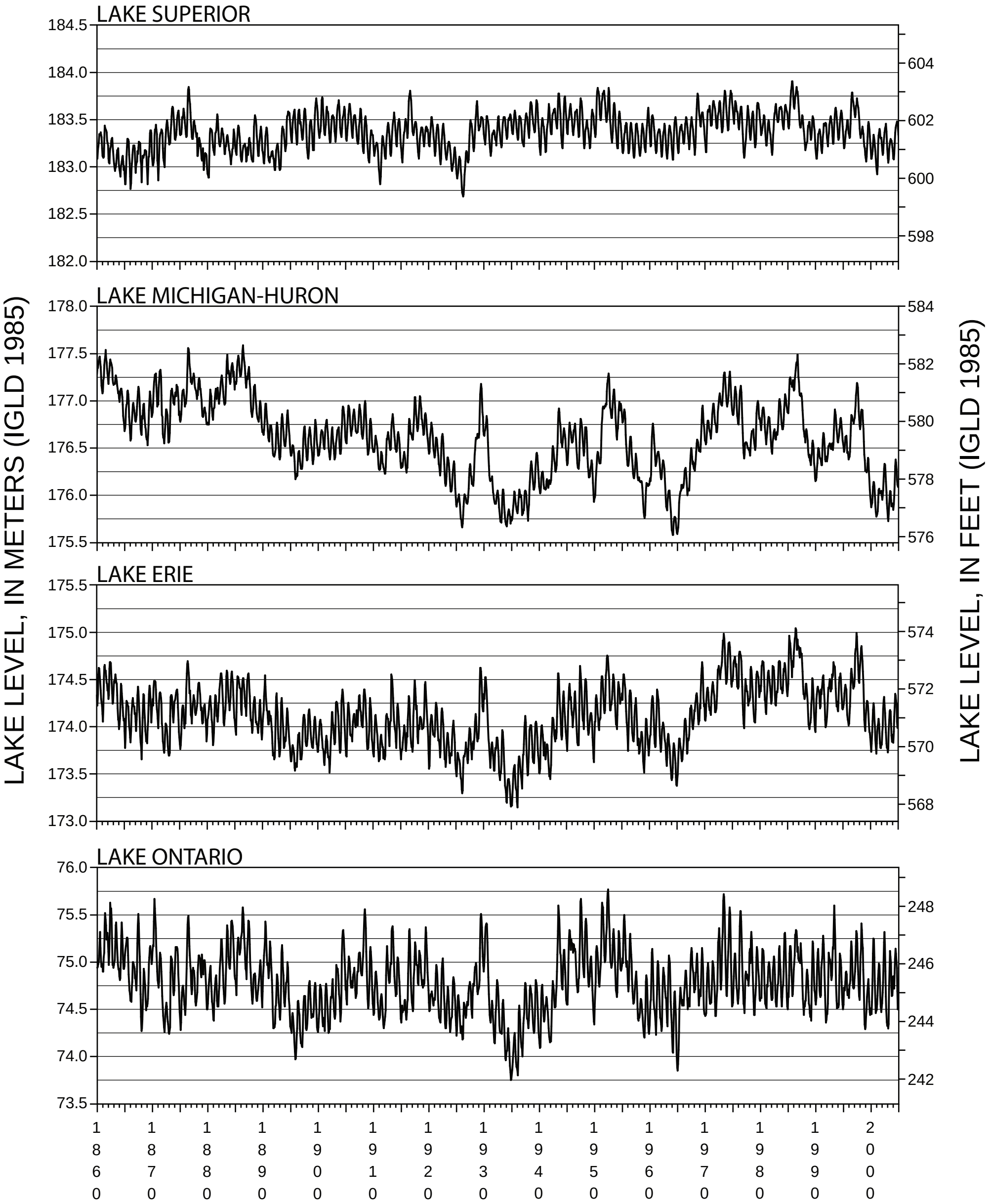
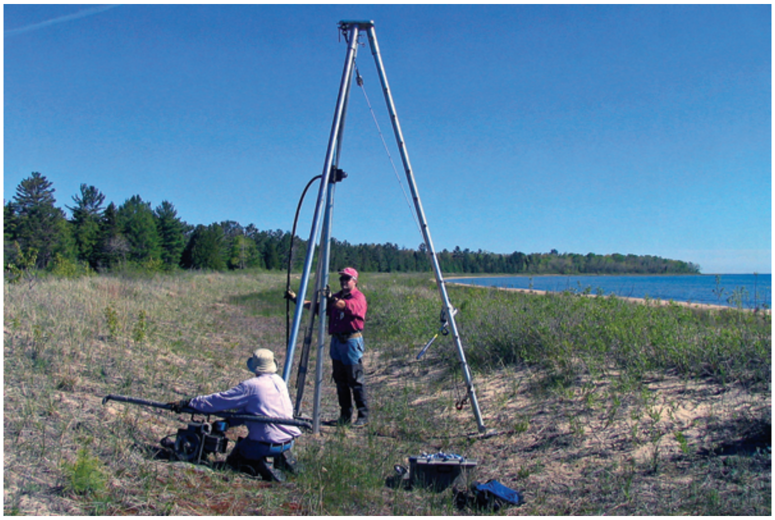


Figure 6. Historical lake levels for the Great Lakes, 1860–2005.

Figure 7. Oblique aerial photograph of a strandplain of beach ridges near Manistique, Michigan. In this photo, individual tree-capped beach ridges are separated by intervening vegetation-covered swales.

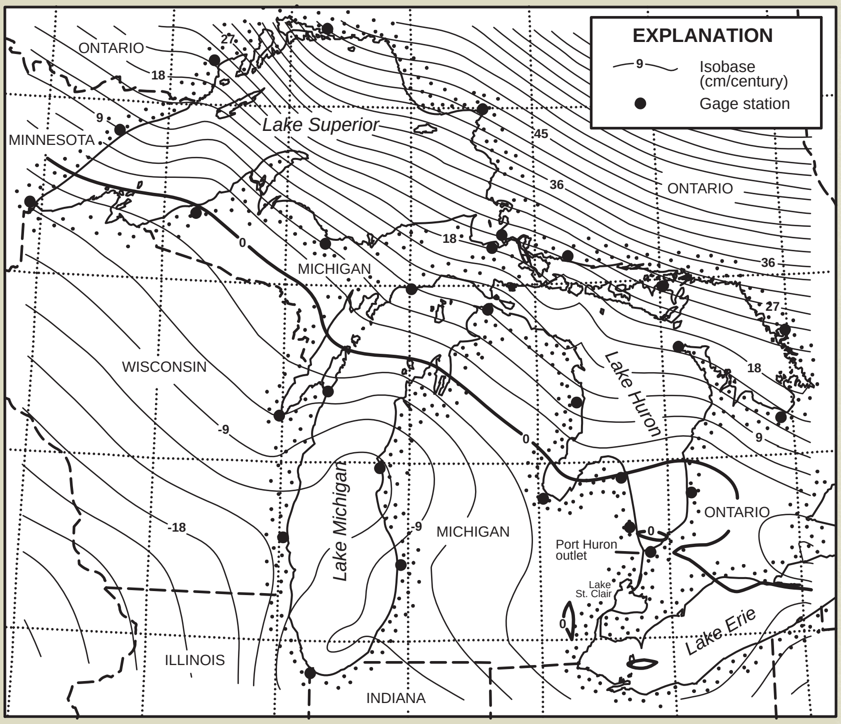


Vibracoring at Negwegon State Park, Michigan. Vibracoring is an important tool needed to understand the subsurface geology of coastal systems throughout the Great Lakes.

The hydrograph for any strandplain records long-term patterns of lake-level change and long-term patterns of vertical ground movement in response to **glacial isostatic adjustment** (GIA; see box 1). If the GIA is removed from an individual strandplain's hydrograph, and if this hydrograph is combined with other overlapping rebound-removed strandplain datasets, a resulting graph representing lake-level change at the lake's outlet can be created. Additionally, maps of long-term patterns of isostatic rebound can be created from the rates of differential rebound calculated from the hydrographs.

For the Lake Michigan Basin, data from five strandplains were combined to produce a hydrograph of lake-level change over the past 4,700 years (Baedke and Thompson, 2000). This graph (fig. 8) illustrates the upper limit of lake level through time and suggests that several periodic lake-level fluctuations were active in the past and are probably still active in the lake basin today. The chart shows that lake level was roughly 13 ft higher 4,500 years ago. This high phase is called the **Nipissing II phase** of ancestral Lake Michigan, and it is represented around the lakes by high, dune-capped ridges, mainland-attached beaches, barrier beaches, and spits. This shoreline commonly was instrumental in isolating small lakes from the larger lake basins. The Nipissing II phase was followed by more than 500 years of lake-level decline during which lake levels dropped to elevations similar to historical averages. Three high phases from 2,300 to 3,300, 1,100 to 2,000, and 0 to 800 years ago followed this rapid decline. Pervasive in the hydrograph is a **quasi-periodic** rise-and-fall pattern of about 160 ± 40 years in duration. This fluctuation can be extended into the historical record, and it appears that the entire historical dataset (mid-1800s to present) may be one such 160-year quasi-periodic fluctuation. Superimposed on this 160-year fluctuation is a short-term fluctuation of 32 ± 6 years in duration (fig. 8). This lake-level rise-and-fall pattern produced the individual beach ridges in most embayments and is also expressed in the historical data, most easily seen in the low levels in the 1930s and 1960s and again starting in the late 1990s.

Box 1. Glacial isostatic adjustment (GIA) is a continuing process in which the Earth's crust is warping in response to the melting of the last glacial ice sheets that crossed the area. Because the glacial ice was thickest north of the Great Lakes Basin, this area of the Earth's crust was depressed the most. Today, areas depressed the most are rising the fastest. In general, the rate of rebound increases northward toward the southeastern tip of Hudson Bay (Mainville and Craymer, 2005), thus tilting the Great Lakes southward. GIA influences long-term lake level by warping each lake's basin and changing the elevation of the lake's coastline in relation to its outlet. Segments of coastline rebounding more rapidly than the lake's outlet experience a long-term lake-level fall, whereas coastlines rebounding more slowly than the outlet experience a long-term lake-level rise. For example, the outlet for Lake Superior is rising more rapidly than the southern coastline of Lake Superior. Consequently, Duluth, Minnesota, at the extreme west end of the lake, experiences a long-term lake-level rise of about 10 in. (25 cm) per century in response to GIA that is unrelated to net basin supply.



Map of the upper Great Lakes showing contoured rates of GIA with respect to the Port Huron outlet. The bold isobase (zero) defines areas of the upper Great Lakes that are moving at a similar vertical rate and direction as the outlet. (Map modified from Mainville and Craymer, 2005; note that scale is in centimeters.)

Relation to Climate

As mentioned earlier, short-term fluctuations lasting minutes to days are primarily related to local meteorological conditions, such as spatial differences in barometric pressure over the lake. At the opposite extreme, lake-level changes spanning several millennia are attributed to geologic processes such as isostatic rebound and outlet incision, although recent evidence suggests that climate also may have played a role (Booth and others, 2002). However, at intermediate timescales ranging from annual to millennial, climate is the primary cause of Great Lakes water-level fluctuations. Understanding relations between climate and lake-level variability, as well as the mechanisms underlying wet and dry extremes, is critically important in light of ongoing and future climate changes.

The importance of climate variability in controlling Great Lakes water levels during the past 5,000 years has been assessed by comparing independent proxy records of past climate variability with the reconstructed water-level history of Lake Michigan inferred from sediments (fig. 9; see box 2). The development of high-resolution and well-dated **paleoclimate** records, such as those from inland bogs and lake sediments, has revealed significant climatic variability in the Great Lakes region at decadal to millennial timescales during the past several thousand years. One unsettling pattern in these records is that, despite being a relatively humid region, severe droughts larger than any observed in the past century occurred several times in the last few thousand years and had large and long-lasting ecological effects. For example, between about 1,000 and 700 years ago, a time interval broadly consistent with the **Medieval Warm Period**, a series of large-magnitude moisture fluctuations occurred over the western Great Lakes region, the Great Plains, and the western United States (Booth and others, 2006). Lake Michigan water levels were greatly affected by these fluctuations, particularly a large drought about 1,050 years ago (fig. 9). This large drought dramatically altered forest composition in southeastern Michigan (Booth and Jackson, 2003) and may have extended well into eastern North America.

Another major drought in the region, which was probably even larger than the Medieval Warm Period droughts, was associated with the large drop in Lake Michigan water levels between 4,500 and 4,000 years ago. At that time, water levels in Lake Michigan dropped at a rate at least five times the rate

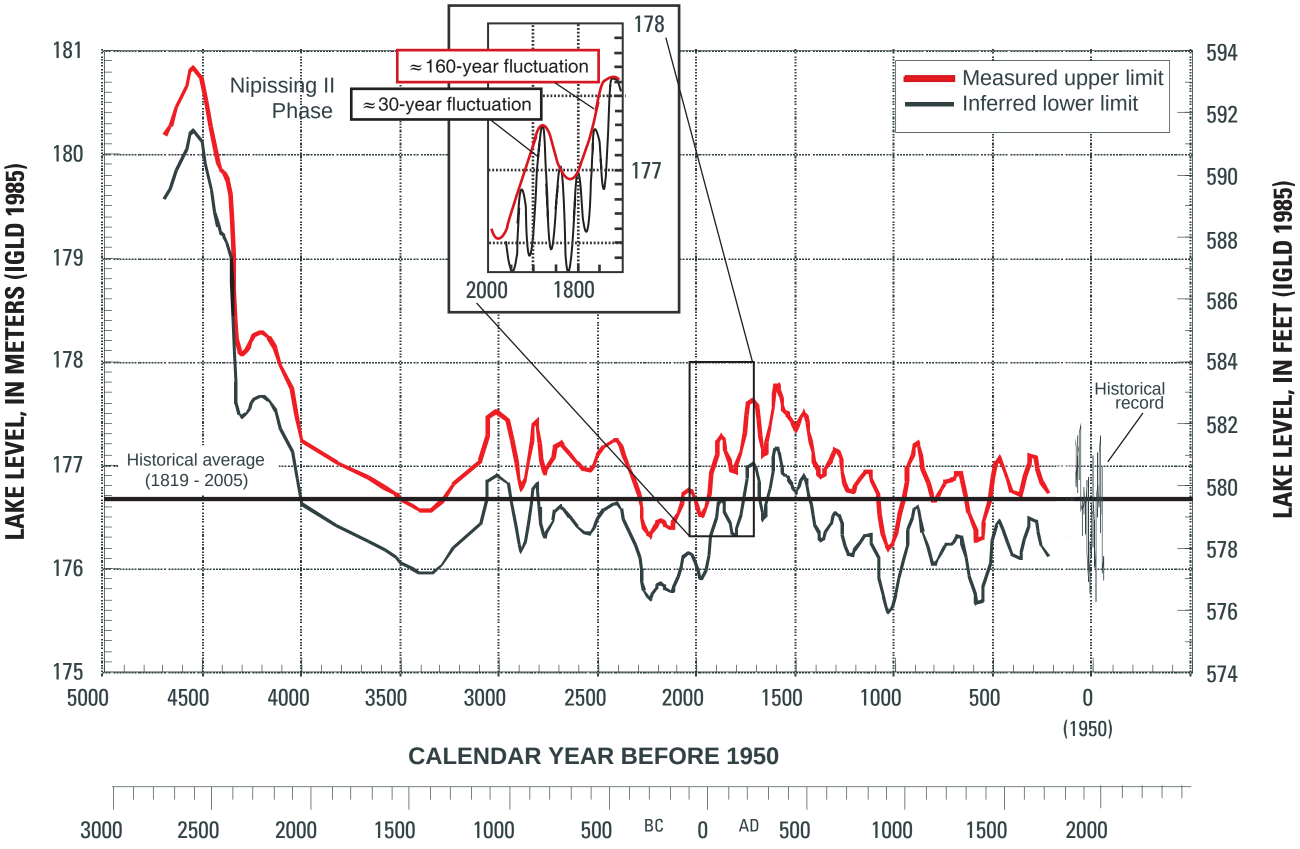
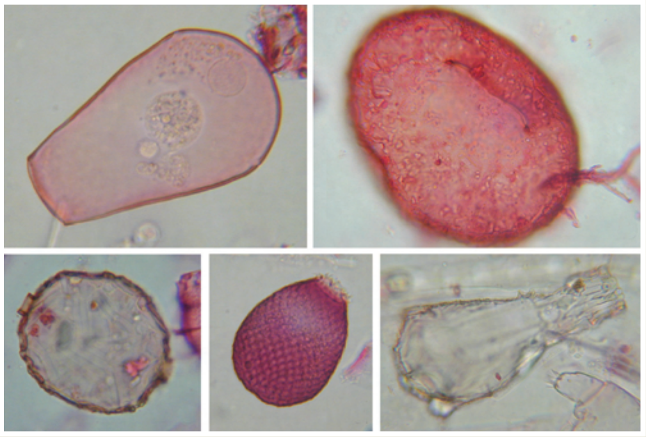


Figure 8. Hydrograph of late Holocene lake level and historical lake level for Lake Michigan-Huron. The red line is interpreted from beach-ridge studies, whereas the lower black line is an inferred lower limit using the range of the historical record as a guide.

Box 2. Proxy records of past climate variability have been developed from various sources in the Great Lakes region, including the archives contained in tree rings, dune soils, and the sediments of small lakes and wetlands. Paleoclimatic proxies vary widely in their climate sensitivity and resolution. **Peatlands** (that is, bogs) are one source of data on past changes in water balance, and the sediments of peatlands that derive all or most of their moisture directly from the atmosphere contain particularly sensitive records of past moisture variability. Reconstructions of bog surface-moisture conditions have been made using a variety of proxies preserved in the peat sediments, including **testate amoebae**—a group of moisture-sensitive protozoa that live on the surface of bogs and produce decay-resistant shells. (See photo at lower right.) Comparison of bog-inferred moisture records with the Great Lakes water-level history has demonstrated the clear linkage between climate variability and Great Lakes water-level fluctuations for the past 3,500 years (fig. 9) (Booth and Jackson, 2003).

Paleoecologist collecting a peat core.



Photographs of testate amoebae that occur in peatlands within the Great Lakes Basin.

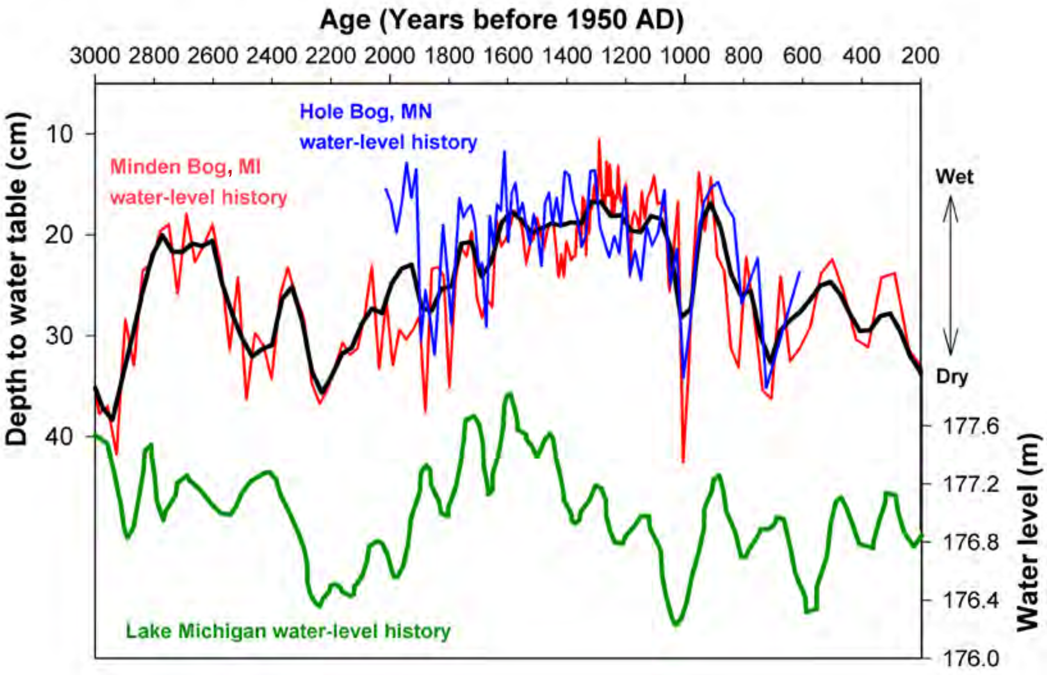


Figure 9. Late Holocene lake level interpreted from beach-ridge studies in relation to surface moisture interpreted from testate amoeba studies in peatlands (modified from Booth and others, 2006).

of isostatic rebound. Although nonclimatic factors may have been involved in this rapid drop, the timing corresponds to a well-documented and widespread centennial-scale drought that affected much of the North American midcontinent—activating dune systems, causing widespread fires, and leading to long-lasting changes in forest composition (Booth and others, 2005). Abrupt climate changes at that time are well documented on most continents, suggesting potential global-scale linkages.

Times of prolonged high water levels in the Great Lakes (highstands) have also been linked to climate variability. For example, bog surface-moisture reconstructions and inland lake records from throughout the Great Lakes region indicate wetter conditions during highstands (for example, Booth and Jackson, 2003; Booth and others, 2004). Pollen records indicate that populations of trees favoring moist conditions also expanded at these times (Booth and others, 2002). Although some climate changes associated with lake-level fluctuations were widespread, others were probably more spatially variable, with different areas of the Great Lakes Basin receiving more or less moisture. The water-level history of the Great Lakes integrates these spatial patterns. Comparison of localized records of climate variability from throughout the Great Lakes Basin (for example, records from small lakes, bogs, and tree rings) with the regionally integrated record of Great Lakes water-level history will allow delineation of these spatial patterns and help develop hypotheses regarding the atmospheric-circulation patterns associated with Great Lakes water-level fluctuations at scales of decades to millennia.

Clearly, the water balance of the Great Lakes region has varied considerably, and the overall variability for the past 14,000 years far surpasses that of the last 100 years in magnitude and ecological effect. Mechanisms behind climatic variability at these long timescales are poorly understood; however, many severe moisture fluctuations of the past century have been linked to dynamics of the ocean-atmosphere system, particularly variability in sea-surface temperatures and the associated changes in atmospheric circulation. For example, sea-surface temperature variability in both the Pacific and the Atlantic has been linked to changes in atmospheric circulation that influence the water balance of the midcontinent, including the Great Lakes region (McCabe and others, 2004; Schubert and others, 2004; Booth and others, 2006). Interactions between land surface and atmosphere, particularly with regard to soil moisture, often extend and amplify a large drought (for example, Delworth and Manabe, 1988; Manabe and others, 2004; Schubert and others, 2004). The extreme fluctuations in water balance evident in the Great Lakes water-level history and other paleoclimatic records may represent interactions and amplifications of this kind, as well as responses of the ocean-atmosphere system to variability in external influences such as solar radiation and volcanic activity (for example, Adams and others, 2003; Meehl and others, 2003; Rind and others, 2004).

Relation to Storage

Because of its large areal coverage and deep basin, Lake Superior stores more water (2,900 mi^3 at chart datum) than all the other lakes combined (2,539 mi^3 at chart datum). The maximum storage in Lake Superior in recorded history was 2,949 mi^3 in October 1985 (fig. 10). Storage was only 2,925 mi^3 during the low-lake-level period in April 1926. The average change in storage from wintertime low to summertime high is 6 mi^3.

Storage at chart datum in Lake Michigan is 1,180 mi^3 and in Lake Huron is 850 mi^3. The maximum storage in recorded history for combined Lake Michigan-Huron was 2,053 mi^3 in

How much water is in a cubic mile?

A cubic mile is about 1.1 trillion gallons or a football field filled to a depth of about 2.5 million feet.

How much water is in the Great Lakes?

Water from the Great Lakes could cover North America, South America, and Africa to a depth of more than 1 foot (Neff and Nicholas, 2005).

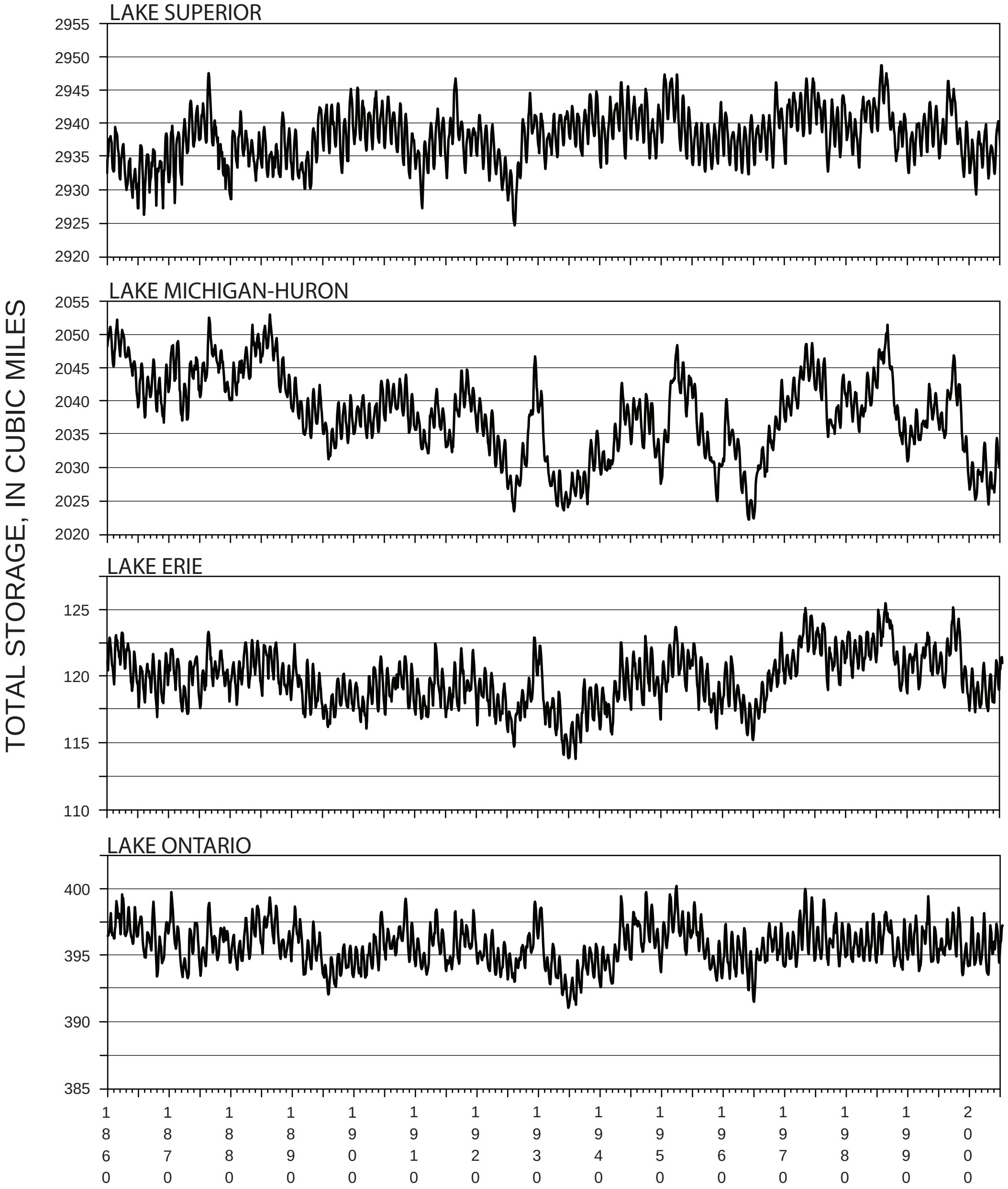


Figure 10. Water storage for the Great lakes, 1860–2005.

June 1886, and the minimum was 2,022 mi^3 in March 1964. The recent drop in the peak lake level from 582.3 ft in October 1986 to 576.5 ft in March 2003 (see fig. 6) resulted in a reduction in storage of nearly 27 mi^3. The average change in storage from wintertime low to summertime high is 4.6 mi^3 in Lake Michigan-Huron.

In Lake Erie, storage at chart datum is 116 mi^3; the maximum storage at high lake level in June 1986 was 126 mi^3, and the minimum storage was 114 mi^3 in February 1936. Total storage changed by about 8 mi^3 between high lake levels in June 1997 and low lake levels in January 2001. On average, the change in storage between wintertime low and summertime high is 2.1 mi^3.

Storage in Lake Ontario at chart datum is 393 mi^3. Maximum recorded water storage was 400 mi^3 in June 1952, and the minimum was 391 mi^3 in November 1934, both prior to lake-level regulation. The variability in storage has been reduced by regulation, with a difference of only 6 mi^3 between the recent high in May 1993 and the low in December 1998. The average change in storage of the regulated lake is 2.4 mi^3 between wintertime low and summertime high.

Because of the large capacities of the lakes, alterations of storage due to diversions are relatively minor. The Chicago diversion from Lake Michigan averages 3,200 ft^3/s, which results in a yearly diversion of about 0.69 mi^3, only about 0.06 percent of the total Lake Michigan storage. One uniform rainstorm dropping less than 2 in. of rain directly on the lake would yield the same volume.

Relation to Coastal Ecosystems

Water-level fluctuations in the Great Lakes are of great ecological importance in the coastal zone because even small changes in lake level can shift large areas from being flooded to being exposed and vice versa. The vegetation of shallow-water areas in the Great Lakes is the one biotic resource most directly affected by natural or regulated changes in water level. Individual plant species and communities of species have affinities and physiological adaptations for certain water-depth ranges, and their life forms may show adaptations for different water-depth environments. Changes in water level add a dynamic aspect to the species-depth relation and result in shifting mosaics of wetland vegetation types. In general, high water levels kill trees, shrubs, and other **emergent** vegetation, and low water levels following these highs result in seed germination and growth of a multitude of species (fig. 11). Some species are particularly well suited to recolonizing exposed areas during low-water phases, and several emergents may coexist there because of their diverse responses to natural disturbance.

In the first year after a reduction in water levels, the distribution of new seedlings is due to the distribution of seeds in the sediments. In ensuing years, the distribution of full-grown plants is due to survival of seedlings as they compete for growing area. If one species is favored in early colonization, its density may be great enough that it can maintain dominance of an area. In most cases, early colonizing species or communities are later lost through competitive displacement, but the opportunity to go through a life cycle allows them to replenish the seed bank in the sediments (see box 3). Occasional low water levels are also needed to restrict growth of plants that require wet conditions, such as cattails, at higher elevations in wetlands that are typically colonized by sedges and grasses (see box 4).

The magnitude of lake-level fluctuations is of obvious importance to bordering wetland vegetation because it directly results in different water-depth environments (Environment Canada, 2002). The different plant communities that develop in a Great Lakes wetland shift from one location to another in response to changes in water depth. The water-depth history largely determines the species composition of a particular site at a given point in time, with resultant zonation patterns sometimes becoming obvious (fig. 12). Forested and shrub-dominated wetlands occur in areas that are rarely covered with water. **Meadow marsh** occurs in areas that are occasionally covered with water. Dense emergent marsh occurs where the substrate is covered and uncovered with water on a short-term basis. Sparse emergent marsh occurs if standing water is deeper and present in most years, and submersed and floating leaf communities dominate if standing water is nearly always present.

The frequency, timing, and duration of water-level fluctuations are also important for several reasons. Effects of seiches are poorly understood, although they can affect zonation of plant communities by keeping soils wet and limiting germination from the seed bank. Seasonal differences in the timing of water-level declines are important, especially in the Great Lakes, where the peak water levels occur in the summer and the lows occur in the winter (opposite the changes in most inland wetlands). An early summer peak and subsequent beginning of water-level decline allows more plants to grow from the seed bank than does a later peak. Water-level declines in winter can result in ice-induced sediment erosion. Consistent annual fluctuations during the growing season favor the species that are most competitive under those conditions, whereas variable summer water levels produce changing environmental conditions and result in variability in the vegetation.

Great Lakes wetlands also provide valuable habitat for fish and wildlife (Wilcox, 1995; Environment Canada, 2002). Many invertebrates are closely associated with **macrophyte** beds; waterfowl, aquatic mammals, and small fish are attracted to these areas because they provide food and shelter. When water levels change, habitats and organism interactions change also. Flooding of emergent plant communities allows access for spawning fish, reduces mink predation on muskrats, and increases **hemi-marsh** habitat (half vegetated, half open water) preferred by waterfowl. Flooded, **detrital** plant materials are also colonized by invertebrates that are fed on by waterfowl. Low water levels can jeopardize fish spawning and reduce waterfowl nesting area; yet, they provide the

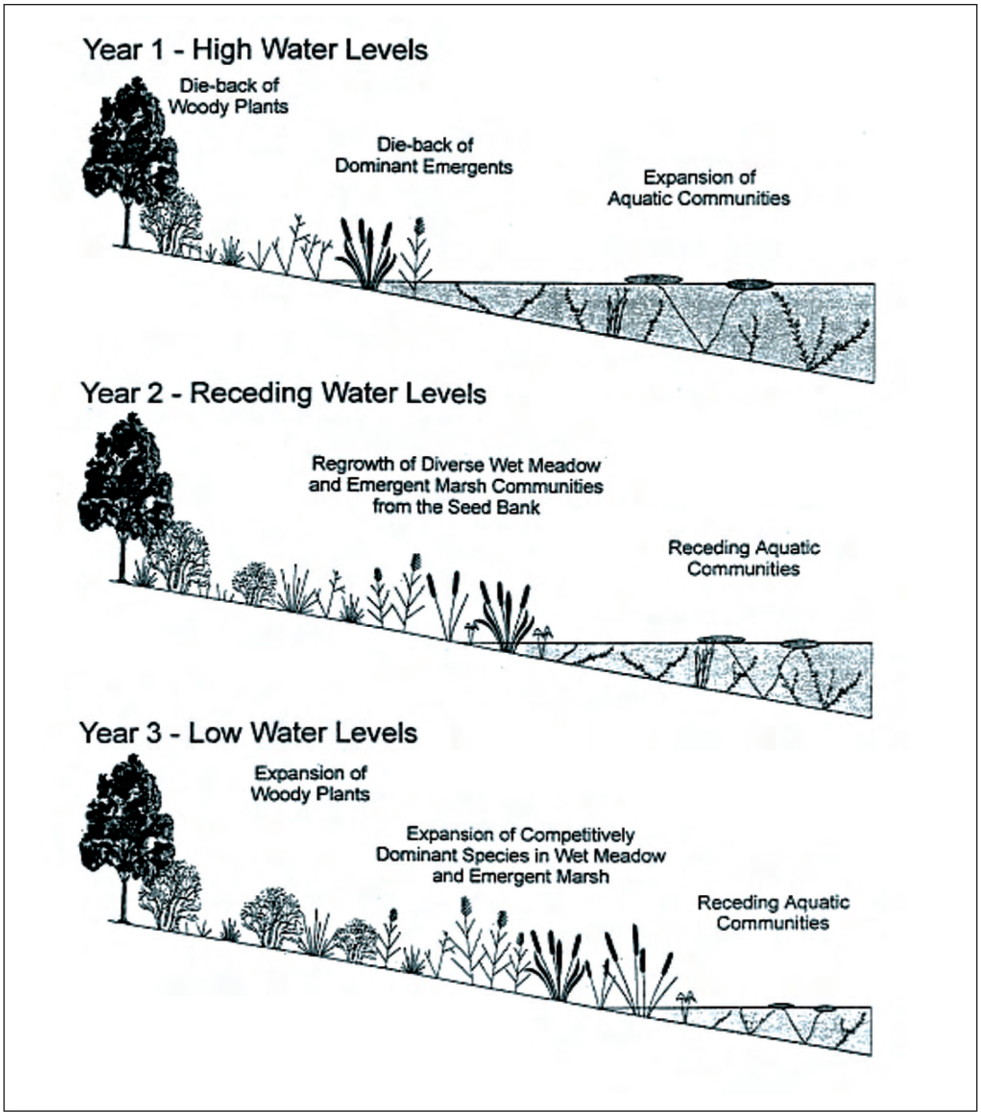


Figure 11. Simplified diagram of the effects of water-level fluctuations on coastal wetland plant communities (from Maynard and Wilcox, 1997).

opportunity for regeneration of the plant communities that are the foundation of the habitat. Water-level fluctuations promote the interaction of aquatic and terrestrial systems and result in higher-quality habitat and increased productivity. When the fluctuations in water levels are removed through stabilization, shifting of vegetation types decreases, more stable plant communities develop, species diversity decreases, and habitat value decreases.

The effect of water-level changes on shorelines varies with the morphology, composition, and dominant processes of the coast. Variability in lake levels causes erosional and depositional processes to take place at different elevations over time. The most dramatic effect is the impact of an elevated storm surge during high lake levels, flooding low-lying areas and eroding mobile substrates. These storms can liberate sediment from upland areas, feeding the **littoral** system, and can ultimately nourish downdrift shorelines. The effects of this nourishment may not be seen until times of low water levels when exposed sand bars, widened beaches, and dune growth are evident.

Water-level fluctuations in the Great Lakes also play a major role in development and stabilization of coastal dunes (fig. 13). Studies of buried soils within dunes along the southeastern shore of Lake Superior and eastern shore of Lake Michigan show that dune building occurred during the high lake-level periods that have recurred about every 160 years.

Box 3. Some species are particularly well suited to recolonizing exposed areas during low-water phases, and several emergents may coexist there because of their diverse responses to natural disturbance.

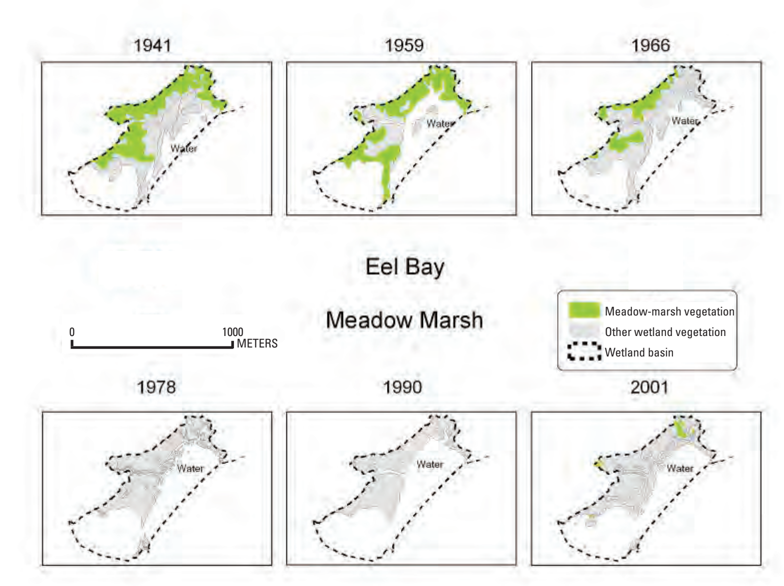
Drowned-river-mouth wetland in Pigeon River near Port Sheldon, Michigan; photo taken in spring 1999 after Lake Michigan water levels dropped more than 1.5 ft from the previous year. Note the lack of emergent vegetation along the shore.

Same wetland in late summer 2000; photo shows mostly annual emergent plants along the shore that grew from the seed bank.

Same wetland in 2001; photo shows perennial emergent plants displacing annuals along the shore.

Same wetland in 2003; photo shows a shift in vegetation to a different perennial plant community.

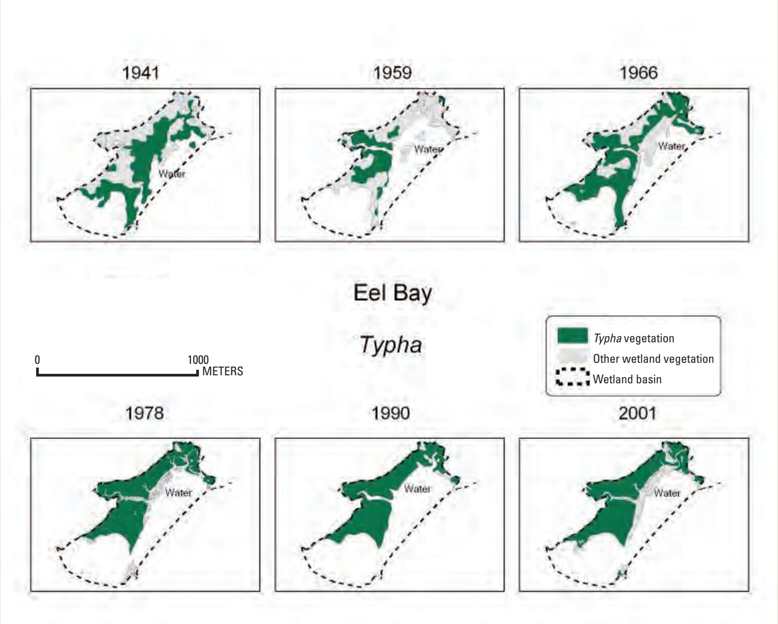
Box 4. The different plant communities that develop in a Great Lakes wetland shift from one location to another in response to changes in water depth.



Vegetation maps from Eel Bay near Alexandria Bay, New York, derived from analyses of aerial photographs taken before regulation of Lake Ontario water levels (1960) and continuing through 2001. The loss of meadow-marsh vegetation following regulation is highlighted.

Meadow-marsh vegetation in a Lake Ontario wetland with invading cattails.

Scientists sampling vegetation in the narrow band of remaining meadow marsh in a Lake Ontario wetland.



Vegetation maps from Eel Bay highlighting the increase in cattail (*Typha*)-dominated plant communities following regulation of lake levels.

Cattail domination of a Lake Ontario wetland extending from near shore to deeper water, with abrupt transition of floating and submersed plant communities.

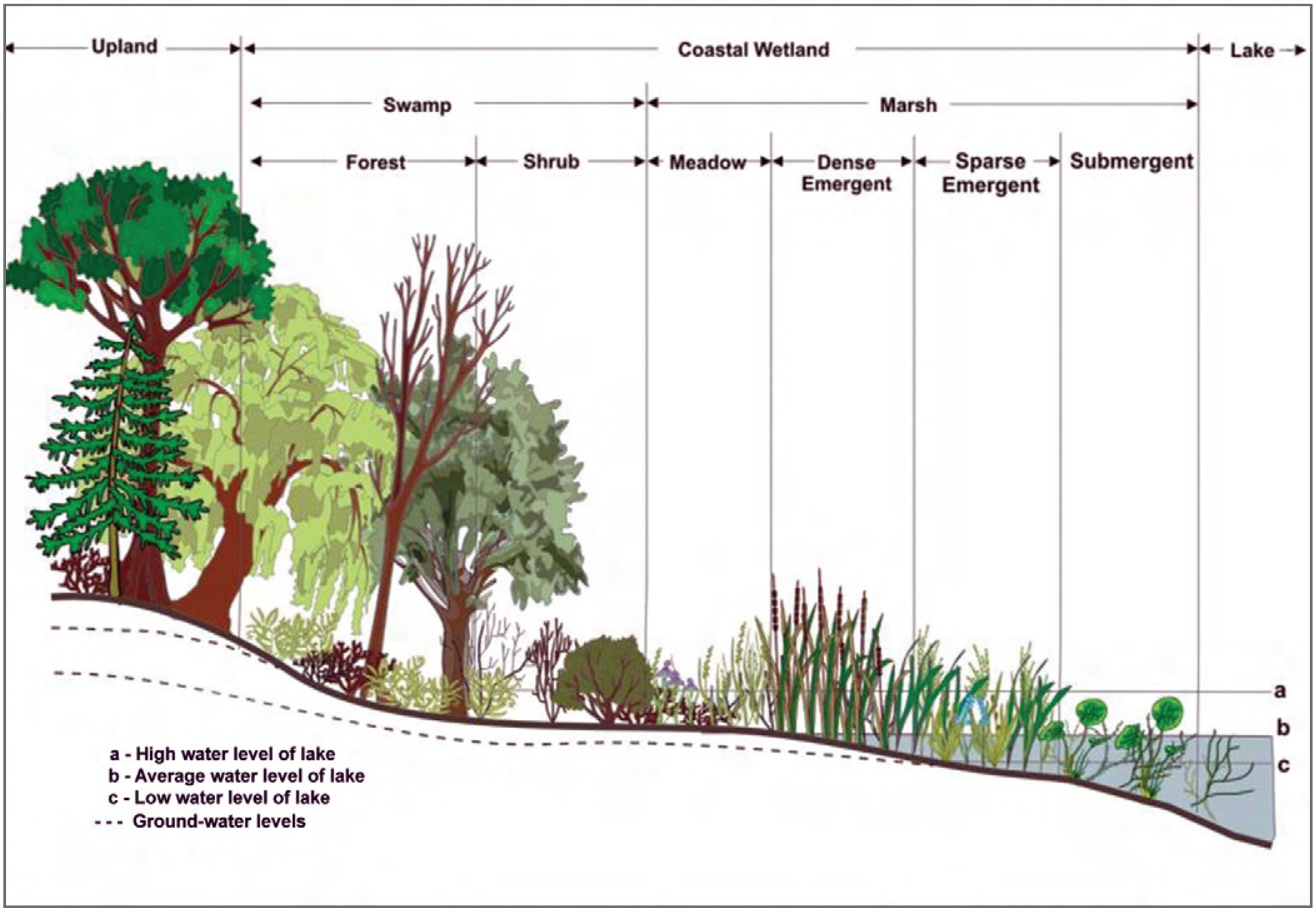


Figure 12. Profile of a typical coastal marsh from lake to upland showing changes in plant communities related to lake-level history (from Environment Canada, 2002).

High lake levels destabilize coastal bluffs and make sand available to leeward **perched dunes**. Intervening periods of lower lake levels and relative sand starvation permit forestation and soil development on the dunes (Anderton and Loope, 1995; Loope and McEachern, 1998; Loope and Arbogast, 2000).

Relation to Human Activities

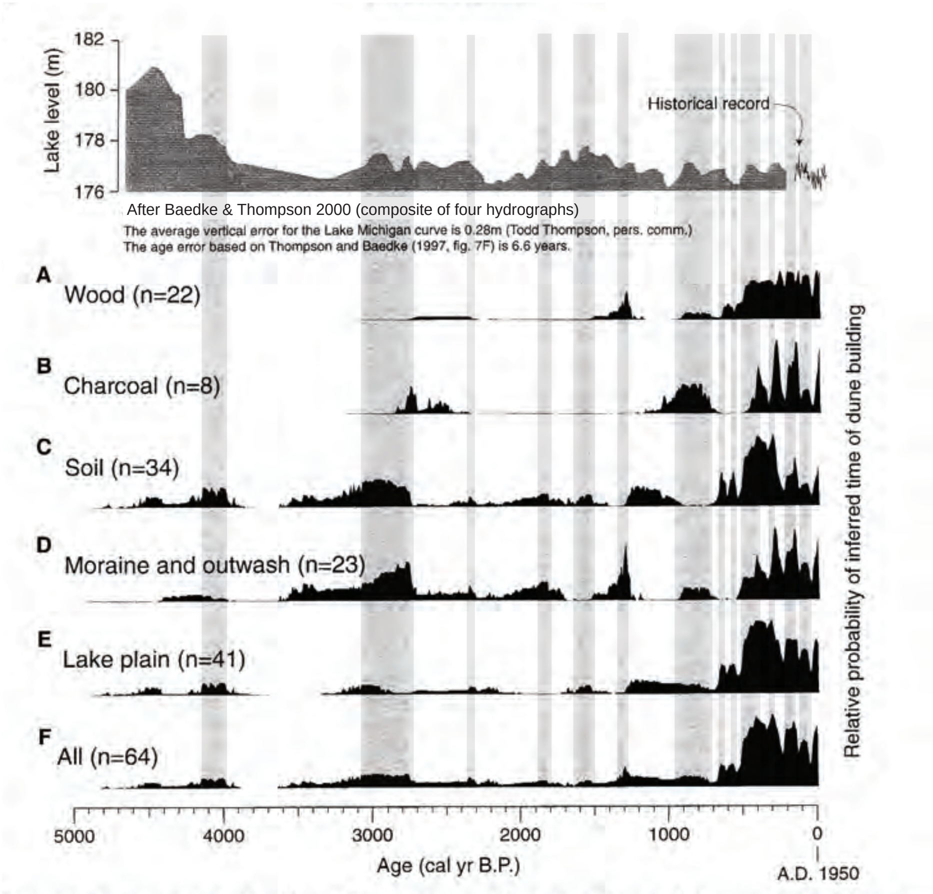
Human activities are also affected by water-level changes, and it is these health and economic activities that receive the most attention. Water-level changes can affect the production of electricity at hydropower facilities, especially those at the outlets of Lakes Superior, Erie, and Ontario. Extreme low water levels in the Great Lakes can jeopardize water-intake structures associated with municipal and industrial water-supply facilities, especially those structures that were built without knowledge of the long-term natural variability in lake levels. Although cargo ships have little difficulty traversing the waters of the Great Lakes proper, even during low lake-level periods, reduced water depths in the connecting channels and the lower St. Lawrence River can limit the amount of cargo

What are the relative magnitudes of natural and human-induced effects on Great Lakes water levels?

Effects of natural and human factors on water levels differ from lake to lake, but the following example for Lakes Michigan and Huron gives a sense of relative magnitudes of changes. Except for the Detroit/St. Clair channel modifications, which induced a change that was comparable to seasonal variability, natural factors are dominant—particularly over the long term.

Long Lac-Ogoki Diversions (inflows)	11 cm
Chicago Diversion (outflow)	-6 cm
Welland Canal	-6 cm
Detroit/St. Clair channel modifications	-40 cm
Niagara River outlet	3 cm
Existing consumptive uses (1993)	-5 cm
Seasonal variability	±1.3 ft
Climate variability (recorded)	±6 ft
Climate variablility (last 2,000 years)	±7 ft

(Values in centimeters (cm) are from International Joint Commission (1999), and those in feet (ft) are from figure 9 of this report.)


After Baedke & Thompson 2000 (composite of four hydrographs)

The average vertical error for the Lake Michigan curve is 0.28m (Todd Thompson, pers. comm.)

The age error based on Thompson and Baedke (1997, fig. 7F) is 6.6 years.

Figure 13. Inferred late-Holocene levels of Lake Michigan compared with peaks in probability of inferred dune building. Gray bars show how composite peaks in inferred dune building (graph F) compare with the inferred lake levels. (Modified from Loope and Arbogast, 2000.)

they carry. Extreme flows in those channels during high-water periods can also hamper navigability. The recreational boating industry in the Great Lakes has grown in recent decades, with more marinas to accommodate the boats and larger boats that require deeper water. Some marinas, especially those built during high-lake-level periods, cannot operate as planned when lake levels are low. Boats of all sizes face greater risk of hitting lake bottom or submerged structures when lake levels are low, especially when traveling routes that were otherwise passable during high-water periods. In contrast, high water levels create problems for lakeshore property owners and industries that have structures in the flood-hazard zone (see box 5).

Regulation of water levels on Lakes Superior and Ontario at their outlets seeks to reduce the occurrence of both high and low lake levels. Regulation of water levels creates problems for wetlands; it reduces the diversity of wetland plant communities and alters habitat values for wetland fauna (Wilcox and Meeker, 1991, 1992). This problem is especially evident on Lake Ontario, where regulation began with operation of the St. Lawrence Seaway in about 1960 (Wilcox and Meeker, 1995; Wilcox and Whillans, 1999). Before regulation, the range of fluctuations during the 20th century was about 6.5 ft (fig. 6). After regulation began, the range was reduced slightly during 1960–76, but low water-supply conditions in the mid-1960s and high supplies in the mid-1970s maintained much of the range. Regulation reduced the range to about 4.4 ft in the years after 1973. The lack of alternating flooded and dewatered conditions, especially the lack of low lake levels, resulted in establishment of extensive stands of cattail at the expense of other plant community types, mostly the sedge/grass community at upper elevations in the wetlands (fig. 14) (Wilcox and Meeker, 1995; Wilcox and others, 2005). New regulation plans for Lake Ontario are currently being evaluated by the International Joint Commission (Hudon and others, 2006).

Water levels on Lake Superior have been regulated since the early years of the 20th century, but the range of fluctuations and the cyclic nature of high and low lake levels were not altered as dramatically as on Lake Ontario. Since 1930, however, low lake levels that occurred on the unregulated lakes did not occur on Lake Superior (fig. 6). Wetland plant

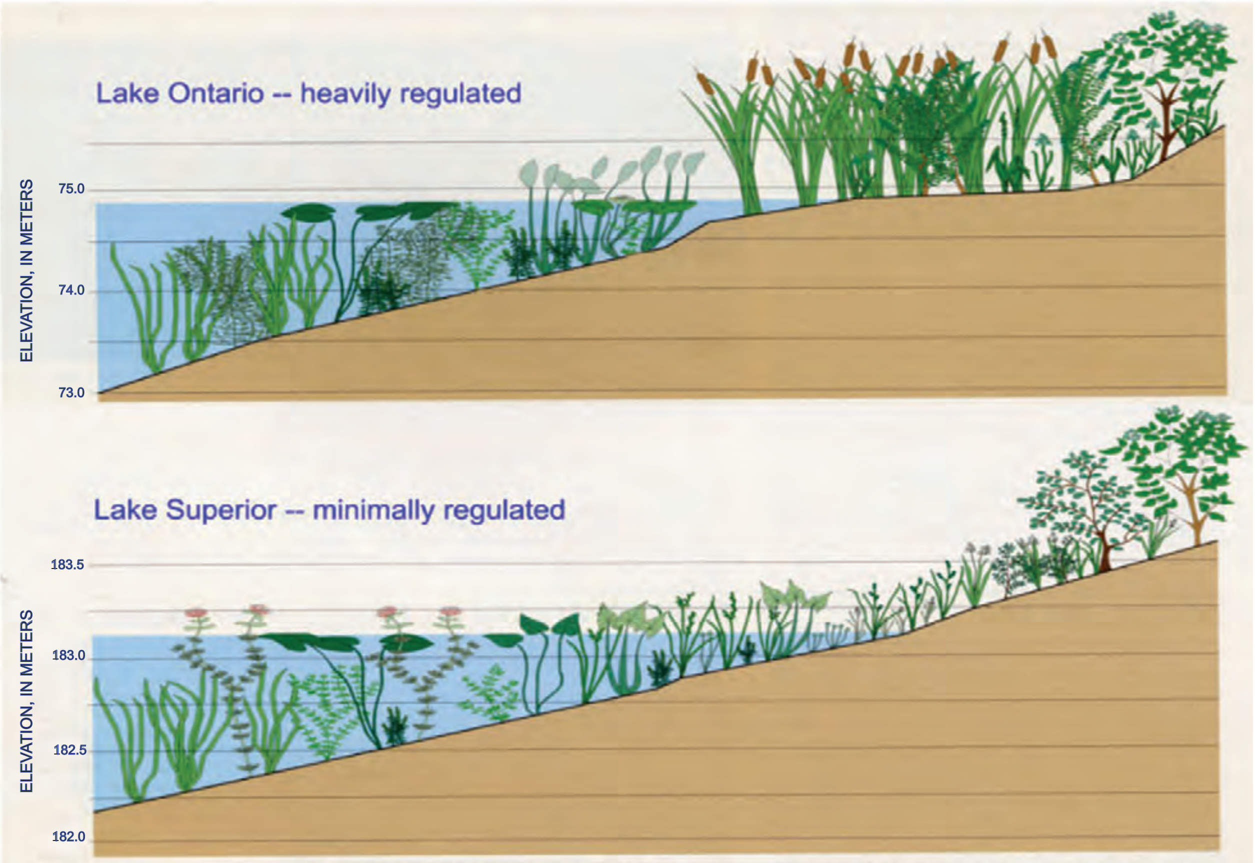


Figure 14. Schematic sections depicting the structural habitat provided by plant communities characteristic of regulated Lakes Ontario and Superior (modified from Wilcox and Meeker, 1995).

communities on Lake Superior have seemingly been prone to fewer problems than those on Lake Ontario (fig. 14), although further studies are needed to make that determination. The International Joint Commission has prepared a plan of study to review of the regulation plan for Lake Superior in the future.

In addition to having adverse effects on wetland plant communities, reduction of water-level fluctuations can affect wetland faunal communities (Wilcox and Meeker, 1992). Periodic high water levels (that is, levels above the historical long-term mean) increase fish access to spawning and nursery habitat in emergent vegetation and increase the hemi-marsh habitat preferred by waterfowl. Detrital plant materials are also colonized by invertebrates that are fed on by fish and waterfowl. Although periodic low water levels can jeopardize fish spawning and reduce waterfowl nesting area, they provide the opportunity for regeneration of the plant communities that are the foundation of the habitat.

Compression of the range of lake-level fluctuations does not reduce erosion—it simply focuses it within a narrower elevation range. A common response to the threat of erosion along the shoreline associated with water-level fluctuations in the Great Lakes is to construct **revetments**, groins, breakwalls, and other hard structures along the shore, with the added intent of reducing flooding (fig. 15). By disrupting natural erosion processes, these structures also reduce the supply of sediments that naturally nourishes the shoreline and replaces eroded sediments that are lost during storms (Silvester and Hsu, 1991). Barrier-beach wetlands may lose the protection of a barrier beach. Hard shoreline structures also shift wave energy further downshore and may locally accelerate erosion of beaches and wetlands elsewhere. When revetments are constructed along the gently sloping shore of a wetland, a “backstopping” effect can result (Wilcox and Whillans, 1999). Wave energy can scour sediments from in front of the revetment, leaving an abrupt boundary between upland and deep water and no migrating, sloping shoreline with the required water depths for various wetland plant communities. Although diking of wetlands is considered a solution to management problems under circumstances where protection from water-level change and wave action is required, dikes also create problems for wetlands (Wilcox and Whillans, 1999). Isolation from lake waters and the surrounding landscape results in elimination or reduction of many of the functional values of wetlands, including flood conveyance, flood storage, sediment control, and improvement of water quality.

Box 5. Human activities are also affected by water-level changes, and it is these activities that receive the most attention.

Freighter passing through the Soo Locks, the outlet of Lake Superior near Sault Ste. Marie, Michigan.

Moses Saunders Power Dam on the St. Lawrence River between Massena, New York, and Cornwall, Ontario.

Mouth of the Salmon River, a Lake Ontario drowned-river-mouth wetland near Pulaski, New York, showing housing development along the lakeshore and marina development along the river channel.

Figure 15. Armored shoreline on Lake Ontario that disrupts natural coastal processes and generally results in accelerated erosion.

Summary

In this report, we present recorded and reconstructed (pre-historical) changes in water levels in the Great Lakes, relate them to climate changes of the past, and highlight major water-availability implications for storage, coastal ecosystems, and human activities. “Water availability,” as conceptualized herein, includes a recognition that water must be available for human and natural uses, but the balancing of how much should be set aside for which use is not discussed.

The Great Lakes Basin covers a large area of North America. The lakes capture and store great volumes of water that are critical in maintaining human activities and natural ecosystems. Water enters the lakes mostly in the form of precipitation and streamflow. Although flow through the connecting channels is a primary output from the lakes, evaporation is also a major output. Water levels in the lakes vary naturally on timescales that range from hours to millennia; storage of water in the lakes changes at the seasonal to millennial scales in response to lake-level changes. Short-term changes result from storm surges and seiches and do not affect storage. Seasonal changes are driven by differences in net basin supply during the year related to snowmelt, precipitation, and evaporation. Annual to millennial changes are driven by subtle to major climatic changes affecting both precipitation (and resulting streamflow) and evaporation. Rebounding of the Earth’s surface in response to loss of the weight of melted glaciers has differentially affected water levels. Rebound rates have not been uniform across the basin, causing the hydrologic outlet of each lake to rise in elevation more rapidly than some parts of the coastlines. The result is a long-term change in lake level with respect to shoreline features that differs from site to site.

The reconstructed water-level history of Lake Michigan-Huron over the past 4,700 years shows three major high phases from 2,300 to 3,300, 1,100 to 2,000, and 0 to 800 years ago. Within that record is a quasi-periodic rise and fall of about 160 ± 40 years in duration and a shorter fluctuation of 32 ± 6 years that is superimposed on the 160-year fluctuation. Recorded lake-level history from 1860 to the present falls within the longer-term pattern and appears to be a single 160-year quasi-periodic fluctuation. Independent investigations of past climate change in the basin over the long-term period of record confirm that most of these changes in lake level were responses to climatically driven changes in water balance, including lake-level highstands commonly associated with cooler climatic conditions and lows with warm climate periods. The mechanisms underlying these large hydroclimatic anomalies are not clear, but they may be related to internal dynamics of the ocean-atmosphere system or dynamical responses of the ocean-atmosphere system to variability in solar radiation or volcanic activity.

The large capacities of the Great Lakes allow them to store great volumes of water. As calculated at chart datum, Lake Superior stores more water (2,900 mi^3) than all the other lakes combined (2,539 mi^3). Lake Michigan's storage is 1,180 mi^3; Lake Huron's, 850 mi^3; Lake Ontario's, 393 mi^3; and Lake Erie's, 116 mi^3. Seasonal lake-level changes alter storage by as much as 6 mi^3 in Lake Superior and as little as 2.1 mi^3 in Lake Erie. The extreme high and low lake levels measured in recorded lake-level history have altered storage by as much as 31 mi^3 in Lake Michigan-Huron and as little as 9 mi^3 in Lake Ontario. Diversions of water into and out of the lakes are very small compared to the total volume of water stored in the lakes.

The water level of Lake Superior has been regulated since about 1914 and levels of Lake Ontario since about 1960. The range of Lake Superior water-level fluctuations and storage has not been altered greatly by regulation. However, fluctuations on Lake Ontario have been reduced from 6.6 ft preregulation to 4.3 ft over the past three decades postregulation, and storage changes have been reduced from 9 mi^3 to 6 mi^3. Regulation affects shoreline property owners and industries that have structures in the flood-hazard zone; they generally desire lower lake levels. Higher lake levels are preferred by recreational boaters and marinas concerned about lake access in shallow areas, as well as by municipal and industrial water-supply facilities concerned about water-intake structures. The shipping industry and hydropower industry prefer increased flow through the connecting channels and lower St. Lawrence River.

Regulation of lake levels has created problems for wetlands of Lakes Superior and Ontario. Periodic high lake levels are needed to kill trees, shrubs, and canopy-dominating emergent plants in Great Lakes wetlands, and low water levels following the highs are needed to promote seed germination and growth of a multitude of species. Occasional low water levels are also needed to restrict growth of plants that require very wet conditions, such as cattails, at higher elevations in wetlands that are typically colonized by sedges and grasses. The diversity of wetland plant communities and the habitats they provide for fish and wildlife in Great Lakes wetlands are dependent on water-level fluctuations. The effects of regulation have been most severe in Lake Ontario, where the natural pattern of high and low lake levels has largely been eliminated. As a result, extensive stands of cattails have become established in nearly all wetlands in Lake Ontario, mostly at the expense of the sedge/grass community, and diversity of habitats has been reduced substantially.

References Cited

Adams, J.B., Mann, M.E., and Ammann, C.M., 2003, Proxy evidence for an El Niño-like response to volcanic forcing: Nature, v. 426, p. 274.

Anderton, J.B., and Loope, W.L., 1995, Buried soils in a perched dunefield as indicators of late Holocene lake level change in the Lake Superior basin: Quaternary Research, v. 44, p. 190–199.

Argyilan, E.P., Forman, S.L., Johnston, J.W., and Wilcox, D.A., 2005, Optically stimulated luminescence dating of late Holocene raised strandplain sequences adjacent to Lakes Michigan and Superior, Upper Peninsula, Michigan, USA: Quaternary Research, v. 63, p. 122–135.

Alley, W.M., Reilly, T.E., and Franke, O.L., 1999, Sustainability of ground-water resources: U.S. Geological Survey Circular 1186, 79 p.

Baedke, S.J., and Thompson, T.A., 2000, A 4,700-year record of lake level and isostasy for Lake Michigan: Journal of Great Lakes Research, v. 26, p. 416–426.

Baedke, S.J., Thompson, T.A., Johnston, J.W., and Wilcox, D.A., 2004, Reconstructing paleo lake levels from relict shorelines along the Upper Great Lakes: Aquatic Ecosystem Health and Management, v. 7, p. 435–449.

Booth, R.K., and Jackson, S.T., 2003, A high-resolution record of late-Holocene moisture variability from a Michigan raised bog, USA: Holocene, v. 13, p. 863–876.

Booth, R.K., Jackson, S.T., Forman, S.L., Kutzbach, J.E., Bettis, E.A., Kreig, J., and Wright, D.K., 2005, A severe centennial-scale drought in continental North America 4200 years ago and apparent global linkages: Holocene, v. 15, p. 321–328.

Booth, R.K., Jackson, S.T., and Gray, C.E.D., 2004, Paleoecology and high-resolution paleohydrology of a kettle peatland in upper Michigan: Quaternary Research, v. 61, p.1–13.

Booth, R.K., Jackson, S.T., and Thompson, T.A., 2002, Paleoecology of a northern Michigan lake and the relationship among climate, vegetation, and Great Lakes water levels: Quaternary Research, v. 57, p. 120–130.

Booth, R.K., Notaro, M., Jackson, S.T., and Kutzbach, J.E., 2006, Widespread drought episodes in the western Great Lakes region during the past 2000 years—Geographic extent and potential mechanisms: Earth and Planetary Science Letters, v. 242, issues 3–4, p. 415–427.

Burkett, V.R., Wilcox, D.A., Stottlemyer, R., Barrow, W., Fagre, D., Baron, J., Price, J., Nielsen, J.L., Allen, C.D., Peterson, D.L., Ruggerone, G., and Doyle, T., 2005, Nonlinear dynamics in ecosystem response to climatic change—Case studies and management implications: Ecological Complexity, v. 2, p. 357–394.

Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data, 1977, Coordinated Great Lakes physical data: Detroit, Mich., and Burlington, Ontario, 12 p.

Croley, T.E., II, Hunter, T.S., and Martin, S.K., 2001, Great Lakes monthly hydrologic data: NOAA Technical Report TM–083, 13 p.

Delworth, T.L., and Manabe, S., 1988, The influence of potential evaporation on the variabilities of simulated soil wetness and climate: Journal of Climate, v. 1, p. 523–547.

Environment Canada [Wilcox, D.A., Patterson, N., Thompson, T.A., Albert, D., Weeber, R., McCracken, J., Whillans, T., and Gannon, J., contributors], 2002, Where land meets water—Understanding wetlands of the Great Lakes: Toronto, Ontario, 72 p.

Fenneman, N.M. [in cooperation with the Physiographic Committee of the Geological Survey], 1946, Physical divisions of the United States: U.S. Geological Survey, scale 1:7,000,000.

Grannemann, N.G., and Weaver, T.L., 1999, An annotated bibliography of selected references on the estimated rates of direct ground-water discharge to the Great Lakes: U.S. Geological Survey Water-Resources Investigations Report 98–4039, 24 p.

Great Lakes Commission, 2003, Toward a water resources management decision support system for the Great Lakes-St. Lawrence River basin—Status of data and information on water resources, water use, and related ecological impacts: Ann Arbor, Mich., 142 p.

Holtschlag, D.J., and Nicholas, J.R., 1998, Indirect groundwater discharge to the Great Lakes: U.S. Geological Survey Open-File Report 98–579, 25 p.

Hudon, C., Wilcox, D.A., and Ingram, J.W., 2006, Modeling wetland plant community response to assess water-level regulation scenarios in the Lake Ontario-St. Lawrence River basin: Environmental Monitoring and Assessment, v. 113, no. 1–3, p. 303–328.

International Joint Commission, 2000, Protection of the waters of the Great Lakes—Final report to the governments of Canada and the United States: Ottawa, Ontario, 69 p.

Loope, W.L., and Arbogast, A.F., 2000, Dominance of a ~150-year cycle of sand-supply change in late Holocene dune-building along the eastern shore of Lake Michigan: Quaternary Research, v. 54, p. 414–422.

Loope, W.L., and McEachern, A.K., 1998, Habitat change in a perched dune system, *in* Mac, M.J., Opler, P.A., Puckett, C.E., Haecker, and Doran, P.D., eds., Status and trends of the Nation’s biological resources, volume 1: U.S. Geological Survey, p. 227–230.

Mainville, A., and Craymer, M.R., 2005, Present-day tilting of the Great Lakes region based on water level gauges: Geological Society of America Bulletin, v. 117, p. 1070–1080.

Manabe, S., Wetherald, R.T., Milly, P.C.D., Delworth, T.L., and Stouffer, R.J., 2004, Century-scale change in water availability—CO_2-quadrupling experiment: Climatic Change, v. 64, p. 59–76.

Maynard, L., and Wilcox, D.A., 1997, Coastal wetlands of the Great Lakes—State of the Lakes Ecosystem Conference 1996 background paper: Environment Canada and U.S. Environmental Protection Agency, EPA 905–R–97–015b, 99 p.

McCabe, G.J., Palecki, M.A., and Betancourt, J.L., 2004, Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States: Proceedings of the National Academy of Science, v. 101, p. 4136–4141.

Meehl, G.A., Washington, W.M., Wigley, T.M.L., Arblaster, J.M., and Dai, A., 2003, Solar and greenhouse forcing and climatic response in the twentieth century: Journal of Climate, v. 16, p. 426–444.

Neff, B.P., and Killian, J.R., 2003, The Great Lakes water balance—Data availability and annotated bibliography of selected references: U.S. Geological Survey Water-Resources Investigations Report 02–4296, 37 p.

Neff, B.P., and Nicholas, J.R., 2005, Uncertainty in the Great Lakes water balance: U.S. Geological Survey Scientific Investigations Report 2004–5100, 42 p.

Rickard, L.V., and Fisher, D.W., 1970, Geologic map of New York, Finger Lakes sheet: New York State Museum and Science Service Map and Chart Series, no. 15, scale 1:250,000.

Rind, D., Shindell, D., Perlwitz, J., Lerner, J., Lonergan, P., Lean, J., and McLinden, C., 2004, The relative importance of solar and anthropogenic forcing of climate change between the Maunder Minimum and the present: Journal of Climate, v. 17, p. 906–929.

Schubert, S.D., Suarez, M.J., Pegion, P.J., Koster, R.D., and Bacmeister, J.T., 2004, On the cause of the 1930s dust bowl: Science, v. 303, p. 1855–1859.

Shaver, R.H., regional coordinator, 1985, Midwestern basins and arches region, *in* Lindberg, F.A., ed., Correlation of stratigraphic units of North America: American Association of Petroleum Geologists, COSUNA Chart Series, 1 sheet.

Sheets, R.A., and Simonson, L.A., 2006, Compilation of regional ground-water divides for principal aquifers corresponding to the Great Lakes Basin, United States: U.S. Geological Survey Scientific Investigations Report 2006–5102, 23 p.

Silvester, R., and Hsu, J.R.C., 1991, New and old ideas in coastal sedimentation: Reviews in Aquatic Sciences, v. 4, p. 375-410.

Thompson, T.A., and Baedke, S.J., 1995, Beach-ridge development in Lake Michigan—Shoreline behavior in response to quasi-periodic lake-level events: Marine Geology, v. 129, p. 163–174.

Thompson, T.A., and Baedke, S.J., 1997, Strandplain evidence for late Holocene lake-level variations in Lake Michigan: Geological Society of America Bulletin, v. 109, p. 666–682.

Thompson, T.A., Baedke, S.J., and Johnston, J.W., 2004, Geomorphic expression of late Holocene lake levels and paleowinds in the upper Great Lakes, *in* Hansen, E.C., ed., The geology and geomorphology of Lake Michigan's coast: Michigan Academician, v. 35, p. 355–371.

U.S. Army Corps of Engineers and Great Lakes Commission, 1999, Living with the lakes: Detroit and Ann Arbor, Mich., 39 p.

Wilcox, D.A., 1995, The role of wetlands as nearshore habitat in Lake Huron, *in* Munawar, M., Edsall, T., and Leach, J., eds., The Lake Huron ecosystem—Ecology, fisheries and management: Amsterdam, SPB Academic Publishing, Ecovision World Monograph Series, p. 223–245.

Wilcox, D.A., Ingram, J.W., Kowalski, K.P., Meeker, J.E., Carlson, M.L., Xie, Y., Grabas, G.P., Holmes, K.L., and Patterson, N.J., 2005, Evaluation of water level regulation influences on Lake Ontario and Upper St. Lawrence River coastal wetland plant communities—Final project report: International Joint Commission, Ottawa, Ontario, and Washington, D.C., 67 p.

Wilcox, D.A., and Meeker, J.E., 1991, Disturbance effects on aquatic vegetation in regulated and non-regulated lakes in northern Minnesota: Canadian Journal of Botany, v. 69, p. 1542–1551.

Wilcox, D.A., and Meeker, J.E., 1992, Implications for faunal habitat related to altered macrophyte structure in regulated lakes in northern Minnesota: Wetlands, v. 12, p. 192–203.

Wilcox, D.A., and Meeker, J.E., 1995, Wetlands in regulated Great Lakes, *in* LaRoe, E.T., Farris, G.S., Puckett, C.E., Doran, P.D., and Mac, M.J., eds., Our living resources—A report to the Nation on the distribution, abundance, and health of U.S. plants, animals, and ecosystems: Washington, D.C., National Biological Service, p. 247–249.

Wilcox, D.A., and Whillans, T.H., 1999, Techniques for restoration of disturbed coastal wetlands of the Great Lakes: Wetlands, v. 19, p. 835–857.

Glossary

For purposes of this circular, the following terms and definitions apply. The definitions are not the only valid ones for these terms.

barrier beach Dune and beach deposits that occur as a shore-parallel topographic high with a landward standing body of water or wetland.

chart datum A reference point for water-level elevation where 95 percent of recorded/historical elevations are above the datum.

consumptive use That portion of water withdrawn or withheld from the Great Lakes Basin and assumed to be lost or otherwise not returned to the Great Lakes Basin because of evaporation, incorporation into products, or other processes.

crustal movement Vertical and horizontal displacement of the Earth's lithosphere.

detrital material Nonliving organic matter (for example, dead organisms or leaves) in water.

diversion A transfer of water from the Great Lakes Basin into another watershed, or from the watershed of one of the Great Lakes into that of another.

emergent Refers to those species that occur on saturated soils or on soils covered with water for most of the growing season. The foliage of emergent aquatics is partly or entirely borne above the water surface.

eolian Pertaining to the action or effects of wind.

glacial isostatic adjustment (GIA) Vertical crustal movement related to the removal of the weight of glaciers. (See box 1 in main text.)

ground water In the broadest sense, all subsurface water; more commonly, that part of the subsurface water in the saturated zone (the subsurface zone in which all openings are full of water).

hemi-marsh An area that is half vegetated and half open water.

highstand The uppermost topographic position or elevation reached by lake level during a specific period in time.

hydrograph A graph showing water level, flow rate, or some other property of water with respect to time.

hydrologic system A zone in three-dimensional space, with a boundary, that receives water and other inputs; stores, processes, and (or) transmits them; and releases them as outputs.

littoral Pertaining to the area of the coast affected by nearshore waves and currents.

macrophytes Plant species that can be observed without the use of optical magnification.

mainland-attached beaches Dune and beach deposits that occur as a shore-parallel topographic high with a landward upland.

meadow marsh Marsh that occurs in areas that are occasionally covered with water, dominated by grasslike plants and wildflowers.

Medieval Warm Period A warm interval lasting several centuries, beginning around 1,000 years ago and particularly well documented in Europe. Climate anomalies during this time period also have been documented in various other regions of the world.

net basin supply The net amount of water entering a Great Lake. Although scientists use various methods to calculate net basin supply, all methods subtract the amount of water leaving a Great Lake from the amount of water entering that Great Lake.

Nipissing Phase One or more high levels of the Great Lakes between 6,000 and 4,000 years ago. Nipissing lake levels were slightly more than 4 meters (13 feet) higher than historical levels.

paleoclimate The climate of a given period of time in the past.

palustrine Refers to inland wetland area.

peatland A wetland where the rate of biomass production exceeds the rate of decomposition, resulting in the accumulation of organic-rich sediment that contains the partially decomposed remains of plants and other organisms.

perched dunes Dunes that sit on a plateau high above the shore; they consist of sand as well as other loose material, and dramatically changing lake levels help to create them.

proxy record A reconstructed history of environmental changes based on the contents of a natural archive (for example, sediments, ice cores), typically using an indicator, measurement, or suite of measurements that are highly correlated with a particular environmental variable (for example, temperature).

quasi-periodic A repetitive behavior that is not uniform in period or amplitude.

revetment A facing of stone, concrete, or other durable material to protect an embankment or shore structure against erosion by wave action or currents.

seiche A stationary wave usually caused by strong winds and (or) changes in barometric pressure. It is found in lakes, semi-enclosed bodies of water, and areas of the open ocean.

spit Dune and beach deposits that occur as a shore-parallel topographic high that extend from a headland. These deposits commonly occur with a landward standing body of water or wetland and contain several or more beach ridges that recurve landward.

strandplain Shore-parallel ridges of sand commonly occurring in embayments along the lakes, forming a washboard pattern inland from the shore.

surficial geology The geology of material at or near the Earth’s surface; can include near-surface bedrock in addition to unconsolidated (loose) material deposited by the activity of streams, glaciers, and weathering.

swash zone The zone of wave action on the beach, which moves as water levels vary.

testate amoebae Amoeboid protozoa that produce decay-resistant and morphologically distinct outer shells and have been used as environmental and paleoenvironmental indicators of water-table depth in peatlands.

water balance An accounting of inflow to, outflow from, and storage in a hydrologic unit, such as the Great Lakes.

wave-cut terraces Erosional scarp and platform cut into bedrock or unconsolidated deposits.

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