Lake-Level Variability and Water Availability in the Great Lakes

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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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[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 ft³/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 ft³/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).

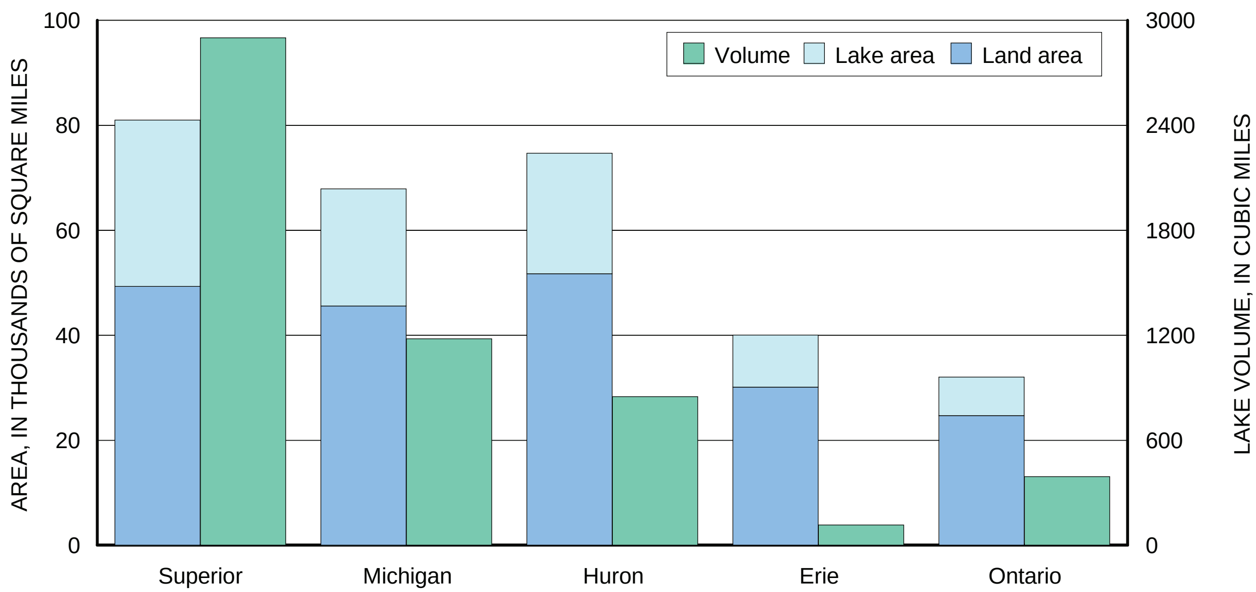

Figure 2. Volume and land and lake area for each of the Great Lakes (modified from Great Lakes Commission, 2003).

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.

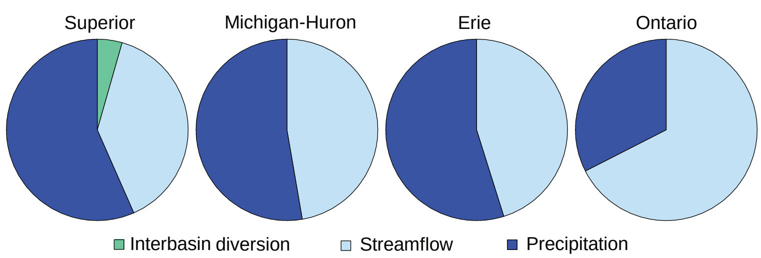

Figure 3. Water inflow to the lakes (modified from Great Lakes Commission, 2003).

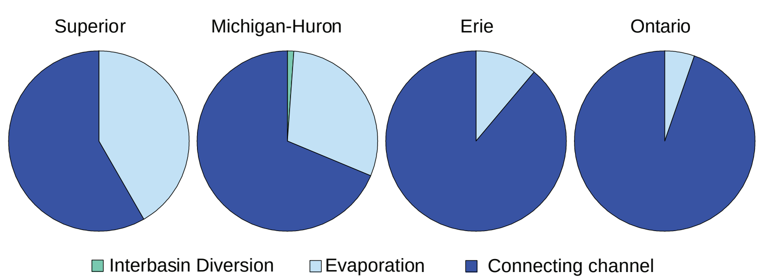

Figure 4. Water outflow from the lakes (modified from Great Lakes Commission, 2003).

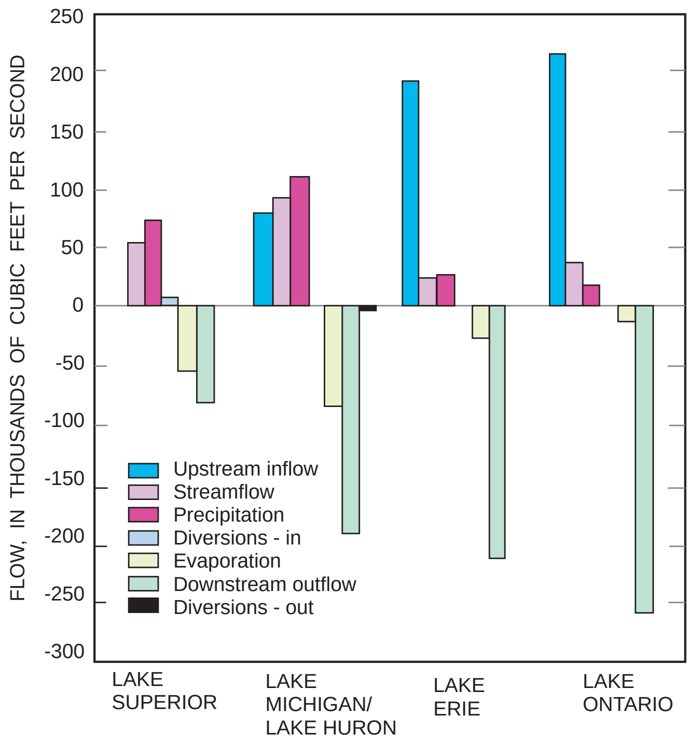

Figure 5. Water balance for the Great Lakes, including types of input to and output from the lakes (from Neff and Nicholas, 2005).

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,