CHAPTER 3
STATUS ASSESSMENT OF GREAT LAKES-ST. LAWRENCE RIVER WATER RESOURCES

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3.1. INTRODUCTION

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

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

This chapter summarizes Great Lakes hydrology, how flows and levels are measured, uncertainty in measurements of flows and levels, and recommends improvements to current monitoring that will provide support for decisionmaking under the new standard. This paper is a summary product from Project Element 2 of the WRDSS project supported by the Great Lakes Protection Fund. 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, and others, 2003). Specific information on flows from 1948 to 1998 can be found in Croley and others (2001).

This chapter discusses the relationship between findings of Project Element 2 and the 2001 Annex to the Great Lakes Charter. The WRDSS project was proposed and began prior to signing of the Annex. Most of the work on Project Element 2 was designed to evaluate the quantity and quality of water-resources data and information on a lake-wide or system-wide scale, not on a subwatershed scale. Specifically, the work and other publications resulting from Project Element 2 focused on flows and levels in the context of net basin supplies to each Great Lake. This chapter, however, goes beyond the core of the work conducted for Project Element 2 and does evaluates water-resources data and information in the context of the 2001 Annex.

3.1.1 PHYSICAL SETTING

The Great Lakes-St. Lawrence system is comprised of (1) Lakes Superior, Michigan, Huron, Erie, and Ontario; (2) their connecting channels, St. Mary's 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 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 299,000 square miles. 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 basin is in the United States; 41 percent is in Canada. The basin is about 700 miles long measured north to south and about 900 miles 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 long and flows through the provinces of Ontario and Quebec.

Surface-water 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 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 0 to over 1000 feet. The topography in the Central Lowlands is generally flat and rolling.

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

3.1.2 HYDROLOGIC SETTING

The natural 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. Lake Superior discharges into Lake Huron by way of the St. Mary's River, which has a long-term average flow of 75,000 cfs. Lakes Huron and Michigan are usually considered as one lake hydraulically, because of 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 by way of 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 discharge of about 238,000 cfs at Cornwall, Ontario/Massena, New York.

Dredging, control structures, locks, dams, hydroelectric facilities, canals, and diversions have altered the hydrology of the Great Lakes-St. Lawrence system. Dredging and control structures have had the largest impacts. For instance, the dredging of the St. Clair River from 1880 to 1965 permanently lowered Lakes Michigan-Huron by about 14 inches. 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 Great Lakes and their connecting channels cover approximately 32 percent of the entire Great Lakes-St. Lawrence River basin above Cornwall/Massena. Figure 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 Lake Superior's basin is 81,000 square miles. The surface area of Lake Superior itself is 31, 700 square miles, or 39 percent of its entire basin area. In contrast, the surface area of Lake Ontario, 7340 square miles, is only 23 percent of Lake Ontario's basin. Clearly, 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 in the form of precipitation directly on the lake's surface and in the form of runoff from its basin tributary streams as well as the amount of water lost through evaporation from its surface.

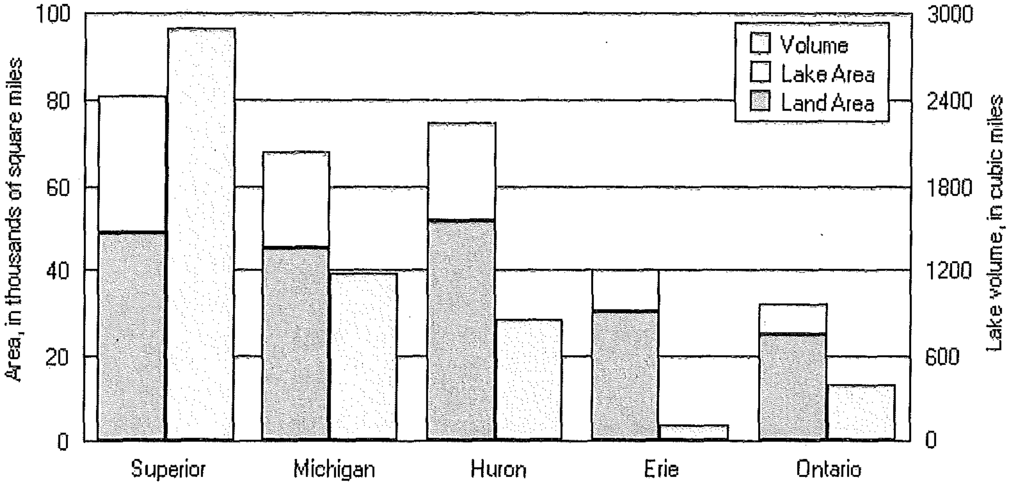

Figure 1. Volumes and areas of the Great Lakes

The climate of the Great Lakes basin 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 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. Precipitation is distributed relatively uniformly throughout the year, but does have variability west to east across the basin, ranging from a mean annual precipitation of 28 inches north of Lake Superior to 52 inches 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 inches, whereas, in snowbelt areas downwind of Lakes Superior and Ontario, snowfall can be as high as 140 inches. 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 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 basin, consumption of water, dredging of outlet channels and the regulation of outflows.

There are three types of water level fluctuations 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 a less than an hour to several days) occur as water levels set-up (rise) or set-down (fall) due to effect of wind and differences in barometric pressure over the lake surface. Seiches can also cause short-term variations in local water levels. A seiche is the free oscillation of water in a closed or semi-closed basin; it is frequently observed in harbours, bays, lakes, and in almost any distinct basin of moderate size. Larger seiches often occur immediately following a storm driven set-up/set-down event. 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 about 0.9 metre in the 51 kilometres 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 NOAA's Great Lakes Environmental Research Lab in Ann Arbor have documented an actual short-term flow reversal under wind set up at the western end of Lake Erie.

The flows in the outlet rivers of the lakes during the winter are often retarded materially by ice formation and ice jamming. These conditions are not predictable for any specific winter, either as to their severity or the exact timing of their occurrence. Aquatic growth in the rivers during the summer also creates outflow retardation, which varies from river to river.

Over time, water levels throughout the Great Lakes are also affected by isostatic rebound, often referred to as crustal movement. Isostatic rebound is the gradual rising or "bouncing back" of the earth's crust from 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 the mid-1800s (Stuntz, 1869, as referenced in Clark and Persoage, 1970). The rate of movement is not uniform throughout the region and results in differential rates of change between specific sites; generally, the rates around lakes Superior and Ontario are greater than those around Lakes Michigan-Huron and Erie.

While the exact picture of absolute movement over the basin remains uncertain, it appears that on a lake-by-lake basis the effects on water levels of differential crustal movement can still be visualized if the lakes are treated as basins that are being tilted by a gradual rising of their northeastern rims. As time goes on, the water levels along shores that are situated south and west of a lake's outlet are rising higher for a given average lake level. Similarly, water levels along the shores at localities north and east of the outlet are receding with respect to the land. On Lake Superior, for example, it appears that the axis of mean crustal movement for the lake runs from the point near where the international border intersects the shoreline south of Thunder Bay through the lakes outlet at Sault Ste. Marie. Therefore, the average land-to-water relationship around the lake would be expected to remain unaffected by crustal movement under stable natural outlet conditions. Water levels along the lake's shore would, however, increase or decrease depending on their location relative to the axis of movement.

3.2. FLOWS AND LEVELS

Flows into and out of the Great Lakes and the levels of the lakes are measured or calculated at hundreds of locations throughout the 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 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. Any gauges funded under the Federal-Provincial cost-share agreements are operated to national standards. The U.S. streamflow-gauging network, on the other hand, has more than 100 different sources of funding. The monitoring is continuous and long-term because flow and levels are highly variable temporally and spatially. Variations in flows and levels can significantly affect navigation, hydroelectric power generation, drinking water intakes, shoreline erosion, ecosystems, and other uses of the waters of the Great Lakes-St. Lawrence system.

3.2.1 FLOWS

Flows into and out of the Great Lakes include/tributary streamflow (also referred to as basin runoff), / confusing groundwater, precipitation, evaporation, connecting channel flows, diversions, and consumptive uses (Figure 2). Consumptive uses are a very small percentage of the total flows and are discussed in Chapter 4 of this paper.

3.2.1.1 Streamflow

Streamflow is a large part of each Great Lake's inflow, but the percentage varies from one lake to another (Figure 3). Excluding inflows from connecting channels, which are discussed separately, streamflow is 47 percent of the inflow to Lakes 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.

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 the application of a stage-discharge model. 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 application of a stage-discharge model, and, at these locations, other types of measurements or models are employed.

Streamflow from ungauged areas is not typically or periodically calculated. 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 the agencies that collect, publish, and archive the data. The two principal sources of data are the U.S. Geological Survey and Environment Canada. Information regarding how to find and obtain streamflow data is discussed by Neff and Killian (2002) and available at www.glc.org.

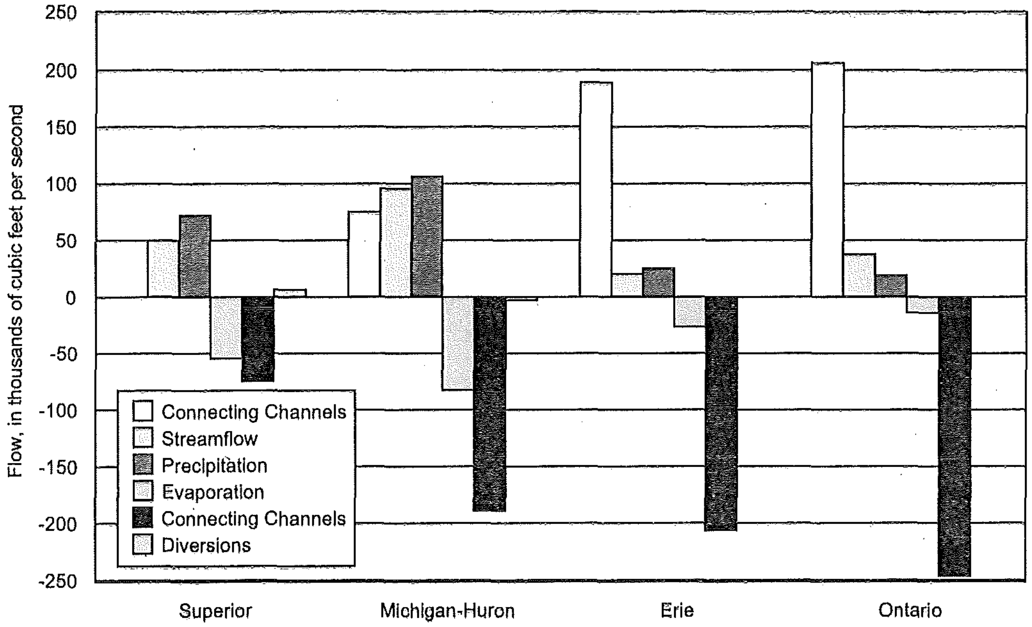

Figure 2. Flows into and out of the Great Lakes

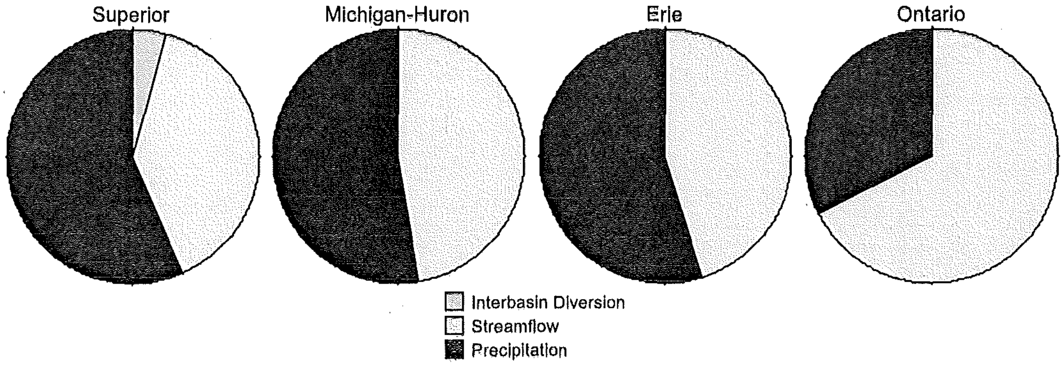

Figure 3. Inflows to the Great Lakes (Note: Intrabasin diversions are included in outflows)

3.2.1.2 Groundwater

The amount of groundwater that discharges directly into the Great Lakes and connecting channels 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 (2002). Locally, groundwater discharge to the Great Lakes may be important to aquatic ecosystems, however, a literature search did not find research results available on the relation of groundwater to aquatic ecosystems in the Great Lakes proper or their connecting channels.

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

In much of the Great Lakes basin, indirect groundwater discharge is a large percentage of the total amount of streamflow (Figure 4). The percentage of streamflow attributable to groundwater is typically calculated by use of long-term streamflow records and application of baseflow-separation models. 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. This surface is similar to the earth's surface in that it has groundwater divides that are analogous to watershed divides. Groundwater on one side of the divide flows towards 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.

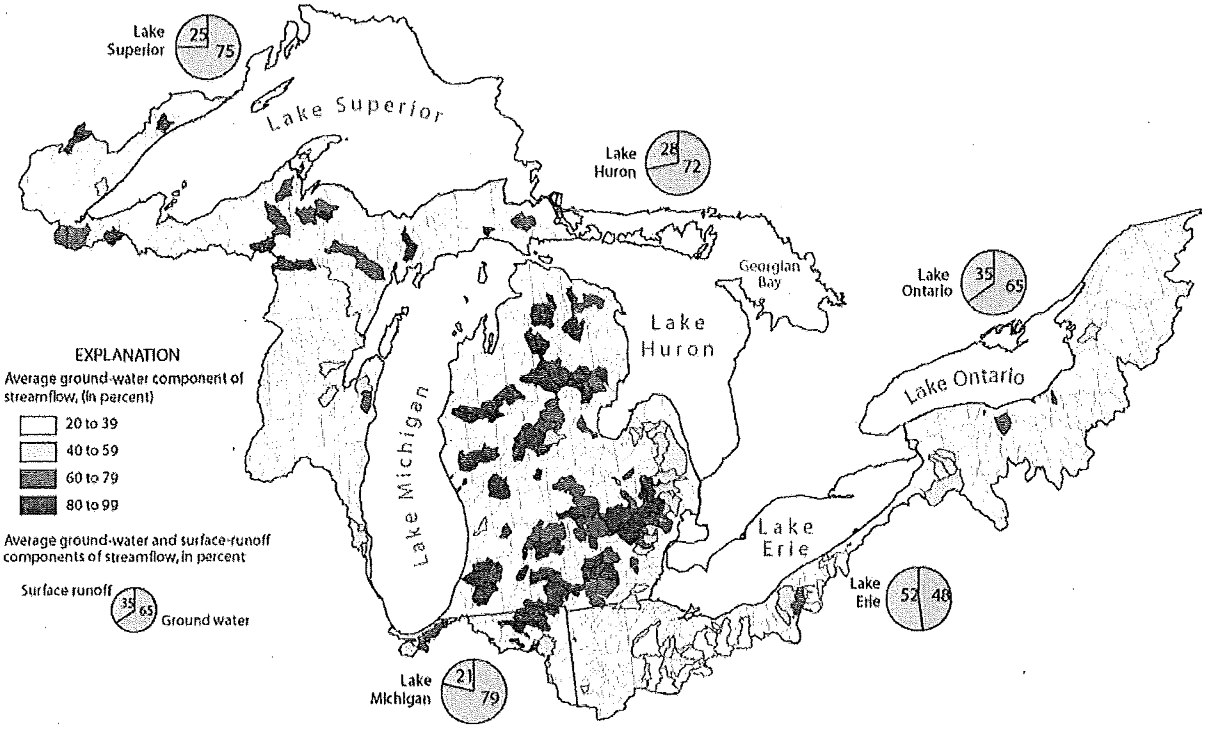

Figure 4. Average groundwater and surface-runoff components of streamflow in the United States portion of the Great Lakes basin

3.2.1.3 Precipitation

Precipitation directly on the Great Lakes is a large part of each Great Lake's inflow (Figure 3). The percentage varies from one lake to another depending mostly upon the area of the lake surface as compared to the area of the watershed draining to the lake.

Precipitation is measured or gauged at hundreds of locations in the Great Lakes basin. All of these gauges are on the land, not on the lakes. Precipitation over the lakes is calculated by interpolation of data from nearshore gauges. Modern radar technology could be used to calculate precipitation on the lakes

Historical and current precipitation data from gauges can be obtained from the agencies that collect, publish, and archive the data. The two principal sources of data are the National Archives and Data Management Branch, Atmospheric Monitoring and Water Survey Directorate, Meteorological Service of Canada and the National Climate Data Center, in Canada and the United States, respectively. Historical monthly over-lake precipitation calculations for each lake are available in Croley and others (2001). Information regarding how to find and obtain precipitation data is discussed by Neff and Killian (2002) and available at www.glc.org.

3.2.1.4 Evaporation

Evaporation from the surface of the Great Lakes is a large part of each Great Lake's outflow (Figure 5). The percentage varies from one lake to another depending mostly 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 off their surfaces which results when cool, dry air passes over the relatively warm water of the lakes.

Evaporation is not measured directly; rather it is calculated using a computer model developed by Croley (1989). Most parameters used to calculate evaporation – air temperature, wind speed, and relative humidity – are measured at on-shore locations. Remote sensing is used to calculate water temperature. Historical monthly evaporation calculations for each lake are available in Croley and others (2001).

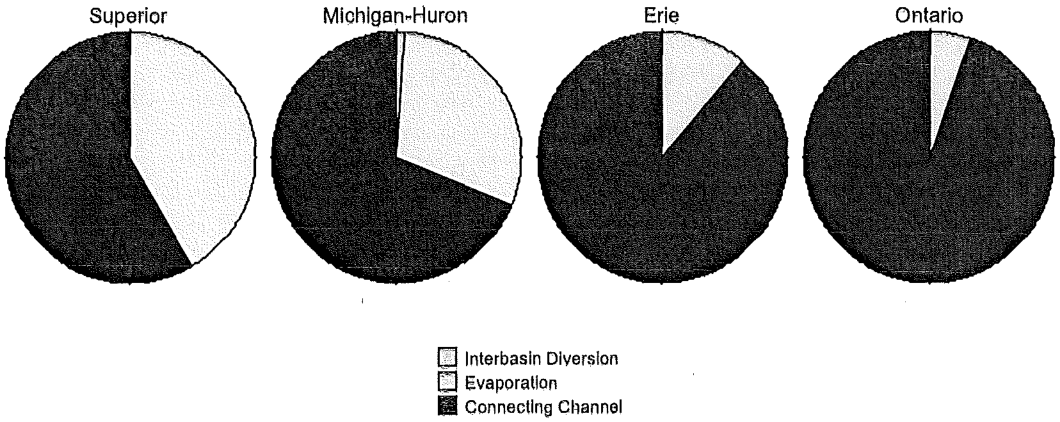

Figure 5. Outflows from the Great Lakes (Note: Intrabasin diversions are included in outflows)

3.2.1.5 Connecting Channels

Connecting channel flows are a large part of each Great Lake's outflow. The percentage generally increases downstream, as each downstream connecting channel flow is larger than the upstream connecting channel flow.

Connecting channel flows are measured or calculated using a variety of methods specific to each. Flows in the St Mary's 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 relation is also available for the upper Niagara River. This relationship is used for operational and modeling purposes. Flows in the St. Clair River and Detroit River are calculated from measurements of stage using a suite of stage- fall-discharge relationships to accommodate the range of ice conditions in the St. Clair/Detroit River system. Field measurements are used to verify and update stage-discharge relations and power plant or control structure rating curves.

Historical connecting channel flows can be obtained from the agencies that collect, publish, and archive the data. The Hydraulic Subcommittee of the Coordinating Committee for Great Lakes 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 International Joint Commission. Information regarding how to find and obtain connecting channel flow data is discussed by Neff and Killian (2002) and available at www.glc.org.

3.2.1.6 Diversions

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, that is, they transfer water from one Great Lake to another Great Lake.

There are three major and five minor interbasin diversions (Figure 6). The Long Lac and Ogoki Diversions are major diversions that transfer water from the Hudson Bay watershed to Lake Superior. The Chicago Diversion is a major diversion that transfers water from Lake Michigan to the Illinois River watershed. Minor interbasin diversions are Forestport (out of Lake Ontario), Portage Canal (into Lake Michigan), Pleasant Prairie (out of Lake Michigan), Ohio & Erie Canal (into Lake Erie) and Akron (out of and into Lake Erie).

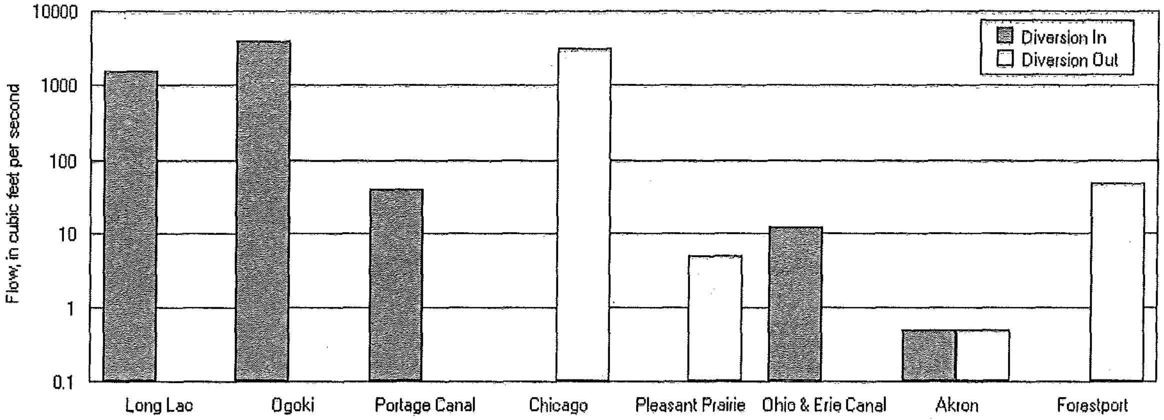

Figure 6. Interbasin diversions in the Great Lakes

Some intrabasin diversions – the Welland Canal, and 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 (Figure 7).

Diversions are measured or calculated using a variety of methods specific to each diversion. Information regarding how to find and obtain flow data for diversions is discussed by Neff and Killian (2002) and available at www.glc.org.

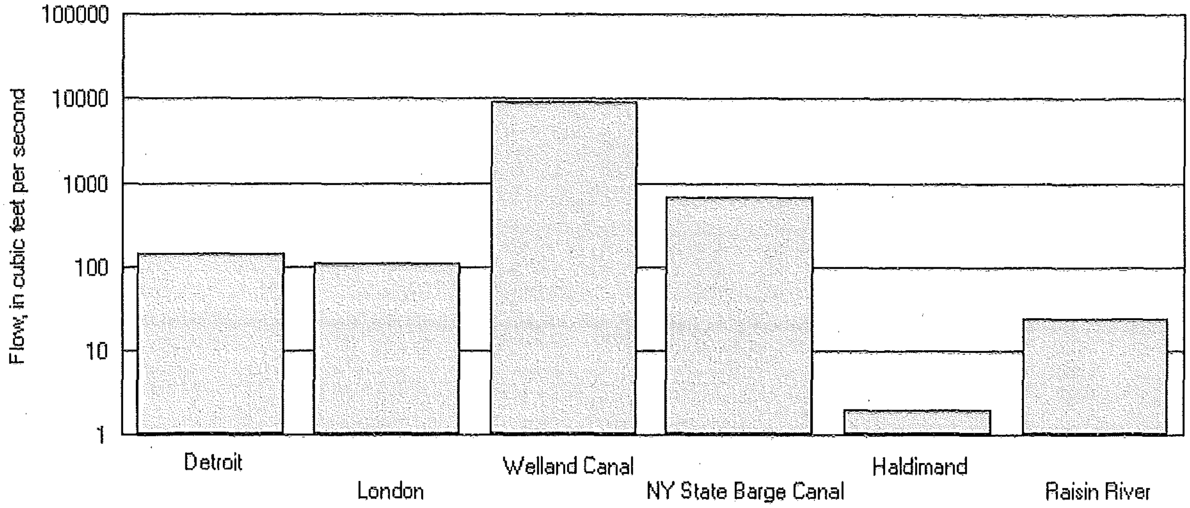

Figure 7. Intrabasin diversions

3.2.2 LEVELS

Great Lakes and connecting channel water levels 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, to predict future water levels, and to calculate changes in storage in each Great Lake.

Water levels are measured or gauged at numerous locations along the shore on the Great Lakes and their connecting channels by the Department of Fisheries and Oceans (DFO) and the National Ocean Service (NOS), in Canada and the United States, respectively. NOS operates 50 permanent and several seasonal water level gauges on the United States side of the Great Lakes system as part of its national network. Similarly, DFO operates 34 permanent water level gauges on the Canadian side of border as part of its national network. NOS collect water level readings every 6 minutes, these readings are the average of 180 one-second samples centered on even six-minute periods. The daily average water level is the average of 24 hourly readings. The Canadian gauges operated by DFO collect water level readings every 15 minutes; these readings are the instantaneous reading taken every 15 minutes. The daily average is the average of 24 hourly readings. Water levels at both US and Canadian gauges are measured and reported to the nearest millimetre. Although the sampling methods used by each agency are different, the daily levels calculated are considered equivalent for calculation purposes. Water level data recorded by NOS and DFO at their respective gauge stations are available from these agencies. In addition to the NOS and DFO gauges, the U.S. Army Corps of Engineers, power entities and others operate additional gauges to meet their specific needs.

Great Lakes levels are expressed in two ways; either as an elevation above sea level or 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 the International Great Lakes Datum to be updated about every 30 to 35 years. IGLD85 is the second internationally coordinated Great Lakes datum, replacing IGLD55. Updating of the datum is carried out by Vertical Control–Water Level Subcommittee of the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data.

The U.S. Army Corps of Engineers 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. These lake-wide average water levels are calculated using point measurements from selected NOS and DFO water-level gauges on each lake chosen to account for short-term water-level fluctuations due to metrological conditions and the long-term affect of differential crustal movement. The level of Lakes Michigan and Huron are reported as a single number because of their hydraulic connection. These daily and monthly lake-wide average levels are reported to the nearest centimetre, which is considered adequate for operational and public information purposes. Information regarding how to find and obtain lake-level data is discussed by Neff and Killian (2002) and available at www.glc.org.

3.2.3 VARIABILITY OF FLOWS AND LEVELS

Flows and levels in the Great Lakes Basin are highly variable, which is the major justification for continuous, long-term monitoring. Factors affecting flows and levels are variations in climate, diversions, and regulation. Variations in climate, both temporal and spatial, are the major factor affecting flows and levels, dwarfing the other two factors.

Long-term variability in water levels results from persistent low or high water supplies. These cause extremely low levels such as were recorded on some lakes in 1926, the mid-1930s and mid-1960s, or extremely high levels such as in 1952, 1973, 1985-86 and 1997. The intervals between periods of high and low levels and the length of such periods can vary widely and erratically 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 (Figure 8) demonstrates the long-term variability of water levels associated with changes in climate. Lake levels derived from the geologic record of the last several thousand years indicate that levels can be much more variable than those of the past 140 years of historical record.

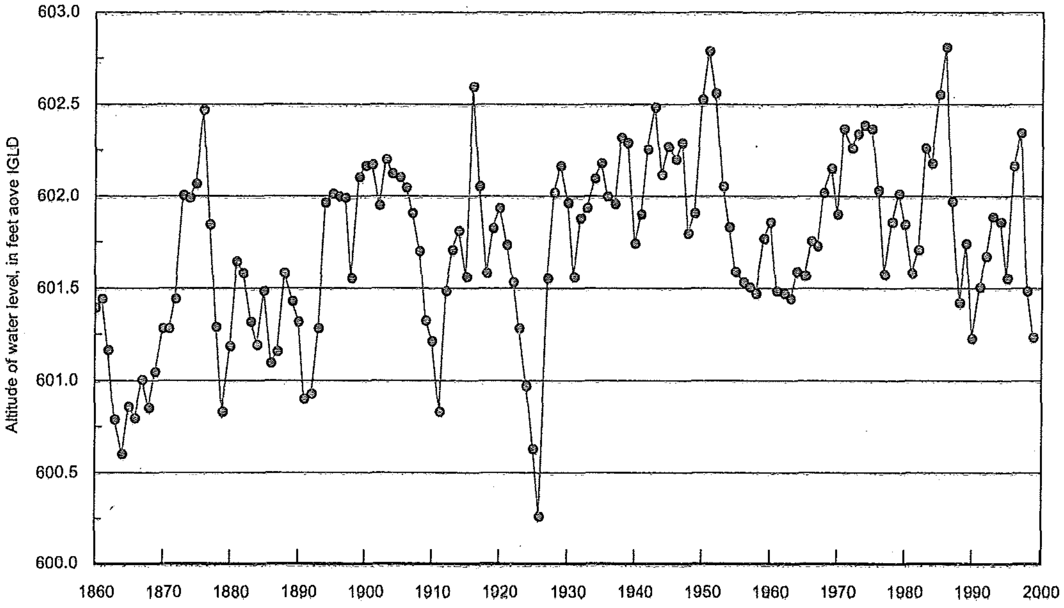

Figure 8. Lake Superior water level, 1860-1999

Seasonal variability in water 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. The maximum lake level usually occurs in June on Lakes Ontario and Erie, in July on Lakes 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 0.4 metres on Lakes Superior, Michigan and Huron, about 0.5 metres on Lake Erie, and about 0.6 metres on Lake Ontario. However, in any one season it has varied from less than 0.2 metres to more than 0.6 metres on the upper lakes, from less than 0.3 metres to more than 0.8 metres on Lake Erie and from 0.2 metres to 1.1 metres on Lake Ontario.

Seasonal variability in flows can be very large. For instance, long-term evaporation from Lake Superior is about –300 cubic feet per second in June and about 10,000 cubic feet per second in January and December (Figure 9). Cold winter temperatures in the northern Great Lakes also cause reduced winter streamflow and substantial spring runoff from melting snow and ice.

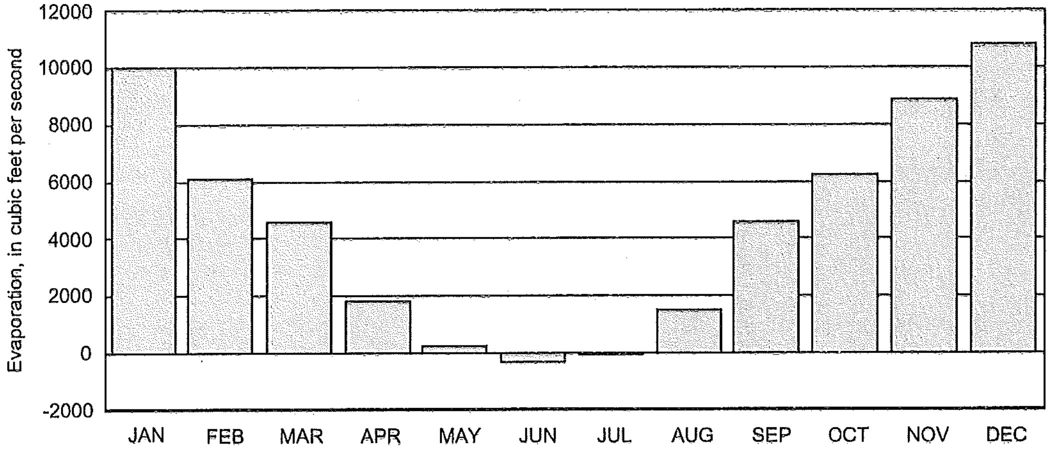

Figure 9. Long-term average monthly evaporation from Lake Superior

Short-term variability in water levels, lasting from a 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 surge of water level rarely exceeds 0.5 metre, but in shallow Lake Erie, water-level differences from one end of the lake to the other of more than 5 metres have been observed. Although the range of fluctuations may be large, there are only minor changes in the volume of water in the lake because as the water levels rise at one end of the lake, they generally fall at the opposite end. 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. Larger seiches often occur immediately following a surge.

Generally speaking, a lake's outflow depends on the elevation of the lake: the higher the lake, the higher the outflow. Low lake levels will bring low outflows. This self-regulating feature helps keep levels on the lake within certain ranges. Because of the size of the Great Lakes and the limited discharge capacity of their outflow rivers, extremely high or low levels and flows sometimes persist for a considerable time after the factors which caused them have changed. Thus, it takes up to 15 years for the effect of changes in flows in the upper lakes to reach Lake Ontario.

It is important to note, that depending on the intended use, users of Great Lakes water levels must be sure they are using the correct data for their purposes. This is particularly true in the case of an analysis where the long-term impact of differential crustal movement on local water levels may be important. For example, as noted earlier, on Lake Superior, the average land-to-water relationship around the lake is unaffected by crustal movement. Water levels along the lake's shore, however, are increasing or decreasing with time depending on their location relative to the axis of movement. While appropriate for water balance calculations, using Lake Superior's lake-wide average levels in an analysis of changes in wetland area around the lake over time, for example, would almost certainly lead to erroneous results. The use of water levels recorded at water level gauges close to the study sites would be more appropriate. Similarly, an analysis of lake-wide or local monthly water levels alone will not provide much information about flood and erosion hazard potential.

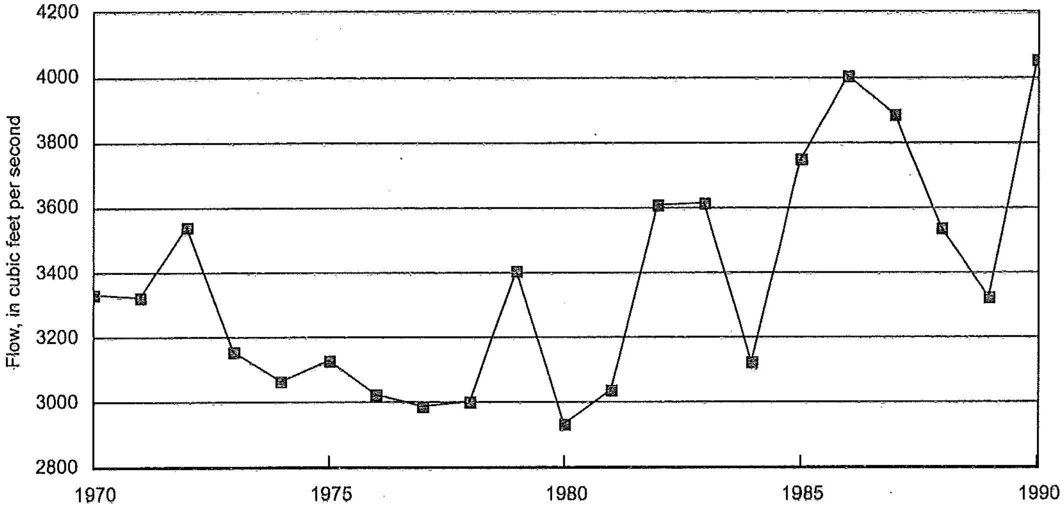

Figure 10. Chicago diversion, 1970 to 1990

In contrast to the effects of climate on flows and levels, the effects of diversions and regulation are generally small. For instance, from 1970 through 1990, the Chicago Diversion ranged between 2934 and 4055 cubic feet per second, a difference of 1121 cubic feet per second (Figure 10). The difference between the impact of a long-term withdrawal of 2935 cubic feet per second and 4055 cubic feet per second at Chicago is only a 0.07-foot change in the water level of Lakes Michigan-Huron and only a 0.6 percent change in the flow of the St. Clair River. Regulation at the outlets of Lake Superior and Lake Ontario serves to reduce the natural variability of water levels on these lakes.

3.3. UNCERTAINTY IN CALCULATIONS OF FLOWS AND LEVELS

All measurements and calculations have uncertainty associated with them. Uncertainty does not indicate errors or flaws in monitoring. In some cases, uncertainty in a measurement or calculation may reflect the 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.

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

There are no published uncertainty calculations associated with any of the flows and levels of the Great Lakes. Therefore, Technical Subcommittee for Project Element 2 used its best professional judgment to estimate ranges of uncertainty for flows and levels. These ranges are presented in this section for the purpose of illustrating how well the hydrology of the Great Lakes- St. Lawrence system is understood and to provide background for recommendations. For consistency in comparison, uncertainties for each type of flow and level are related to the Chicago Diversion, the level of Lakes Michigan-Huron, and the flow of the St. Clair River. For additional detail regarding uncertainty in flows and levels see Neff and others (2002).

3.3.1 GAUGED STREAMFLOW

As noted earlier, streamflows are generally determined by measuring water level elevations at a stream gauge site, then converting these levels to flows using a stage-discharge relationship established at the site based on field measurements. Uncertainty in gauged streamflow derives mostly from the stage-discharge relationship. Periodic field measurements are used to verify or update this relationship, and it is used in the computation of continuous, daily, and annual flows. Some gaging 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 in-stream flow measurement, in general, the accuracy of the relationship is lower during periods of very high or very low flows and when ice is present than at more moderate flow conditions While the volumetric error may be larger under high flow conditions, the stage-discharge relationship may not be sensitive to changes in streamflow level under low water conditions.

Uncertainty in gauged streamflow may range from 5 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 5500 cfs, a period-of-record low flow of 3 cfs an uncertainty of 10 percent, these flows may have errors of 20, 550, and 0.3 cfs.

Total gauged annual mean streamflow to Lake Michigan is about 30,000 cfs. An uncertainty of 10 percent results in a potential error of 3000 cfs. This is about 94 percent of the Chicago Diversion and about 1.6 percent of the St. Clair River flow. A flow of 3000 cfs results in a change of 0.18 feet in the level of Lakes Michigan-Huron.

3.3.2 UNGAUGED STREAMFLOW

Uncertainty in ungauged streamflow derives mostly from (1) uncertainty in the gauged streamflow of adjacent watersheds that are used to calculate streamflow in ungauged watersheds and (2) differences between rainfall-runoff characteristics in the gauged watershed and the ungauged watershed. The latter source of uncertainty can be reduced by employing an estimation method that incorporates watershed characteristics, rather than relying upon simple drainage area-runoff relationships.

Uncertainty in ungauged streamflow is unknown, however, it will not be less than the uncertainty of gauged streamflow, and may range from 10 to 20 percent. For an average-size ungauged stream with a drainage area of 350 square miles, a long-term annual mean flow of 200 cfs, and an uncertainty of 15 percent, this flow may have an error of 30 cfs.

Total ungauged streamflow to Lake Michigan is about 9000 cfs. An uncertainty of 15 percent results in a potential error of 1350 cfs. This is about 40 percent the Chicago Diversion and about 0.7 percent of the St. Clair River flow. A flow of 1350 cfs results in a change of 0.08 feet in the level of Lakes Michigan-Huron.

3.3.3 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 greater than zero and likely a few percent of the total inflows for each lake. Grannemann and Weaver (1999) roughly estimated groundwater discharge to Lake Michigan to be 2700 cfs or 3 percent of the lake's inflows.

For comparison to other flows, assume that groundwater discharge to Lake Michigan is 2700 cfs. This is about 84 percent of the Chicago Diversion and about 1.4 percent of the St. Clair River flow. A flow of 2700 cfs results in a change of 0.17 feet in the level of Lakes Michigan-Huron.

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 flows and levels. For predicting the effects of proposed groundwater withdrawals on streamflow, however, it is necessary to understand the magnitude and uncertainty of indirect groundwater discharge, also called baseflow.

Uncertainties in baseflow calculations have not been quantified, although this is an area of ongoing research. Assuming that the uncertainty in the baseflow component of streamflow is greater than the uncertainty of streamflow, then it may range from 10 to 20 percent for a gauged stream. An average-size stream that has a flow of 200 cfs, of which 70 percent is baseflow, will have a potential error in baseflow of 14 to 28 cfs. 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.

3.3.4 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 and the lack of rain gauges on the lake with which to calibrate and verify weather radar calculations.

Uncertainty in precipitation over the Great Lakes is unknown, however, it may range from 15 to 60 percent. If the uncertainty for precipitation on Lakes Superior, Michigan, Huron, Erie, and Ontario is 40 percent, then errors may be 28,500, 20,600, 22,000, 10,200, and 7210 cfs, respectively.

Precipitation on Lake Michigan is calculated to be 51,600 cfs. An uncertainty of 40 percent results in a potential error of 20,600 cfs. This is about 6.4 times the Chicago Diversion and about 11 percent of the St. Clair River flow. A flow of 20,600 cfs results in a change of 1.3 feet in the level of Lakes Michigan-Huron.

3.3.5 EVAPORATION

Uncertainty in evaporation from the Great Lakes derives mostly 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 unknown, however, it may range from 15 to 60 percent. If the uncertainty for evaporation from Lakes Superior, Michigan, Huron, Erie, and Ontario is 40 percent, then errors may be 21,600, 16,500, 16,600, 10,300 and 5580 cfs, respectively.

Evaporation from Lake Michigan is 41,200 cfs. An uncertainty of 40 percent results in a potential error of 16,500 cfs. This is about 5.2 times the Chicago Diversion and about 8.8 percent of the St. Clair River flow. A flow of 16,500 cfs results in a change of 1.0 feet in the level of Lakes Michigan-Huron.

3.3.6 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, weed-feed conditions, in some cases, flow estimates must be adjusted to account for these factors. 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.

The uncertainty of connecting channel flows has not been rigorously calculated for all connecting channels. Calculated uncertainties for St. Mary's River, St. Clair River, Niagara River, and the Lake Ontario outfall may be 10, 10, 5, and 3 percent, respectively. Potential errors for average flows of these connecting channels, therefore, may be 7550, 18,800, 10,300, and 7390 cfs, respectively.

Outflow from Lakes Michigan-Huron by way of the St. Clair River is 188,000 cfs. An uncertainty of 10 percent results in a potential error of 18,800 cfs. This is about 5.9 times the Chicago Diversion. A flow of 18,800 cfs results in a change of 1.2 feet in the level of Lakes Michigan-Huron.

3.3.7 DIVERSIONS

Uncertainty in diversions derives from the various methods to compute different flows. Sources of uncertainty in the flows of the Chicago, Long Lac, and Ogoki diversions are discussed in the next paragraphs. Sources of uncertainty in the flows of the remaining diversions are discussed by Gauthier and others (2003).

3.3.7.1 Chicago Diversion

Uncertainty in the Chicago diversion derives mostly from (1) the accuracy of the ADCP instrument, (2) the velocity-discharge relationship, (3) rainfall-runoff model, and (4) calculations of groundwater return flow. State whether or not any more likely than another to reduce uncertainty. State whether or not measurement at points of diversion preferable in terms of uncertainty and problems with measurement thereof. Still awaiting workshop summary to complete this paragraph(s)

The uncertainty of the Chicago diversion may range from 5 to 15 percent. An uncertainty of 10 percent results in a potential error of 340 cfs, which is about 0.2 percent of the St. Clair River flow. A flow of 340 cfs results in a change of 0.02 feet in the level of Lakes Michigan-Huron.

3.3.7.2 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 4377 square kilometres (1690 square miles) directly into Lake Superior.

The volume 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 Flows 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, therefore, similar to that of gauged streamflow and may range from 5 to15 percent, but is most likely closer to the lower value. An uncertainty of 10 percent results in a potential error of 140 cfs, which is about 0.09 percent of the St. Clair River flow. A flow of 140 cfs results in a change of less than 0.01 feet in the level of Lakes Michigan-Huron.

3.3.7.3 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 Nigigon River, into Lake Superior. The Waboose Dam on the Ogoki River impounds the water that would normally flow northward in the Ogoki reservoir and redirects it southward into Lake Nipigon. Summit Dam controls the rate of the diversion from the Ogoki reservoir into Lake Nipigon. Although the long-term average diversion from the Ogoki into Lake Nipigon has be about 114 m3/s (4026 cfs), monthly diversions from the Ogoki reservoir have varied from 0 m3/s to 425 m3/s (0 cfs to 15,000 cfs). However, since the quantities diverted from the Ogoki River in any month are not necessarily representative of the amounts of diverted water reaching Lake Superior in that month since water is stored in Lake Nipigon for later release through the power plants during fall and winter months when inflow is low. Therefore, uncertainty related to the Ogoki Diversion must be view in two fashions: 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 the amount of water diverted to Lake Superior on a monthly basis.

Although the question of whether or not all of the water that is diverted into Lake Nipigon from the Ogoki River reaches Lake Superior has been raised, if losses do occur they are likely within measurement error. 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 any other gauged streamflow site, ranging from 5 to 15 percent, but very likely closer to the lower value. An uncertainty of 10 percent results in a potential error of 400 cfs, which is about 0.2 percent of the St. Clair River flow. A flow of 400 results in a change of 0.03 feet in the level of Lakes Michigan-Huron.

If the amount of water diverted Ogoki River in Lake Nipigon is used as the diversion into Lake Superior in monthly water balance calculation purposes, an error in the monthly values will result because we know the quantities of water diverted from the Ogoki river during any month are not necessarily representative of the amount of water reaching Lake Superior because water is stored in Lake Nipigon for later release. During any given month, the portion of Lake Nipigon's outflow to Lake Superior that is made up of water originally diverted from the Ogoki river, may be very little or many times the volume of water diverted into Lake Nipigon during the month in question. If little or no year-to-year storage of water on Lake Nipigon occurs, it may possible to estimate an average seasonal redistribution of the Ogoki diversion through to Lake Nipigon to estimate the diversion into Lake Superior. This could be applied to the actual yearly total diversion to produce monthly estimates. It must be noted, however, that due to the assumptions that would be necessary to establish the montlhy estimates, they will be highly uncertain and will not be available until the total diversion for the year is know.

3.3.8 LEVELS

Uncertainty in lake levels derives mostly from (1) adequacy of the network, (2) accuracy of gauge datum (3) accuracy of recording equipment, (4) the proper selection and averaging of water levels recorded at individual water-level gauges to establish lake-wide water-level values while accounting for the impact of short-term weather conditions and the long-term impact of differential crustal movement

There is a robust network of water level gauges maintained throughout the Great Lakes and their connecting channels. NOS and DFO operate more than 80 gauging stations throughout the Great lakes system as part of their respective national networks. In addition, agencies such as the U.S. Army Corps of Engineers operate a number of gauges for operational purposes. 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 or the Internet. Daily and longer period lake-wide averages levels are calculated based on selected gauge networks and are available in a timely fashion. While reductions in the network have occurred or been considered in the recent past, the network appears stable at this time and appears adequate for water management purposes.

Water levels are measured and reported referenced to an internationally coordinated Great Lakes Datum, which is updated as necessary under the auspices of the Coordinating Committee for Great Lakes Hydrologic and Hydraulic Data to compensate for the impact of differential crustal movement throughout the system. Water levels are measured accurately, however, there are technical differences in the sampling methods used by NOS and DFO to generate hourly water level values. The hourly values are considered equivalent for calculations purposes and any differences between them will be reduced as lake-wide daily, monthly, yearly and long-term period of record water levels are calculated. In addition, 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 centimetre only.

Uncertainty in Great Lakes levels may range from 0.002 to 0.011 foot. If the uncertainty for levels is 0.006 foot for each lake, then the amount of storage associated with this uncertainty is 5.3, 7.5, 1.7, and 1.2 billion cubic feet, for Lakes Superior, Michigan-Huron, Erie, and Ontario, respectively.

If the monthly level of Lakes Michigan-Huron has a potential uncertainty of 0.006 foot and an associated amount of potential uncertainty in the amount of water stored of 7.5 billion cubic feet, this equates to an inflow of 2900 cfs, assuming a 30-day month. This is about 90 percent of the Chicago Diversion and about 1.5 percent of the St. Clair River flow.

3.3.9 DISCUSSION

Potential uncertainties translate into large quantities of water, some much larger than others. For instance, uncertainties in precipitation on Lakes Michigan-Huron are about plus or minus 40,000 cfs, whereas uncertainties in the Chicago Diversion are about plus or minus 300 cfs (Figure 11).

Considering flows on a sytem-wide scale, diversions are very small (Figure 12). Clearly they are much smaller than the potential uncertainties associated with major flows – streamflow, precipitation, evaporation, and connecting channels.

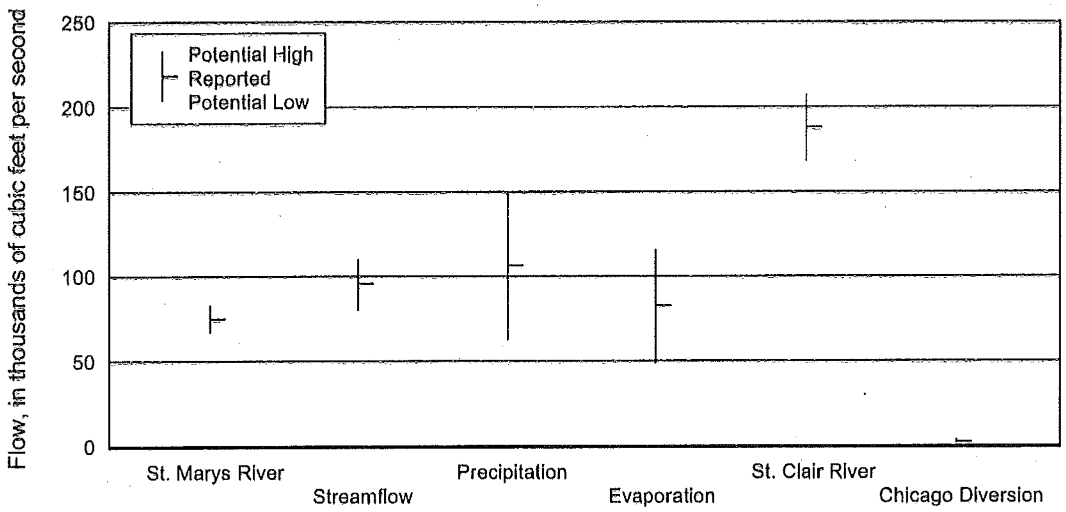

Figure 11. Potential uncertainties in flows to and from Lakes Michigan-Huron

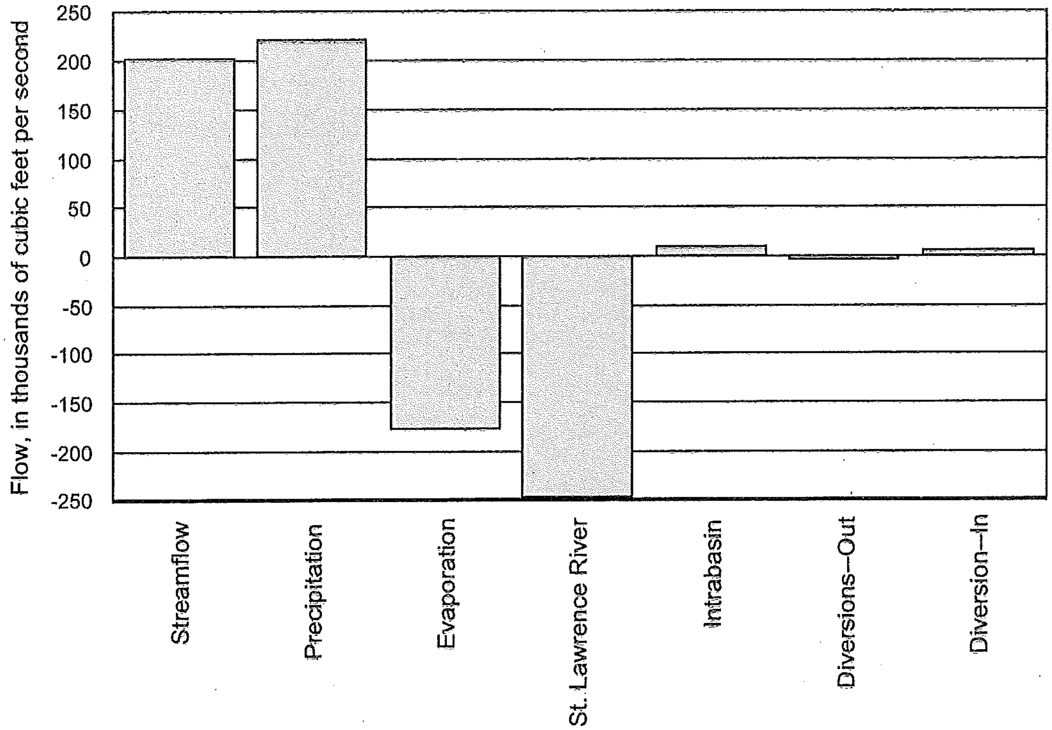

Figure 12. Flows into and from the Great Lakes.

On a lake-wide or system-wide scale, potential uncertainties are much larger than any potential withdrawal. Even a very large new withdrawal could 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 flows. Note, however, that although this effect cannot be detected by direct measurement, the impact of removing water from the system will lower Great Lakes flows and levels, and the amount that flows and levels will be lowered can be predicted. Current hydrologic models of the Great Lakes system can predict how much a withdrawal will lower a lake level, reduce a connecting channel flow, 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.

3.4. FINDINGS AND RECOMMENDATIONS

The many findings and recommendations in this section have four cross-cutting themes. First, binational standards for collecting, analyzing, reporting, and accessing Great Lakes hydrologic and hydraulic data need to be established. Second, uncertainties in flows and levels have not been quantified. Third, the initial step in many recommendations is that 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 this out is implicit.

3.4.1 FINDINGS

This chapter provides and assessment and lays the groundwork for a decision support system that is applicable to a broad range of variables and geographic areas ranging from small sub-basins (e.g., a single tributary) to the entire Great Lakes system.

Although significant hydrologic monitoring occurs in the Great Lakes basin, current monitoring targets specific needs that may not be identical to the needs of the Annex's decisionmaking standard. Several agencies collect Great Lakes hydrologic data and calculate flows and levels, and agencies often use distinct methods to collect data and calculate flows. Binationally coordinated and agreed upon data are not available for all flows, and the coordination of data is infrequent. Potential problems include the diversity of hydrologic data and information sources, inconsistencies in metadata, lack of compatibility with geographic information systems for some data, and inadequate accessibility to data on the Internet.

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

On a lake-wide scale, uncertainties in flows and levels of the Great Lakes dwarf any potential withdrawal. Even a large potential withdrawal could not be detected by connecting channel flow or lake level measurements. However, if uncertainty associated with major flows could be substantially reduced, the effects of large withdrawals could become measurable. Even though the effects of a withdrawal on flows and levels cannot currently be detected by measurements, existing models can accurately predict the effects of a withdrawal on a connecting channel flow, lake level, or hydroelectric production. These models do not currently calculate the uncertainty of these predicted effects.

On a sub-watershed scale, sufficient streamflow and groundwater data are available in many areas of the basin to predict effects of in-stream and groundwater withdrawals. Only large-scale groundwater 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 available to collect the hydrologic information needed to make decisions on in-stream and groundwater withdrawals.

3.4.2 RECOMMENDATIONS

1. **Develop common data standards and common reporting practices for hydrologic data and information relevant to the Annex.** The data and information should be coordinated regularly so that it is current within one year. The collection and coordination of hydrologic data and

information relevant to the Annex should be carried out under the auspices of the Coordinating Committee for Great Lakes Hydrologic and Hydraulic Data.

2. **Evaluate current monitoring networks within the context of the Annex, after a decisionmaking standard is agreed upon.** The evaluation should propose specific additions to or modifications of current networks, if needed.
3. **Develop a single Internet gateway that accesses primary data sources and provides consistent data and metadata by way of a geographic information system, such as ARC/IMS.**
4. **Systematically evaluate current streamflow gaging so as to (1) quantify uncertainties, (2) identify optimal locations for new gauges, if needed, and (3) recommend a core minimum and optimal network of gauges that will meet decisionmaking needs.** This core network should be funded by small number of agencies that have a long-term direct interest in the implementation of the 2001 Annex.
5. **Develop a robust method to calculate streamflow for ungauged areas that (1) makes use of statistically significant physical characteristics of the watershed and (2) calculates an associated uncertainty for the flow.**
6. **Develop a preliminary groundwater flow model for the Great Lakes basin that (1) incorporates known groundwater divide locations, (2) identifies and prioritizes data needs, and (3) identifies locations and quantities of groundwater discharge directly to the Great Lakes.** Focus research regarding the relationship of groundwater to nearshore aquatic ecosystems in geographic areas identified by the model to have significant groundwater discharge.
7. **Develop coordinated binational calculations for the entire Great Lakes basin using common data standards and models.**
8. **Develop a basin-wide standard model to calculate precipitation directly on the lake surface that makes use of remote sensing technology, such as weather radar (NEXRAD in the U.S. and the MSC radar network in Canada), and that incorporates calculations of uncertainty.** Determine optimal locations for on-shore gauges to calibrate the model and reduce uncertainty.
9. **Develop a basin-wide standard model to estimate evaporation from the Great Lakes that makes maximum use of remote sensing technology and that incorporates calculations of uncertainty.** Determine optimal locations for on-shore and off-shore data-collection platforms.
10. **Develop a common set of standards for calculating flow and a "best approach" for each connecting channel that includes calculations of uncertainty.** 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, periodically evaluate efficiency and accuracy of "best approach" for each connecting channel.
11. **Develop a common set of standards for calculating flow and a "best approach" for each diversion that includes calculations of uncertainty.** The standards need to be flexible enough to be adapted to all hydraulic situations. Where technically feasible measure or determine diversion flows at the point of the diversion itself and at points suitable for water-balance purposes.
12. **Support the continued maintenance and enhancement of the Great Lakes water level gauging network.** Quantify and report on uncertainties related to differences in instrumentation, sampling methodologies, and reporting and, if necessary, recommend changes to reduce differences. A paper describing the various spatial and temporal forms in which water levels are available and their appropriate and inappropriate use should be prepared.

13. **Secure agency commitments to core, long-term, geographically distributed monitoring needed to implement the decision standard.**
14. **Continue development and refinement of system-wide hydraulic models, so that effects of proposed withdrawals and the uncertainty of the effects can be predicted.** Make the model and results available by way of the Internet gateway where hydrologic data and information are accessed.
15. **Develop common standards for collecting and analyzing the hydrologic information that is necessary to make decisions and that is suitable for predicting ecological impacts.** Develop basin- wide maps showing where different types of data and information are available. Make these maps available by way of the Internet gateway where hydrologic data and information are accessible.
16. **Incorporate an understanding of variability and uncertainty in flows and levels into the decisionmaking process.** Consider end points in the ranges of variability and maximum likely uncertainty in determining the potential hydrological and ecological impacts of proposed withdrawals. Requests for proposed withdrawals should account for variability and uncertainty at appropriate temporal and spatial scales.

3.5. SELECTED REFERENCES