Chapter Two

Status Assessment of Great Lakes-St. Lawrence River Water Resources

Introduction

In June 2001, the governors and premiers of the eight Great Lakes states and two provinces signed an Annex to the 1985 Great Lakes Charter. The Annex calls for, among other items, hydrologic data and information to support a new decision standard regarding proposals to withdraw water from the Great Lakes-St. Lawrence River basin. No current monitoring networks are designed with the specific purpose of providing this decision support.

Great Lakes levels and flows are monitored by many federal, state and provincial agencies, and are done for a number of purposes, including floods, droughts, transportation, and regulatory issues. Monitoring is typically long-term and at the core of agency missions.

This chapter, a product of Project Element Two (Status Assessment of Water Resources), summarizes Great Lakes-St. Lawrence River system hydrology and explains how levels and flows are measured, discusses uncertainty in measurements of levels and flows, and recommends improvements to current monitoring that will provide support for decisionmaking under Annex 2001. More detailed information is available from two other project reports*: The Great Lakes Water Balance: Data Availability and Annotated Bibliography of Selected References* (Neff and Killian, 2003) and Uncertainty in the Great Lakes Water Balance (Neff et al., publication pending). Specific information on flows from 1948 to 1998 can be found in Croley et al. (2001).

This decision support system project was proposed and initiated prior to the signing of the Annex in June 2001. Most of the work on Project Element Two was designed to evaluate the extent, content and accuracy of water resources data and information on a lake-wide or systemwide scale. Publications resulting from Project Element Two focused on levels and flows in the context of net basin supplies to each Great Lake. This chapter builds upon that work and also evaluates water resources data and information in the context of Annex 2001. Emphasis is placed on relating the magnitude of uncertainties associated with levels and flows within the Great Lakes-St. Lawrence River system to those uncertainties associated with cumulative withdrawals and their effects. This status assessment does not address hydrologic conditions beyond the international reach of the St. Lawrence River, even though impacts can occur downstream.

Physical Setting

The Great Lakes-St. Lawrence River system is comprised of: 1) Lakes Superior, Michigan, Huron, Erie and Ontario; 2) their connecting channels, the St. Marys River, St. Clair River, Lake St. Clair, Detroit River and Niagara River; and 3) the St. Lawrence River, which carries the waters of the Great Lakes to the Atlantic Ocean. The system also includes several man-made canals and control structures that either interconnect the 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/Massena, New York, covers about 302,000 square miles (782,000 square kilometers). It includes parts of eight states and one province: Minnesota, Wisconsin, Illinois, Indiana, Michigan, Ohio, Pennsylvania, New York and Ontario. Fifty-nine percent of the surface area of the Great Lakes basin is in the United States; 41 percent is in Canada. The Great Lakes basin is about 700 miles (1,100 kilometers) long measured north to south and about 900 miles (1,500 kilometers) long measured west to east, at the outlet of Lake Ontario at Cornwall, Ontario/Massena, New York. The St. Lawrence River below Cornwall, Ontario/Massena, New York is about 540 miles (870 kilometers) long and flows through the provinces of Ontario and Québec.

Surface and groundwater flows are significantly affected by the surficial geology and topography of the Great Lakes basin, which is variable. Pre-Cambrian metamorphic and igneous rocks surround most of Lake Superior and northern Lake Huron, in what is known as the Pre-Cambrian Shield physiographic region. This area is very rocky and has little or no overburden. The remainder of the Great Lakes basin is in the Central Lowlands physiographic region and is covered mostly by unconsolidated deposits from glaciers and glacial meltwater. Thickness of the glacial deposits ranges from less than one foot to more than 1000 feet (0.3 to 300 meters). The topography in the Central Lowlands is generally flat and rolling.

In 1990, the population of the Great Lakes basin was about 33 million. About 52 percent of the Great Lakes basin is forested; 35 percent is in agricultural uses; 7 percent is urban/suburban; and 6 percent is in other uses. Major industries in the Great Lakes basin include manufacturing, tourism, and agriculture, valued at about $308 billion, $82 billion, and $48 billion (U.S.) per year, respectively.

Hydrologic Setting

The Great Lakes-St. Lawrence River hydrologic system is complex and highly dynamic. The Lake Superior basin is at the upstream end of the Great Lakes-St. Lawrence River system. Lake Superior discharges into Lake Huron by way of the St. Marys River. The St. Marys River has a long-term average flow of 76,000 cubic feet per second (cfs) (2,150 cubic meters per second (cms)). Lake Superior outflows have been as high as 132,000 cfs (3,740 cms) and as low as 41,000 cfs (1,160 cms) per month. Lakes Huron and Michigan are usually considered as one lake hydraulically, due to their 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 through the Niagara River. A small portion of water from Lake Erie also reaches Lake Ontario by way of the Welland Canal and the DeCew Falls power plant tailrace. Lake Ontario discharges to the St. Lawrence River, which has a long-term average flow of about 242,000 cfs (6,870 cms) at Cornwall, Ontario/Massena, New York. Lake Ontario outflows have been as high as 350,000 cfs (9,910 cms) and as low as 154,000 cfs (4,360 cms).

Dredging, control structures, locks, dams, hydroelectric facilities, canals and diversions have altered the hydrology of the Great Lakes-St. Lawrence River system. Of these, dredging and outflow control have been the most significant. Dredging has had a major permanent impact on water levels on the middle Great Lakes. Dredging in the St. Clair and Detroit rivers began as early as 1855. Further improvements were made incrementally to deepen these navigation channels, with major dredging projects occurring in the 1930s and 1960s. In addition, sand mining occurred in the St. Clair River from 1909 through 1926 to support local manufacturing. From 1880 to 1965, dredging and/or sand mining in the St. Clair River caused a permanent lowering of Lake Michigan-Huron by about 14 inches (35 centimeters).

Outflow 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. The outflow from Lake Superior has been affected by human modifications beginning in 1822, with subsequent expansions occurring over time. The current outflow control structures have been in place since 1921. Outflows are adjusted monthly under the direction of the International Joint Commission (IJC) with an objective of maintaining the water levels on lakes Superior and Michigan-Huron in relative balance to their long-term seasonal averages. The St. Lawrence Seaway and Power Project, opened in 1960, incorporates outflow control structures to regulate Lake Ontario water levels, maintain hydropower operations, provide adequate depths for commercial navigation, and protect the lower St. Lawrence River from flooding.

The surface area of the Great Lakes, their connecting channels and the St. Lawrence River cover approximately 32 percent of the entire Great Lakes-St. Lawrence River basin above Cornwall, Ontario/Massena, New York. Figure 2-1 provides 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 square miles (210,000 square kilometers). The surface area of Lake Superior itself is 31,700 square miles (82,100

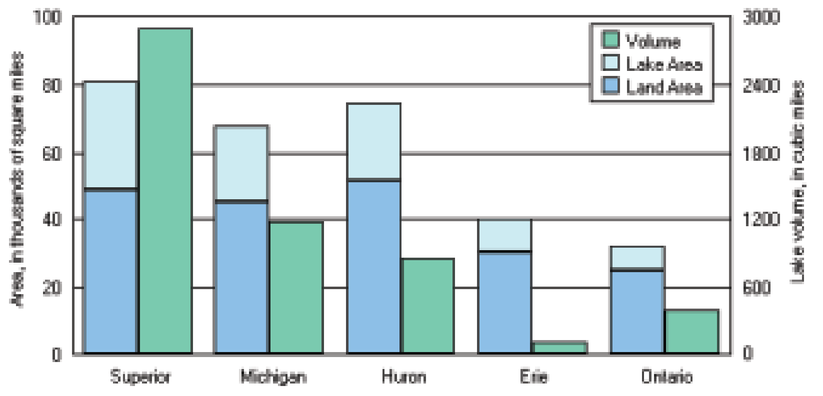

Figure 2-1
Volumes and areas of the Great Lakes

square kilometers), or 39 percent of its entire basin area. In contrast, the surface area of Lake Ontario, 7,340 square miles (18,960 square kilometers), is only 23 percent of the Lake Ontario basin.

Clearly, the proportion of a lake's basin area that is lake surface area directly affects the amount and timing of water that comes into a lake as precipitation directly on the lake's surface and as runoff from its tributary streams. It also affects the amount of water lost through evaporation from its surface.

The Great Lakes basin climate varies widely due to its 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° Fahrenheit (-19° Celsius) in the north to 28° Fahrenheit (-2° Celsius) in the south, and the mean July temperature ranges from 64° Fahrenheit (18° Celsius) in the north to 74° Fahrenheit (23° Celsius) in the south. Precipitation is distributed relatively uniformly throughout the year, but does have variability west to east across the Great Lakes basin, ranging from a mean annual precipitation of 28 inches (71 centimeters) north of Lake Superior to 52 inches (132 centimeters) 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 each lake. For instance, in the southern areas of the Great Lakes basin, annual snowfall is about 20 inches (51 centimeters) whereas, in snowbelt areas downwind of lakes Superior and Ontario, snowfall can be as high as 140 inches (355 centimeters). 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 on the Great Lakes in nearshore areas due to temperature differences between the lakes and the air moving over them.

Fluctuations in Great Lakes water levels are the result of several natural factors and may also be influenced by human activities. These factors operate on a time scale that varies from hours to years. The levels of the Great Lakes depend on their storage capacity, outflow characteristics of the outlet channels, operating procedures of the regulatory structures, and the amount of water supply received by each lake. The primary natural factors affecting lake levels include precipitation on the lakes, run-off from the drainage basin, evaporation from the lake surface, inflow from upstream lakes, and outflow to the downstream lakes. Man-made factors include diversions into or out of the Great Lakes basin, consumption of water, dredging of outlet channels and regulation of outflows.

Three types of water-level fluctuations occur on the Great Lakes. Long-term (or multi-year) fluctuations result from persistent low or high water supplies. Seasonal (one-year) fluctuations of the Great Lakes levels reflect the annual hydrologic cycle, which is characterized by higher net basin supplies during the spring and early summer, and lower net basin supplies during the remainder of the year. Short-term fluctuations (lasting from less than an hour to several days) occur as water levels set-up (rise) or set-down (fall) due to wind and barometric pressure differences over the lake surface. Set-up is also referred to as storm surge. While all of the Great Lakes are affected by these meteorologic-induced phenomena, Lake Erie is particularly prone to major set-up/set-down events, occasionally causing major water level differences between Buffalo, New York, and Monroe, Michigan, of 12 feet (3.6 meters) or more. Such large events are almost always followed by seiches that can disturb water levels for two to three days. A seiche is the free oscillation of water in a closed or semi-closed basin; it is frequently observed in harbors, bays, lakes, and in almost any distinct basin of moderate size. Wind generated waves are superimposed on all three categories of water-level fluctuations.

Short-term changes in outflows can occur as a result of storm surge or seiches. If water levels increase at the outlet end of the lake, outflows can temporarily increase. Conversely, if levels decline at the outlet end of the lake, outflows will be reduced. The Detroit River descends nearly 3.0 feet (0.9 meters) in the 32 miles (51 kilometers) that it flows from Lake St. Clair to Lake Erie. This makes flows through the Detroit River particularly sensitive to wind set-up and seiche on Lake Erie. During times of wind set-up at the west end of Lake Erie, the flow in the Detroit River slows dramatically. Researchers from the National Oceanic and Atmospheric Administration (NOAA), Great Lakes Environmental Research Laboratory have documented short-term flow reversals under wind set-ups at the western end of Lake Erie.

The flows in the outlet rivers of the lakes during the winter are often constrained by ice formation and occasionally by ice jamming, with the St. Clair and Detroit rivers being most affected. Ice booms deployed upstream of the Niagara River and throughout the St. Lawrence River help stabilize ice cover in these rivers, reducing ice retardation most of the time. Ice conditions are a consequence of prevailing climate conditions, and their severity and exact timing are not predictable for any specific winter. Plant growth in the rivers during the summer also creates flow retardation, and varies from river to river. Plant growth is also variable from year to year, since it is affected by changes in water temperatures.

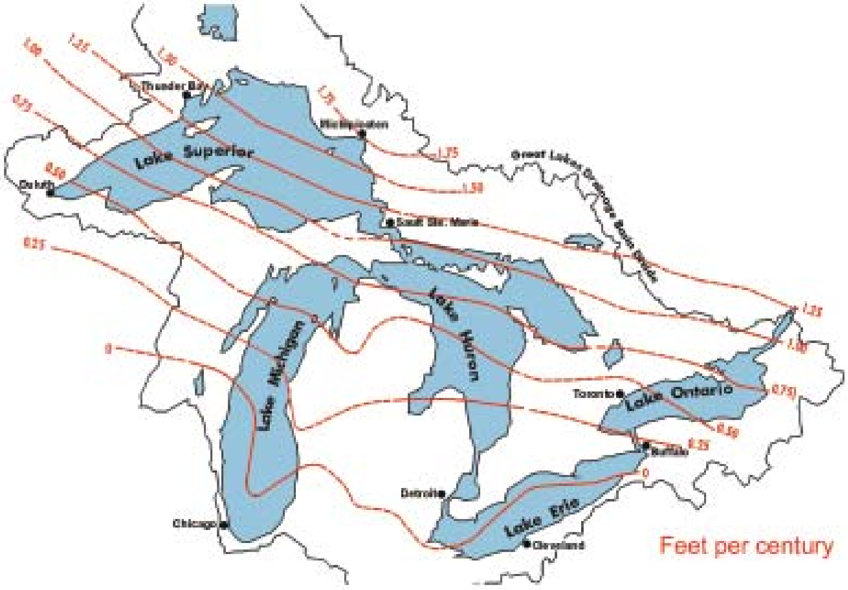

Figure 2-2.
Rates of isostatic rebound

Over time, water levels throughout the Great Lakes are affected by isostatic rebound, often referred to as crustal movement. Isostatic rebound is the gradual rising of the earth's crust from the removal of the weight of the glaciers that covered the Great Lakes-St. Lawrence River region during the last ice age. The phenomenon of crustal movement was recognized as early as 1869 (Clark and Persoage, 1970). The rate of movement is not uniform throughout the region and results in differential rates of change between specific sites, as shown in Figure 2-2 (USACE and GLC 1999). Generally, the rates around lakes Superior and Ontario are greater than those around lakes Michigan-Huron and Erie.

The effects on water levels of differential crustal movement can be visualized if the lakes are considered to be basins that are tilting by a gradual rising of their northeastern rims. Generally, water depths along the southern or western shores relative to the lake's outlet are increasing for a given average lake level as time goes by, while levels along the northern or eastern shores are becoming shallower. On Lake Superior, for example, the axis of mean crustal movement runs from the international border south of Thunder Bay, Ontario, through the lake's outlet at Sault Ste. Marie, Michigan and Ontario. The average land-to-water relationship around the lake remains unaffected by crustal movement under stable natural outlet conditions, but water depths recorded along its shorelines either increase or decrease depending on their location relative to this axis of movement. This discussion is important to the implementation of the Charter Annex because reductions of water levels caused by cumulative withdrawals in one location could be offset or exacerbated by local effects of differential crustal rebound. An example of this situation would be the Cootes Paradise wetland complex on the western end of Lake Ontario. A theoretical 4-inch (10 centimeter) drop in water levels in this area over a 35-year period caused by cumulative withdrawals would be completely offset by an increase in depth of the same magnitude caused by differential crustal rebound.

Levels and Flows

Water levels of the Great Lakes, and flows into and out of the lakes, are measured or calculated at hundreds of locations throughout the Great Lakes basin. Although lake levels are measured directly, most flows are based on estimates or measurements of other parameters and are calculated using simple models. Many agencies conduct the continuous and long-term monitoring necessary for maintaining a current understanding of the Great Lakes-St. Lawrence River system. Funding sources for monitoring are diverse, ranging from federal governments to state, provincial and municipal agencies, and the private sector. For instance, in Canada, the national streamflow-gauging network is funded and operated under cost sharing agreements between the Canadian federal government and the individual provinces and territories. Additional gauges are funded and operated by agencies such as power entities, municipalities and other federal departments. The U.S. streamflow-gauging network has more than 100 different sources of funding. The monitoring is continuous and long-term because levels and flows are highly variable temporally and spatially. Variations in levels and flows can significantly affect navigation, hydroelectric power generation, drinking water intakes, shoreline erosion, and other uses and conditions of the waters of the Great Lakes-St. Lawrence River system.

Levels

The water levels of the Great Lakes and connecting channels are measured for numerous 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 lake.

Water levels are measured or gauged at over 100 locations along the shore on the Great Lakes and their connecting channels by NOAA and the U.S. Army Corps of Engineers (USACE) in the United States and by Fisheries and Oceans Canada (DFO). NOAA operates 50 permanent and several seasonal water level gauges along the Great Lakes shoreline, the connecting channels and the St. Lawrence River. The USACE operates 17 water level gauges on the St. Marys, St. Clair, Detroit and Niagara rivers. Similarly, DFO operates 34 permanent water level gauges on the Canadian side of the border as part of its national network. Water levels at both U.S. and Canadian gauges are measured and reported to the nearest millimeter, although the sampling methods used by each agency differ. Daily average levels calculated by each agency, however, are considered equivalent for calculation purposes. Water level data recorded by NOAA, USACE and DFO at their respective gauge stations are available from these agencies via the Internet. Power entities and others operate additional gauges, principally on the Niagara and St. Lawrence rivers, to meet their specific needs.

Great Lakes levels are expressed in two ways, either as: 1) an elevation above sea level or; 2)as an amount above or below Chart Datum on the lake or connecting channel where the gauge is located. Great Lakes water levels are currently referenced to the International Great Lakes Datum of 1985 (IGLD85). The impact of differential crustal movement on Great Lakes water levels requires that this datum be updated every 30 to 35 years. IGLD85 is the second internationally coordinated Great Lakes datum, replacing IGLD55. The IGLD is updated by the Vertical Control-Water Levels Subcommittee of the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data.

The USACE and Environment Canada calculate and report lake-wide daily and monthly mean levels for each of the Great Lakes under the auspices of the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data. The lake-wide average water levels are calculated from selected NOAA and DFO water level gauges on each lake, which account for short-term water level disturbances and long-term effects of differential crustal movement. The level of lakes Michigan and Huron are reported as a single number due to their hydraulic connection. The daily and monthly lake-wide average levels are reported to the nearest centimeter, which is considered adequate for operational and public information purposes. Information on how to find and obtain lake level data is provided by Neff and Killian (2003).

Flows

Flows into and out of the Great Lakes include tributary streamflow (also referred to as basin runoff), groundwater, precipitation, evaporation, connecting channel and St. Lawrence River flows, diversions and consumptive uses. Consumptive uses are a very small percentage of the total flows and are discussed in Chapter three. Figure 2-3 shows

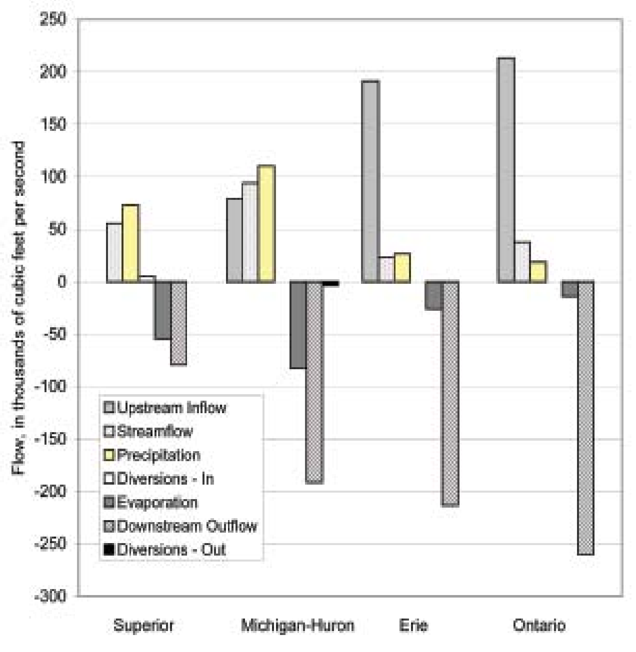

Figure 2-3
Flows into and out of the Great Lakes

the magnitude of each hydrologic component for each of the lakes.

Streamflow

Streamflow is a large part of each Great Lake's inflow, but the percentage varies from one lake to the next. Figure 2-4 depicts the relative role of streamflow for each lake. Excluding inflows from connecting channels, which are discussed separately, streamflow is 46 percent of the inflow to Lake Michigan-Huron and 67 percent of the inflow to Lake Ontario. This variability is primarily a function of the land-to-lake surface ratio in each lake basin.

Figure 2-4
Inflows to the Great Lakes (excluding connecting channel inflows)

Tributary streamflow is measured or gauged at several hundred locations throughout the Great Lakes basin. Gauged areas account for about 60 percent of the land area of the Great Lakes watershed. Streamflow in most gauged watersheds is calculated from continuous measurements of water level (or stage) and used to model a stage-discharge relationship. The relationship of stage to discharge is periodically checked and updated by direct measurements of discharge at gauging locations. A few gauging locations are not suitable for generation of a stage-discharge relationship and, at these locations, other types of measurements or models are employed.

Streamflow from ungauged areas is not typically calculated by monitoring agencies. However, NOAA does regularly calculate monthly mean streamflow from ungauged areas for calculations of net basin supply. These calculations use a simple procedure that relates ungauged streamflow to streamflow-drainage area ratios in nearby gauged watersheds.

Historical and current streamflow data can be obtained from agencies that collect, publish and archive the data. The two principal sources of data are the U.S. Geological Survey (USGS) and Environment Canada. Information on how to find and obtain streamflow data is provided by Neff and Killian (2003).

Groundwater

The amount of groundwater that discharges directly into the Great Lakes, their connecting channels and the St. Lawrence River is small relative to other flows into the Great Lakes and is not measured. For these reasons, direct groundwater 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 Neff and Killian (2003). Locally, direct groundwater discharge to the Great Lakes may be important to aquatic ecosystems. However, a literature search did not yield information on the relation of groundwater to aquatic ecosystems in the Great Lakes proper, their connecting channels or the St. Lawrence River.

Groundwater also discharges to the Great Lakes, their connecting channels and the St. Lawrence River indirectly by way of tributary streams. From the perspective of long-term water-balance calculations for the Great Lakes proper, this indirect groundwater discharge can be ignored because it is a part of streamflow computations. From a water management perspective, however, indirect groundwater discharge must be calculated because it supports instream ecosystems by maintaining base flows and moderating water temperatures. It also allows for computation of allowable point discharges during periods of low flow. In some cases, groundwater discharge may be a significant source of nonpoint source pollution in streams.

In much of the Great Lakes basin, indirect groundwater discharge is a large percentage of the total amount of streamflow, as shown in Figure 2-5. The percentage of streamflow attributable to groundwater is typically calculated by use of long-term streamflow records and application of baseflow-separation models. However, these calculations are reliable only in areas where human factors such as flow regulation and wastewater discharge are minimal. Binational efforts are currently underway to expand, and improve upon, earlier calculations by Holtschlag and Nicholas (1998).

Each aquifer that contributes groundwater to the Great Lakes or their tributary streams has a "potentiometric surface," which is a measure of the static head of groundwater in an encased well. This potentiometric surface is similar to the earth's surface in that it has groundwater divides that are analogous to surface watershed divides. Unlike surface water divides, groundwater divides are not static and may vary in response to groundwater withdrawals. Groundwater on one side of the divide flows toward the Great Lakes; groundwater on the other side flows away from the Great Lakes. Only a part of the Great Lakes region and only some of the aquifers have mapped potentiometric surfaces and groundwater divides. In the remainder of the region, the area that contributes groundwater to the Great Lakes is unknown.

Precipitation

Precipitation directly on the Great Lakes basin is a large part of each Great Lake's inflow as shown in Figure 2-4. The percentage varies from one lake to another, and is largely a function of the land-to-lake surface ratio in each lake basin.

Precipitation is measured or gauged at hundreds of locations in the Great Lakes basin. All of these gauges are on land; precipitation over the lake surface is calculated by interpolation of data from these gauges. Modern radar technologies are deployed in the United States and Canada to calculate precipitation over land masses. These systems have the potential for estimating precipitation over lake surfaces as well but, heretofore, have not been exploited for this application.

Historical and current precipitation data from gauges can be obtained from agencies that collect, publish and archive the data. The two principal sources of data are the National Climate Data Center, in the United States and the National Archives and Data Management Branch, Atmospheric Monitoring and Water Survey Directorate, Meteorological Service of Canada. Historical monthly over-lake precipitation calculations for each lake are available in Croley et al. (2001). Information regarding how to find and obtain precipitation data is discussed by Neff and Killian (2003).

Evaporation

Evaporation from the surface of the Great Lakes is a large part of each Great Lake's outflow as shown in Figure 2-6. The percentage varies from one lake to another depending primarily upon the area of the lake surface as compared to the area of the watershed draining to the lake. Much of the seasonal decline the lakes experience each fall and early winter is due to the increase in evaporation from their surfaces when cool, dry air passes over the relatively warm water of the lakes.

Evaporation is not measured directly; it is calculated using a computer model developed by Croley (1989). Most parameters used to calculate evaporation (e.g., air temperature, wind speed, relative humidity) are measured at on-shore locations. Since the early 1990s, satellite imagery and other remote sensing techniques have been used to calculate surface water temperatures. Historical monthly evaporation calculations for each lake are available in Croley et al. (2001).

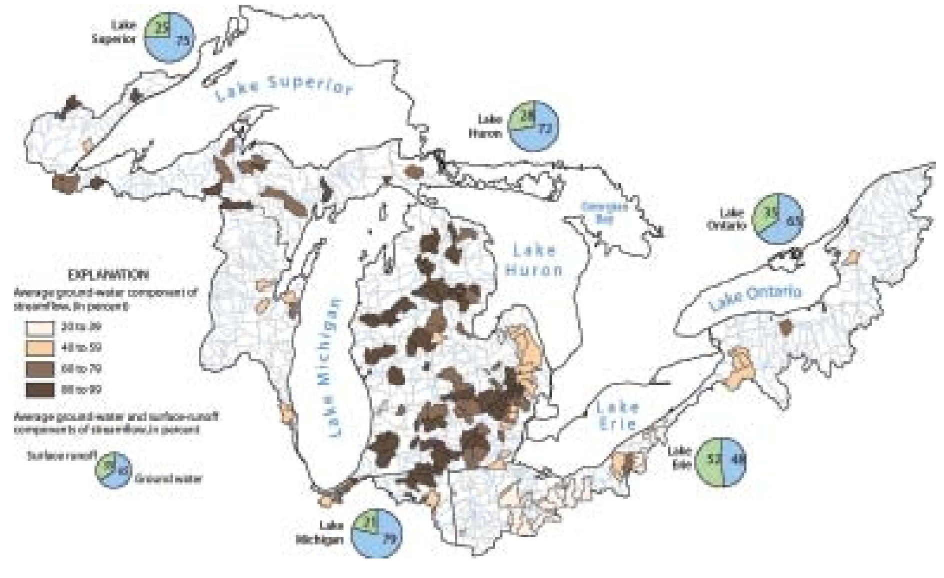

Figure 2-5
Average groundwater and surface-runoff components of streamflow in the United States portion of the Great Lakes basin

Connecting Channels and the St. Lawrence River

Connecting channel flows are a large part of each Great Lake's outflow. The percentage increases downstream through the Great Lakes as shown in Figure 2-6. Increased discharges are due to the additional overland and over-lake water supplies to the immediate upstream lake.

Flows in all of the connecting channels and the St. Lawrence

River have been altered by human activities since 1855. Some of these flow modifications have not been compensated for, effectively causing a permanent change in hydraulic conditions (higher or lower water levels) upstream of their locations. Major hydraulic regime changes occurred throughout the system when the navigation channels were deepened to 25 feet in 1933-1936 and to 27 feet in 1960-1962.

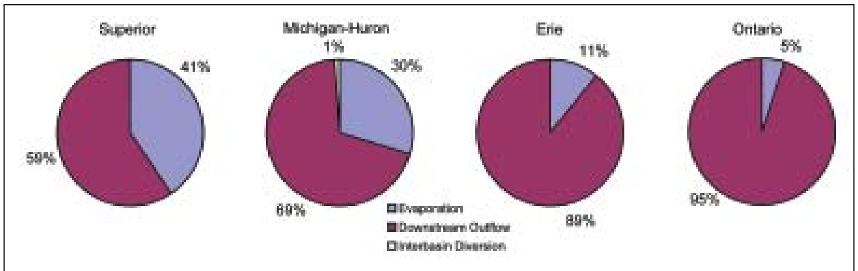

Figure 2-6.
Outflows from the Great Lakes (Note: Intrabasin diversions are included in outflows)

Connecting channel and St. Lawrence River flows are measured or calculated using a variety of methods specific to each. Flows in the St. Marys River, Niagara River and St. Lawrence River are calculated as the sum of flows through power plants, selected river sections, shipping locks, and other structures. A stage-discharge relationship is also available for the upper Niagara River that is used for operational and modeling purposes. Flows in the St. Clair and Detroit rivers are calculated from measurements of stage using a set of stage-fall-discharge relationships. These relationships accommodate the range of vegetative growth and ice conditions that can occur in the St. Clair-Detroit rivers system. Periodic discharge measurements are used to verify and update stage-fall-discharge relations and power plant or control structure rating curves.

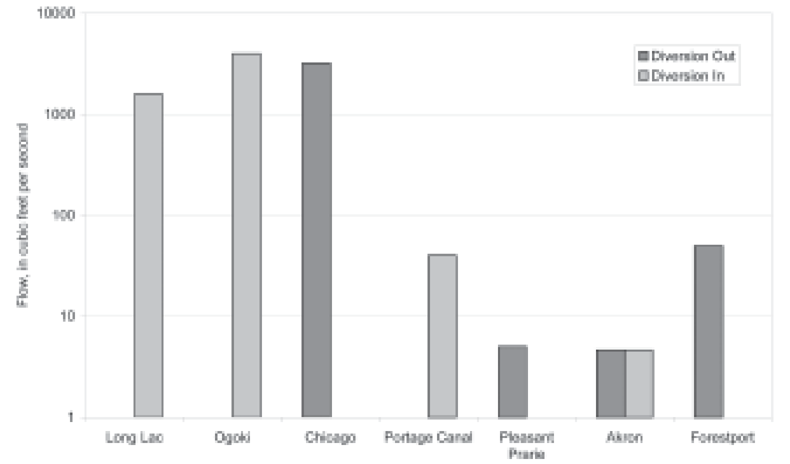

Figure 2-7
Interbasin diversions (logarithmic scale)

Historical connecting channel flows can be obtained from the agencies that collect, publish and archive the data. The Hydraulic Subcommittee of the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data regularly meets to discuss and agree upon binationally accepted flow values. Binationally coordinated data from this subcommittee are calculated and published, typically in response to a reference from the IJC.

Information regarding how to find and obtain connecting channel flow data is discussed by Neff and Killian (2003).

Diversions

Diversions account for only a small portion of total Great Lakes flows. Diversions are either interbasin, transferring water into or out of the Great Lakes basin, or intrabasin, transferring water from one Great Lake to another.

There are three major and five minor interbasin diversions, listed in Figure 2-7, which uses a logarithmic scale so that diversions of different orders of magnitude can be compared. The Long Lac and Ogoki diversions are major diversions that transfer water from the Hudson Bay watershed to Lake Superior. The Lake Michigan Diversion at Chicago, Illinois, is a major diversion that transfers water from Lake Michigan to the Illinois River watershed. Minor interbasin diversions are Forestport, New York (out of Lake Ontario), Portage Canal, Indiana (into Lake Michigan), Pleasant Prairie, Wisconsin (out of Lake Michigan), Ohio & Erie Canal (into Lake Erie) and Akron, Ohio (out of and into Lake Erie).

Some intrabasin diversions – the Welland Canal, the New York State Barge Canal and the Raisin River Diversion – are measured and accounted for as part of the outflow of their respective Great Lake. The remaining intrabasin diversions – Detroit, London and Haldimand – are generally ignored in water-balance computations because they are relatively small compared to other flows as shown in Figure 2-8, which also uses a logarithmic scale.

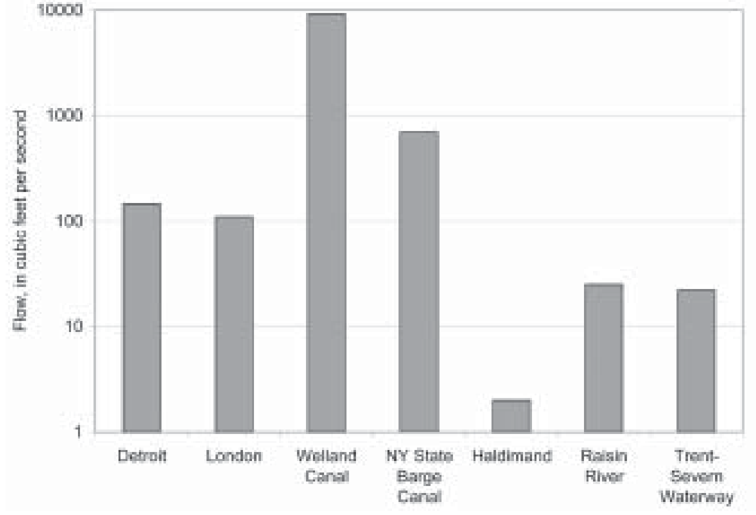

Figure 2-8
Intrabasin diversions (logarithmic scale)

Diversions are measured or calculated using a variety of methods specific to each diversion. Information on how to find and obtain flow data for diversions is provided by Neff and Killian (2003).

Variability of Levels and Flows

Levels and flows in the Great Lakes basin are highly variable, suggesting the need for continuous, long-term monitoring. Factors affecting levels and flows are variations in climate, diversions and outflow regulation. Variation in climate, both temporal and spatial, is the major factor affecting levels and flows, dwarfing the other two factors.

Long-term variability in water levels results from persistent low or high water supplies. Such variability caused extremely low levels on some lakes in 1926, the mid-1930s and mid-1960s, and extremely high levels in years such as 1952, 1973, 1985-86 and 1997. The intervals between periods of high and low levels, and the length of such periods, can vary widely over a number of years and only some of the lakes may be affected. The ranges of levels on lakes Michigan-Huron, Erie and Ontario reflect not only the fluctuation in supplies from their own basins, but also the fluctuations of the inflow from upstream lakes.

The historical record for levels of Lake Superior from 1860-1999 is shown in Figure 2-9. This plot demonstrates the long-term variability of water levels primarily affected by climate variability. Lake levels derived from the geologic record over the last five thousand years indicate that levels can be more variable than those of the past 140 years of historical record.

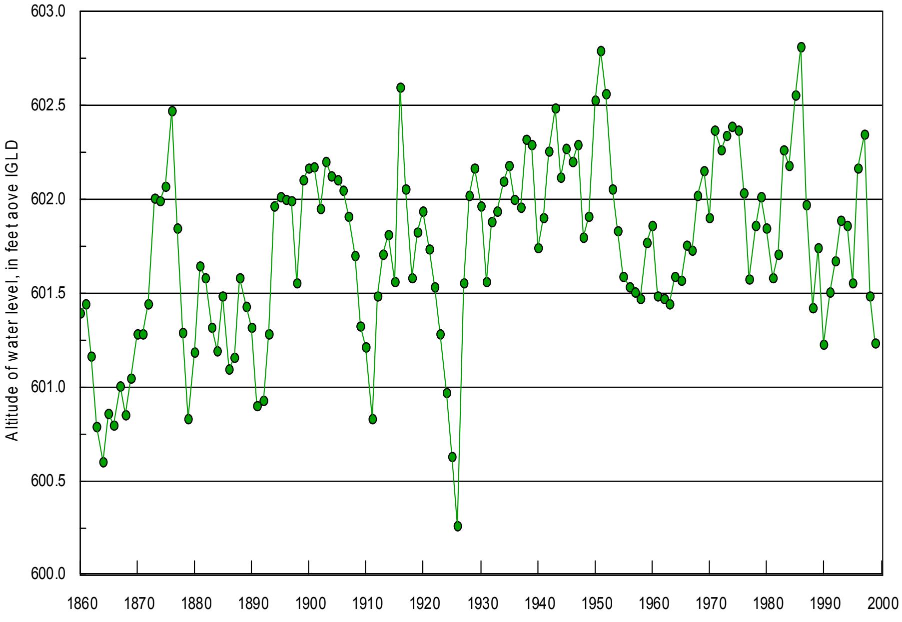

Figure 2-9
Lake Superior water level, 1860-1999

Seasonal variability in water levels reflects the annual hydrologic cycle, which is characterized by higher net basin supplies during the spring and early summer and lower net basin supplies during the remainder of the year. The maximum lake level usually occurs in June on lakes Ontario and Erie, in July on Lake Michigan-Huron, and in August on Lake Superior. The minimum 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 seasonal fluctuations are relatively small, averaging about 1.3 feet (0.4 meters) on lakes Superior, Michigan and Huron, about 1.6 feet (0.5 meters) on Lake Erie, and about 2.0 feet (0.6 meters) on Lake Ontario. However, in any one season it has varied from less than 0.7 feet (0.2 meters) to more than 2.0 feet (0.6 meters) on lakes Superior and Michigan-Huron, from less than 1.0 foot (0.3 meters) to more than 2.6 feet (0.8 meters) on Lake Erie, and from 0.7 feet (0.2 meters) to 3.6 feet (1.1 meters) on Lake Ontario.

Seasonal variability in flows can be very large. For instance, long-term evaporation from Lake Superior is about -300 cfs (-8.5 cms) in June and about 10,000 cfs (280 cms) in January and December, as shown in Figure 2-10. Cold winter temperatures in the northern Great Lakes also cause reduced winter streamflow and substantial spring runoff from melting snow and ice.

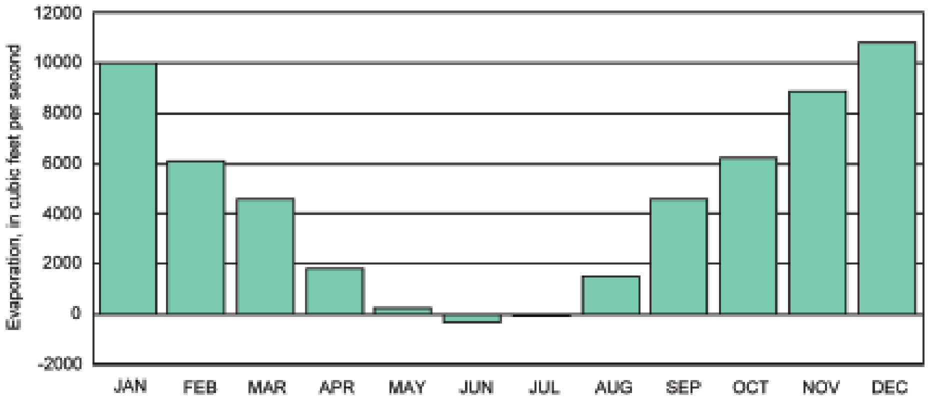

Figure 2-10
Long-term average monthly evaporation from Lake Superior

Short-term variability in water levels, lasting from less than an hour to several days, is caused by meteorological conditions. The effect of wind and differences in barometric pressure over the lake surface create temporary imbalances in the water level at various locations. Storm surges are largest at the ends of an elongated basin, particularly when the long axis of the basin is aligned with the wind. In deep lakes such as Lake Ontario, the water level surge rarely exceeds 1.5 feet (0.5 meters) but, in shallow Lake Erie, water level differences from one end of the lake to the other of more than 16 feet (4.9 meters) have been observed, followed by major seiches causing water levels to oscillate and diminish for several days. The range of fluctuations may be large, but only minor changes occur in the volume of water in the lake because, as the water levels rise at one end, they generally fall at the opposite end.

Generally, a lake's outflow depends on its water level; the higher the level, the higher the outflow. Accordingly, low lake levels are characterized by low outflows. This self-regulating feature helps keep levels on the lake within standard ranges, as long as unremediated dredging or other factors do not modify outflow channels. Due to the size of the Great Lakes and the limited discharge capacity of their outflow rivers, extremely high or low levels and flows can persist for a considerable time after the factors that caused them have changed. Thus, many years can pass before the effect of changes in flows in the upper lakes reaches Lake Ontario.

Great Lakes water level data must be used appropriately, or analyses will be misleading. This is particularly true where the long-term impact of differential crustal movement on local water levels may be important. While appropriate for water-balance calculations, using a lake-wide average level to analyze changes over time in wetland areas around a lake would lead to erroneous results. For this example, more appropriate data would come from water level gauges close to the study sites that are adjusted for local isostatic rebound. Similarly, use of monthly lake-wide average levels would be inappropriate for most flood and erosion studies.

In contrast to the effects of climate on levels and flows, the effects of diversions and outflow regulation are generally small. For instance, from 1970 through 1990, the Lake Michigan Diversion at Chicago, Illinois, ranged between 2934 cfs and 4055 cfs (83 cms and 115 cms), a difference of 1121 cfs (32 cms) as seen in Figure 2-11. The difference between the impact of a long-term withdrawal of 2934 cfs and 4055 cfs through the diversion, theoretically, is a 0.07-foot (2 centimeter) change in the water level of lakes Michigan-Huron and a 0.6 percent change in the average flow of the St. Clair River. The regulation of outflows from Lake Superior reduces the natural variability of water levels on lakes Superior and Michigan-Huron. Outflow controls in the St. Lawrence River likewise reduce the natural variability of water levels on Lake Ontario.

Figure 2-11 shows the non-certified and certified outflows through the Lake Michigan Diversion. Local authorities computed diversion flows prior through 1980 but, after that water year, diversion outflows were computed and certified by the USACE, in accordance with U.S. Supreme Court directives.

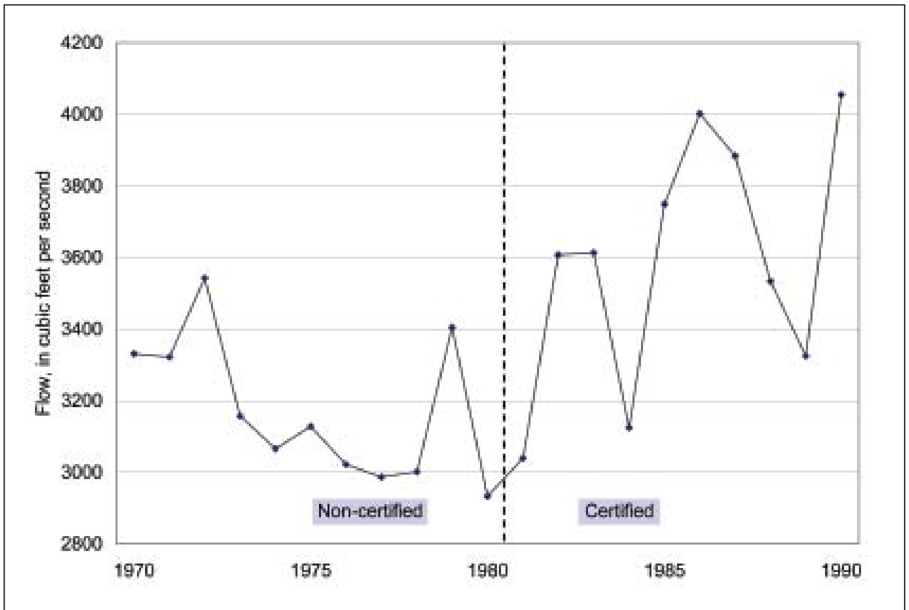

Figure 2-11
Lake Michigan Diversion at Chicago, Illinois, 1970 to 1990

Uncertainty in Calculations of Levels and Flows

All measurements and calculations have uncertainty associated with them. The term "uncertainty" is used within this chapter, not in a formal statistical manner, but as a means for quantifying errors and biases associated with measurements, calculations and estimates. In some cases, uncertainty in a measurement or calculation may reflect the level of accuracy of state-of-the-art instrumentation or estimation methods used. In other cases, uncertainty may be reduced by additional monitoring or by the application of more advanced instrumentation and estimation methods. The degree of uncertainty can vary as a function of the magnitude of the physical process being measured, computed or estimated. For example, uncertainties may be greater or lesser at higher outflows than at average outflows for a natural system.

Uncertainty in calculations of levels and flows is closely linked to Charter Annex issues. If part of the system is poorly understood (i.e., has high uncertainty), then it will be difficult to predict the effects of a proposed withdrawal on levels and flows, and on the ecosystem. Conversely, if part of the system is well understood, then the effects of a withdrawal on levels or flows may be easier to predict and could be used to evaluate ecological impacts.

There are no published uncertainty calculations associated with any of the levels and flows of the Great Lakes. The Status Assessment of Water Resources Technical Subcommittee, therefore, used its best professional judgment to estimate ranges of uncertainty for levels and flows. These ranges are presented in this section for the purpose of illustrating how well the hydrology of the Great Lakes-St. Lawrence River system is understood and to provide background for recommendations. For consistency in comparisons, uncertainties for each type of level and flow are related to: 1) the average outflow through the Lake Michigan Diversion at Chicago, Illinois; 2) the level of Lake Michigan-Huron; and 3) the average flow of the St. Clair River. Comparison between flows assumes identical time periods (instantaneous, hourly, weekly, monthly, etc.). Comparison with levels on Lake Michigan-Huron assumes persistence over an indeterminate time to achieve equilibrium throughout the system. For additional detail regarding uncertainty in levels and flows see Neff et al. (publication pending).

Levels

Uncertainty in the calculation of lake level fluctuations derives primarily from adequacy of the gauge network, accuracy of gauge datum and accuracy of recording equipment. An additional consideration is the proper selection and averaging of water levels recorded at individual water level gauges for calculation of lake-wide water level values. These calculations must also account for the impact of short-term weather conditions and the long-term impact of differential crustal movement.

A robust network of water level gauges is maintained throughout the Great Lakes and their connecting channels. NOAA, USACE and DFO operate more than 100 gauging stations throughout the Great Lakes-St. Lawrence River system. Instantaneous and hourly water levels at individual gauges are available to both the public and water managers on a real or near-real time basis through the use of voice announcing gauges, the Internet or phone interrogation. Daily and longer period lake-wide average levels are calculated based on selected gauge networks. Reductions in the network have occurred or been considered in the recent past; it must be adequately maintained and enhanced as needed, to address current and anticipated data requirements.

Water level data are referenced to an internationally coordinated Great Lakes datum, which is updated periodically to compensate for the impact of differential crustal movement throughout the system. This work is completed by United States and Canadian federal agencies participating in the Coordinating Committee on Great Lakes Basic Hydrologic and Hydraulic Data. Water levels are measured accurately, despite technical differences in the sampling methods used by NOAA, USACE and DFO to generate hourly water level values.

The NOAA and DFO hourly observations are considered equivalent for calculation of lake-wide daily, monthly, yearly and long-term mean water levels. While hourly values generated at an individual gauge are reported to the nearest millimeter, the lake-wide daily, monthly, yearly and long-term period of record levels are generally reported to the nearest centimeter only. Since the lake mean water levels are adjusted averages of many individual stations, they have significantly greater accuracy.

Uncertainty in Great Lakes levels may range from 0.002 to 0.011 feet (0.06 to 0.03 centimeters). If the uncertainty for levels is 0.006 feet for each lake, for example, then the amount of lake storage associated with this uncertainty is 5.3, 7.5, 1.7 and 1.2 billion cubic feet (0.15, 0.21, 0.05 and 0.03 billion cubic meters), for lakes Superior, Michigan-Huron, Erie, and Ontario, respectively. The uncertainty and storage figures for Lake Michigan-Huron equate to an inflow of 2,900 cfs (80 cms), assuming a 30-day month. This is about 90 percent of the Lake Michigan Diversion and about 1.5 percent of the average St. Clair River flow.

Gauged Streamflow

As noted above, streamflows are generally determined by measuring water level elevations at a stream gauge site, and then converting these levels to flows using a stage-discharge relationship established at the site based on field measurements. Uncertainty in gauged streamflow derives primarily from the stage discharge relationship. Periodic field measurements are used to verify or update this relationship, which is used in the computation of continuous, daily and annual flows. Some gauging locations have a stable stage discharge relationship, whereas others do not. The accuracy of the relationship is dependent upon natural factors that cannot be altered, such as channel stability, and ones that vary seasonally, such as vegetation and ice. Since the stage-discharge relationships are established based on instream flow measurement, the accuracy of the relationship is generally lower during periods of very high or very low flows and when ice is present.

Uncertainty in gauged streamflow can range from 5 percent to 15 percent. For an average-size stream that has a long-term annual mean flow of 200 cfs, a period-of-record peak flow of 5,500 cfs, a period-of-record low flow of 3 cfs, and an uncertainty of 10 percent, these flows may have uncertainties of 20 cfs, 550 cfs, and 0.3 cfs, respectively.

Total gauged annual mean streamflow to Lake Michigan is about 30,000 cfs (850 cms). An uncertainty of 10 percent results in a potential uncertainty of 3,000 cfs (85 cms). This is about 94 percent of the average outflow of the Lake Michigan Diversion and about 1.6 percent of the average St. Clair River flow. A flow of 3,000 cfs results in a change of 0.18 feet (5.5 centimeters) in the level of Lake Michigan-Huron after equilibrium is achieved.

Ungauged Streamflow

Uncertainty in ungauged streamflow derives primarily from differences between rainfall-runoff characteristics in a gauged watershed and an adjacent ungauged watershed. This uncertainty can be reduced by employing an estimation method that incorporates watershed characteristics, rather than relying upon simple drainage area-runoff relationships. There is also uncertainty in using the streamflow of the gauged watershed to calculate streamflow in the ungauged watershed.

Uncertainty in ungauged streamflow cannot be computed with precision, but exceeds the uncertainty of gauged streamflow. For an average-size ungauged stream with a drainage area of 350 square miles (910 square kilometers), a long-term annual mean flow of 200 cfs (5.7 cms), and an uncertainty of 15 percent, this flow may have an uncertainty of 30 cfs (0.9 cms).

Total ungauged streamflow to Lake Michigan is about 9,000 cfs (255 cms). An uncertainty of 15 percent results in a potential uncertainty of 1,350 cfs (38 cms). This is about 40 percent of the average outflow of the Lake Michigan Diversion and about 0.7 percent of the average St. Clair River flow. A flow of 1,350 cfs results in a change of 0.08 feet (2.5 centimeters) in the level of Lake Michigan-Huron after equilibrium is achieved.

Groundwater

The amount of groundwater that discharges directly into the Great Lakes and connecting channels has not been calculated and is unknown. In fact, the subsurface areas that contribute groundwater flow to the Great Lakes or their tributary streams have not been delineated. However, the amount of groundwater that discharges directly to the Great Lakes is likely a small percentage of the total inflows for each lake.

Grannemann and Weaver (1999) roughly estimated groundwater discharge to Lake Michigan to be about 2700 cfs (75 cms), or 3 percent of the lake's inflows. A groundwater discharge to Lake Michigan of 2700 cfs is about 84 percent of the average for Lake Michigan-Huron after equilibrium is achieved.

Groundwater that discharges to tributary streams – indirect groundwater discharge to the Great Lakes – is accounted for in streamflow calculations. Therefore, it is not necessary to discuss the relationship of uncertainty to lake-wide levels and flows. For predicting the effects of proposed groundwater withdrawals on streamflow, however, the magnitude, timing and uncertainty of indirect groundwater discharge, also called baseflow, must be understood.

Uncertainties in baseflow calculations have not been quantified; this is an area of ongoing research. Assuming that the uncertainty in the baseflow component of streamflow is greater than the uncertainty of streamflow, it may range from 10 percent to 20 percent for a gauged stream. An average-size stream that has a flow of 200 cfs (6 cms), of which 70 percent is baseflow, will have a potential uncertainty in baseflow of 14 cfs to 28 cfs (0.4 cms to 0.8 cms). For comparison, a typical domestic well has a capacity of 0.002 cfs, a municipal or irrigation well has a capacity of 1 cfs, and a medium-sized community withdraws 10 cfs. Note that these withdrawal amounts are smaller than the uncertainty associated with the flow of an average-size stream.

Precipitation

Uncertainty in precipitation over the Great Lakes derives from: 1) measurement uncertainty at rain gauges; 2) differences between precipitation over the lakes and over the land, where rain gauges are located; and 3) the interpolation method used to calculate precipitation over the lakes. Potentially, the use of weather radar (NEXRAD in the U.S. and the MSC radar network in Canada) to calculate precipitation over the lakes would do away with the latter two sources of uncertainty, but introduces new ones inherent to the weather radar technology.

Uncertainty in precipitation over the Great Lakes is generally believed to range from 15 percent to 60 percent. If the uncertainty for precipitation on lakes Superior, Michigan, Huron, Erie and Ontario is 40 percent, then uncertainties would be 28,500 cfs, 20,600 cfs, 22,000 cfs, 10,200 cfs and 7,210 cfs (810 cms, 585 cms, 625 cms, 290 cms and 205 cms), respectively.

Precipitation on Lake Michigan is calculated to average 51,600 cfs (1,460 cms). An uncertainty of 40 percent results in a potential uncertainty of 20,600 cfs (585 cms). This is about 6.4 times the average outflow of the Lake Michigan Diversion and about 11 percent of the average St. Clair River flow. A flow of 20,600 cfs results in a change of 1.3 feet (40 centimeters) in the level of Lake Michigan-Huron after equilibrium is achieved.

Evaporation

Uncertainty in evaporation from the Great Lakes derives primarily from: 1) measurement uncertainties in the parameters used to calculate evaporation – lake-surface temperature, air temperature, wind speed, and relative humidity; 2) the thermodynamic model used to calculate evaporation; 3) unaccounted for lake-surface-area variations caused by waves; and 4) spatial averaging of parameters and model calculations. The recent use of remote sensing to measure lake-surface temperatures reduces the uncertainty of this measurement and the uncertainty associated with its spatial averaging.

Uncertainty in evaporation from the Great Lakes is generally believed to range from 15 percent to 60 percent. If the uncertainty for evaporation from lakes Superior, Michigan, Huron, Erie and Ontario is 40 percent, then uncertainties may be 21,600 cfs, 16,500 cfs, 16,600 cfs, 10,300 cfs and 5580 cfs (610 cms, 465 cms, 470 cms, 290 cms and 160 cms), respectively.

Evaporation from Lake Michigan averages 41,200 cfs (1,165 cms). An uncertainty of 40 percent results in a potential uncertainty of 16,500 cfs (465 cms). This is about 5.2 times the average outflow from the Lake Michigan Diversion and about 8.8 percent of the average St. Clair River flow. A flow of 16,500 cfs results in a change of 1.0 foot (30 centimeters) in the level of Lake Michigan-Huron after equilibrium is achieved.


Niagara Falls

Connecting Channels

Uncertainty in connecting channel flows derives from the various methods used to compute different flows, including stage-fall-discharge relationships, water-control structure ratings, turbine ratings at hydroelectric facilities, and lock use and leakage through these structures. The uncertainty of stage-fall- discharge relationships depends upon accurate stage measurements, sufficient fall of the stage over the reach for which discharge is being calculated, and periodic measurements of discharge to update and verify the relationship. Since stage-discharge relationships are developed for open-water, ice-free, vegetation-free conditions, flow estimates must be adjusted to account for these factors, whenever appropriate. The uncertainty of flows through turbines depends upon the accuracy of the turbine rating and the availability of flow measurements to update and verify the ratings. Generally, newer turbines can be assumed to have a more accurate rating than older turbines. The uncertainty of flow through locks by use or leakage depends upon the accuracy of the calculation of lock volume, the amount of use, and the frequency and accuracy of field measurements of lock leakage. Sources of uncertainty in the flows of the connecting channels and St. Lawrence River are discussed by Gauthier et al. (2003).

The uncertainty of connecting channel flows has not been rigorously calculated for all connecting channels. Uncertainties for the St. Marys River, St. Clair River, Niagara River, and Lake Ontario average outflows may be 10 percent, 10 percent, 5 percent and 3 percent, respectively. Potential uncertainties for average flows of these connecting channels, therefore, may be 7,600 cfs, 18,200 cfs, 10,300 cfs and 7,390 cfs (215 cms, 535 cms, 290 cms and 210 cms), respectively.

The average outflow from Lake Michigan-Huron by way of the St. Clair River is 182,000 cfs (5,155 cms). During extreme conditions, flows have been recorded as high as 232,000 cfs (6,570 cms) and as low as 106,000 cfs (3,000 cms) per month. An uncertainty of 10 percent in computing the average St. Clair River flows results in a potential uncertainty of 18,200 cfs (515 cms). This is about 5.9 times the average outflow of the Lake Michigan Diversion. A flow of 18,200 cfs results in a change of 1.2 feet (36 centimeters) in the level of Lake Michigan-Huron after equilibrium is achieved.

Diversions

Uncertainty in diversions derives from the various methods to compute flows. Sources of uncertainty in the flows of the Lake Michigan, Long Lac and Ogoki diversions are discussed below. Sources of uncertainty in the flows of the remaining diversions are discussed by Gauthier et al. (2003).

Lake Michigan Diversion at Chicago, Illinois

Water has been diverted from Lake Michigan at Chicago, Illinois, since 1848, with subsequent changes in the flow volume, control structures and accounting procedures. Since 1981, the diversion outflow has been managed in accordance with a U.S. Supreme Court Decree that limits flows to 3,200 cfs (90.6 cms), averaged over a 40-year period. Uncertainty in the Lake Michigan Diversion derives mostly from: 1) the accuracy of the acoustic flow meters placed in the system; 2) velocity-discharge relationships; 3) the rainfall-runoff models; and 4) calculations of groundwater return flow.

The uncertainty of the Lake Michigan Diversion may range from 5 percent to 15 percent.

An uncertainty of 10 percent results in a potential uncertainty of 340 cfs (10 cms), which is about 0.2 percent of the average St. Clair River flow. A flow of 340 cfs results in a change of 0.02 feet (6 centimeters) in the level of Lake Michigan-Huron after equilibrium is achieved.

Long Lac Diversion

The Long Lac Diversion connects the headwaters of the Kenogami River (which originally drained north through the Kenogami and Albany Rivers into James Bay) with the Aguasabon River, which naturally discharges into Lake Superior. As a result, it diverts the runoff from about 1690 square miles (4375 square kilometers) directly into Lake Superior. The volumes of the Long Lac Diversion are measured and reported by Ontario Power Generation Inc. (OPG). Discharges through the Long Lake Control Dam to the Aguasabon River are determined based on the current sluice-rating table for the structure. OPG verifies and updates the sluice-rating table on a periodic basis using accepted engineering practices.

The uncertainty of the Long Lac Diversion is similar to that of gauged streamflow and may range from 5 percent to 15 percent, but is most likely closer to the lower value. An uncertainty of 10 percent results in a potential uncertainty of 140 cfs (4 cms), which is about 0.09 percent of the average St. Clair River flow. A flow of 140 cfs results in a change of less than 0.01 feet (0.3 centimeters) in the level of Lake Michigan-Huron after equilibrium is achieved.

Ogoki Diversion

The Ogoki Diversion connects the upper portion of the Ogoki River (which originally drained through the Albany River into James Bay) with the headwaters of the Little Jack River, which flows into Lake Nipigon and, from there, through the Nipigon River into Lake Superior. The Waboose Dam on the Ogoki River impounds water that would normally flow northward in the Ogoki reservoir and redirects it southward into Lake Nipigon. The Summit Dam controls the rate of the diversion from the Ogoki reservoir into Lake Nipigon. Although the long-term average outflow from the Ogoki reservoir into Lake Nipigon has been about 4020 cfs (115 cms), monthly diversions have varied from 0 cfs to 15,000 cfs (0 cms to 425 cms).

The quantity of water diverted from the Ogoki River in any month is not necessarily representative of the quantity reaching Lake Superior for the same month. This is due to the water being stored in Lake Nipigon for later release through the power plants during fall and winter months when inflows are lower. Therefore, uncertainties related to the Ogoki Diversion must be viewed in two ways: 1) uncertainty in the amount of water diverted from the Ogoki River into Lake Nipigon, which represents the short- and long-term diversions to the Great Lakes basin; and 2) the amount of water diverted to Lake Superior on a monthly basis.

A question is occasionally raised as to whether or not all of the water diverted into Lake Nipigon from the Ogoki River reaches Lake Superior. While a precise answer is not available, it is believed that, if losses do occur, they are likely within the quantitatively identified measurement accuracy. Discharges from the Ogoki reservoir to Lake Nipigon are determined based on a stage-discharge relationship. OPG verifies and updates the stage-discharge relationship though periodic field measurement to accepted standards. The stage-discharge relationship used for the Ogoki diversion has remained stable over time. Therefore, the uncertainty for both the daily and monthly flow values reported for the diversion from the Ogoki River to Lake Nipigon, and the resulting long-term average diversion into Lake Superior, is similar to any other gauged streamflow site, ranging from 5 percent to 15 percent, but very likely closer to the lower value. An uncertainty of 10 percent results in a potential uncertainty of 400 cfs (11 cms), which is about 0.2 percent of the average St. Clair River flow. A flow of 400 cfs results in a change of 0.03 feet (0.9 centimeters) in the level of Lake Michigan-Huron after equilibrium is achieved.

Discussion

Potential uncertainties associated with different components of the hydrologic cycle translate into large quantities of water, some much larger than others. For instance, uncertainties in precipitation on Lake Michigan-Huron are estimated to be plus or minus 40,000 cfs (1,130 cms), whereas uncertainties in the Lake Michigan Diversion are estimated to be plus or minus 300 cfs (8 cms), as shown in Figure 2-12.

When considering flows on a systemwide scale, diversions are very small. Clearly they are much smaller than the magnitude of major hydrologic

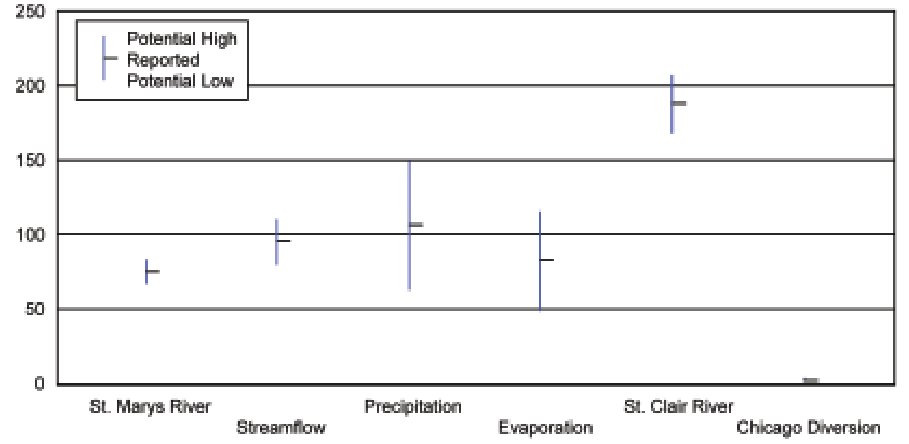

Figure 2-12
Potential uncertainties in flows to and from lakes Michigan-Huron

components, including streamflow, precipitation, evaporation and connecting channel and St. Lawrence River outflows shown in Figure 2-13.

On a lake-wide or systemwide scale, potential uncertainties are much larger than any current withdrawal. Even the flow impacts of large, new withdrawals, for example, likely would not be detected by measurement of a connecting channel flow or a lake level because of natural variability in the system and potential uncertainties in measuring or computing flows. However, while this effect is unlikely to be detected by direct measurement, the impact of removing water from the system can be predicted to some extent. Current hydrologic models of the Great Lakes system can predict how withdrawals will change supplies to each of the lakes, and thus, lower lake levels, reduce connecting channel flows, or reduce hydroelectric generation. The accuracy of the predicted effect of a withdrawal is limited only by the accuracy with which the model simulates the physical system.

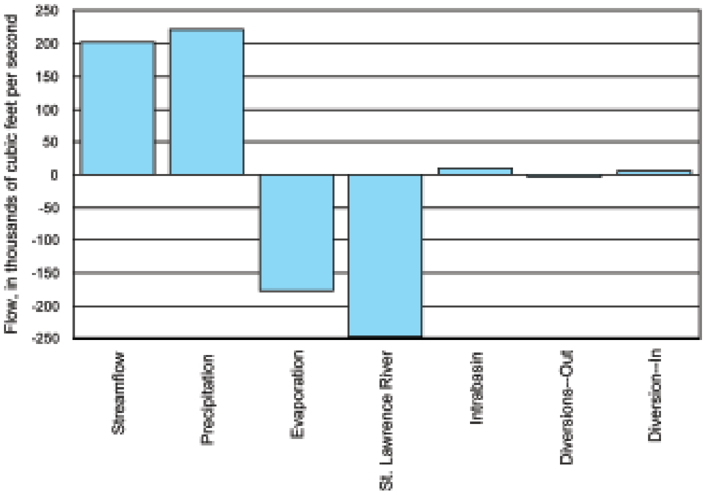

Figure 2-13
Flows into and from the Great Lakes

Findings and Recommendations

The many findings and recommendations in this section have four cross-cutting themes. First, a binational coordination framework needs to be established for collecting, analyzing, reporting and accessing Great Lakes hydrologic and hydraulic data. Second, uncertainties in levels and flows have not been quantified. Third, a formal and robust evaluation of current monitoring should be undertaken with the goals of quantifying data gaps and making specific recommendations to reduce uncertainties. Fourth, all recommendations assume an increased quantity and quality of monitoring and reporting. The need for resources to carry out this work is implicit.

Findings

Although a significant amount of hydrologic monitoring occurs in the Great Lakes basin, current efforts target specific needs that do not fully address the decisionmaking standard embodied in the Great Lakes Charter Annex. Several agencies collect Great Lakes hydrologic data and calculate levels and flows, typically using different methods. Further, data are not available for all flows on a binational basis; coordination between U.S. and Canadian jurisdictions on collection and analysis is inadequate.

Problems include the diversity of hydrologic data and information sources, inconsistencies in metadata, lack of compatibility with geographic information systems for some data, and limited accessibility to data on the Internet.

Decisionmakers do not always understand or consider the variability of the hydrologic system and the limitations of hydrologic measurement. All levels and flows are variable in the short- and long-term and at many spatial scales. Also, all measurements and calculations are inherently uncertain. However, most reported flows are long-term averages at large spatial scales, and associated data uncertainties are not reported and often not calculated.

Uncertainties associated with measurements of levels and flows hinder the ability to assess ecological effects from withdrawals on a systemwide level. Even though the effects of a withdrawal on levels and flows cannot currently be detected by measurements, existing models can accurately predict the effects of withdrawals on connecting channel flows, lake levels or hydroelectric production.

On a sub-watershed scale, streamflow and groundwater data are insufficient in many areas of the basin to predict ecological effects of instream and groundwater withdrawals. Only large-scale groundwater or cumulative withdrawals are likely to be detected in streamflow, but this ability depends on the scale of withdrawal relative to the scale of baseflow. Standard approaches are, for the most part, available to collect the hydrologic information needed to make decisions on instream and groundwater withdrawals, but they have not yet been applied to all areas of the basin.

The contribution of groundwater to the hydrology of the Great Lakes has only recently been more fully recognized. As a result, the complex dynamics of groundwater recharge, flow and discharge, and the implications of these factors relative to both water quantity and quality, require special attention.

Recommendations

Monitoring/Modeling

1. **Evaluate the adequacy of hydrologic/hydraulic monitoring systems, within the context of the Annex, after a decisionmaking standard is agreed upon.**

   The evaluation should include specific additions to or modifications of current networks, as well as changes to operating and reporting methods.

2. **Secure agency commitments to core, long-term, geographically distributed hydrologic/hydraulic monitoring that will be needed to implement the decisionmaking standard.**

   Sustained investment in hydrologic/hydraulic monitoring networks and programs is crucial to assessing cumulative impacts of withdrawals. Continual records of levels and flows throughout the system have long-term strategic value for protection of the resource and, as such, their availability needs to be factored into the design of a decision support system.

3. **Support the continued maintenance and enhancement of the Great Lakes water level gauging network, and quantify and report uncertainties.**

   Substantial improvements have been made to instrumentation and reporting methods from U.S. water level gauging stations over the last few years, but not all data are collected and distributed uniformly or in a timely manner. Analysis should be conducted to quantify and report on uncertainties related to instrumentation accuracies, sampling methodologies, and reporting between U.S. and Canadian sites, with the objective of reducing differences and uncertainties.

4. **Develop coordinated binational methods for evaluating groundwater flow directly and indirectly to the Great Lakes-St. Lawrence River system using common data standards and models.**

   A conceptual model of groundwater flow and associated mapping tools for the Great Lakes basin should be developed that includes known groundwater divides, identifies and prioritizes data needs, and identifies locations and quantities of groundwater discharge directly to the Great Lakes. Research should be focused on developing relationships between direct groundwater discharge and adjacent nearshore aquatic ecosystems. Standardized methods should be developed between countries for computing indirect groundwater discharge to tributary streams and coordinate results.

5. **Systematically evaluate the adequacy of existing tributary stream gauging to meet Annex implementation needs and develop coordinated binational methods for calculating streamflow for all ungauged areas.**

   The assessment of the adequacy of existing streamflow gauging networks should include quantification of uncertainties, identification of optimum gauging locations, and recommendations of core networks to meet Annex needs. Determination of streamflow for ungauged watersheds should be based upon coordinated methods between countries that make maximum use of known surface runoff characteristics and flow processes, including calculations of associated uncertainties.

6. **Develop coordinated binational methods, with measures of uncertainty, for calculating over-lake precipitation and evaporation processes using existing remote sensing techniques.**

   Over-lake precipitation can be estimated from ground-based radar systems in the United States and Canada. This will require a significant commitment of funds for applied research. Improvements in evaporation estimates are also possible, using satellite observations of water surface temperatures, ambient air temperatures and other related meteorologic parameters, as input to new-generation thermo-dynamic models.

7. **Develop coordinated binational methods, with measures of uncertainty, for calculating and/or measuring flows, customized for each connecting channel, St. Lawrence River and diversion into/out of the Great Lakes.**

   These may include use of hydrodynamic flow models, permanent installation of acoustic flow meters, and/or more frequent direct measurements of flow to support calculations. Since instrumentation and models are subject to frequent changes in technology, the efficiency and accuracy of accepted methods need to be periodically evaluated. The standards need to be flexible enough to be adapted to all hydraulic situations, particularly since channel modifications can occur through natural physical processes or human intervention. Flows in diversion canals also can be affected by changes in maintenance over time.

8. **Continue development and refinement of systemwide hydraulic routing models so that effects of proposed withdrawals and the uncertainty of the effects can be predicted.**

   Complex hydrologic/hydraulic processes can be simplified via computer modeling, while providing substantial visualization abilities. Computer models should be accessible via the Internet, with model inputs and outputs well documented and readily available for wide application.

Information Availability

9. **Develop common data standards and reporting practices for hydraulic/hydrologic data and other information relevant to the Annex, with emphasis on determining watershed impacts.**

   Data and information should be coordinated regularly so that it is current. The collection and coordination of hydrologic data and information relevant to the Annex should be carried out by agencies under the auspices of the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data.

10. **Ensure easy access to hydraulic/hydrologic data for decisionmakers and other interested parties via clearinghouse services, and conventional and electronic communications technology.**

    Access can be enhanced by development of a comprehensive Internet clearinghouse, coordination of web pages from primary data sources, and promotion of consistent data and metadata that can be used in a geographic information system (GIS). Metadata is descriptive information about data that typically addresses its lineage, quality, condition, or characteristic. Sensitive information (proprietary, personal and security) will need to be protected and managed accordingly.

Information Use

11. Incorporate an understanding of hydrologic variability and uncertainty at the appropriate temporal and spatial scales in the decisionmaking process.

The uncertainty and variability of levels and flows assessed on a Great Lakes basin-wide scale will differ significantly from those assessed at a sub-watershed or individual stream basis. A withdrawal from an individual watershed should not therefore be assessed based on information compiled at the Great Lakes basin level. Data, information and measures of uncertainties at the appropriate temporal and spatial scale are extremely important to the decisionmaking process.

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