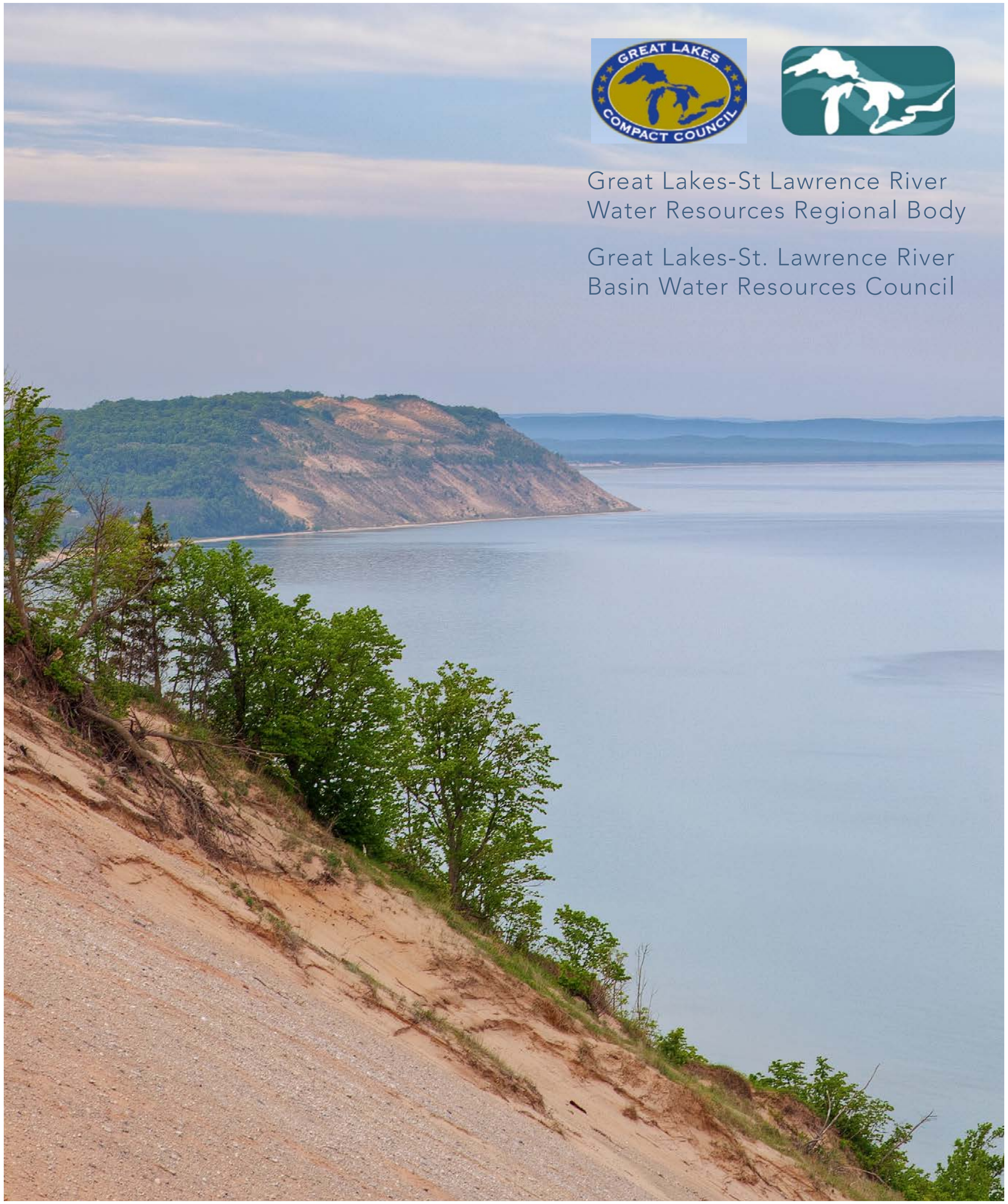
CUMULATIVE IMPACT ASSESSMENT

of Withdrawals, Consumptive Uses & Diversions

2016 - 2020



Great Lakes-St Lawrence River Water Resources Regional Body

Great Lakes-St. Lawrence River Basin Water Resources Council

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EXECUTIVE SUMMARY

CUMULATIVE IMPACT ASSESSMENT OF WITHDRAWALS, CONSUMPTIVE USES & DIVERSIONS

In the Great Lakes-St. Lawrence River Basin Sustainable Water Resources Agreement (Agreement), the Great Lakes and St. Lawrence River States and Provinces

> **(the Parties) commit to periodically assess the cumulative impacts of Withdrawals, Consumptive Uses and Diversions of Water from the Great Lakes—St. Lawrence River Basin (Basin).**

Similar commitments are included for the Great Lakes States in the companion Great Lakes-St. Lawrence River Basin Water Resources Compact (Compact). As required by the Agreement and Compact, the cumulative impact assessment will be conducted for each Lake and St. Lawrence River watershed and for the entire Basin. The assessment fulfills the requirement of the Compact and Agreement. The assessment will be used for a review of decision making standards and their application, and for other purposes.

The Basin water budget is an accounting of water flows into and out of the Basin. Some of these flows are natural and some are constructed or affected by humans. Withdrawals, Consumptive Uses, and Diversions are part of the water budget. These flows vary from year to year, either due to variability in climate or due to human activities. **The timeframe for this assessment is 2016-2020.** For comparative purposes, longer data sets for flows are presented to provide a historical context for 2016-2020 data. The longer data sets are 1950-2015.

Inflows include precipitation on the surface of the Lake(s), surface water runoff to the Lake(s) or River, Diversions into some Lakes, and connecting channel flows into each of the Lakes or River, except for Lake Superior which does not have an inflowing connecting channel. Outflows include evaporation from the surface of the Lake(s), Diversions from some Lakes, connecting channel flows out of each of the Lakes, and Consumptive Uses. The St. Lawrence River is the outflow for Lake Ontario and the entire Basin. **Although Withdrawals are a component of water budgets, this assessment considers only the hydrologic effect of Consumptive Uses and Diversions.**

Consumptive Use is the portion of water withdrawn but not returned due to evaporation, incorporation into products, and other processes.

The cumulative hydrologic effect of Consumptive Uses and Diversions are small relative to inflows. Further, while inflows fluctuate from 2016-2020, the cumulative hydrologic effect of Consumptive Uses and Diversions is fairly constant for these annual averages.

The net effect of Consumptive Uses and Diversions is positive for the Basin's water budget for 2016-2019. In other words, more water is diverted into the Basin than the total combined amount of water diverted out of the Basin or withdrawn and not returned. In 2020, the net effect was slightly negative.

The specific contribution made by Diversions and Consumptive uses at any given point in time or space, separate and apart from natural variability, is uncertain given the complex hydrologic, geographic, and temporal variability of uses, and other factors. Since Diversions and Consumptive Uses are small compared to natural flows, their cumulative hydrologic effect on water levels is likewise small. A small hydrologic effect, however, does not necessarily mean that there are no cumulative impacts. On the contrary, a small hydrologic effect may still lead to significant impacts on ecosystems or other water uses depending on the scale or type of impacts being evaluated. Future assessments may reflect advancements in science, data, information, and assessment methods, and will investigate this distinction further.

A significant addition to this Cumulative Impact Assessment report is a more robust consideration of uncertainty in historical water balance components, and of the extent to which historical water balance components might have been impacted by climate change.

It is important to note (as indicated in previous reports) that not only is the magnitude of historical water balance components much greater than that of diversions and consumptive uses, but also that the uncertainties in historical water balance components are often greater than the cumulative effects of diversions and consumptive uses. **To address this challenge, a new analysis framework was developed for the Great Lakes Basin that uses statistical methods to solve a basin-wide, lake-to-lake water balance model. This new modeling framework, which is presented in detail in a Supplementary Report titled, "Analysis of Great Lakes Water Balance Components," leads to water balance component estimates with significantly reduced uncertainty.**

The additional assessment of climate change impacts prepared for this Cumulative Impact Assessment (also included in detail in the above-mentioned Supplementary Report) indicates that

precipitation and evaporation are both likely to increase over the coming decades.

Historical records indicate that long-term average precipitation is already increasing across the Great Lakes Basin, and that both precipitation and evaporation (while increasing) have exhibited periods of increased interannual variability.

These historical patterns, along with projected trends from climate models, suggest that future long-term average (i.e., over multiple decades) water levels on the Great Lakes are unlikely to be significantly higher or lower than the historical long-term average. It is possible, however, that water level variability over shorter time periods could be exacerbated, as observed during the rapid water level rise from 2013 (a period of record lows) to 2020 (a period of record highs).

INTRODUCTION

In the Great Lakes-St. Lawrence River Basin Sustainable Water Resources Agreement (Agreement), the Great Lakes and St. Lawrence River States and Provinces (the Parties) commit to periodically assess the cumulative impacts of Withdrawals, Consumptive Uses and Diversions of Water from the Great Lakes—St. Lawrence River Basin (Basin). Similar commitments are included for the Great Lakes States in the companion Great Lakes-St. Lawrence River Basin Water Resources Compact (Compact). As required by the Agreement and Compact, the cumulative impact assessments will be conducted for each Lake and St. Lawrence River watershed and for the entire Basin. The assessment fulfills the requirement of the Compact and Agreement. The assessment will be used for a review of decision-making standards and their application, and for other purposes.

PURPOSE

Pursuant to Article 209 of the Agreement and Section 4.15 of the Compact the Parties [1]"....shall collectively conduct within the Basin, on a Great Lake and St. Lawrence River Basin basis, a periodic assessment of the Cumulative Impacts of Withdrawals, Diversions and Consumptive Uses from the Waters of the Basin. The assessment of the Cumulative Impacts shall be done upon the earlier of:

a. Every 5 years;
b. Each time the incremental losses to the Basin reach 50,000,000 gallons (190,000,000 litres) per day average in any 90-day period in excess of the quantity at the time of the last assessment; or,[2]
c. At the request of one or more of the Parties.

The assessment of Cumulative Impacts shall form a basis for the review of the Standard and the Exception Standard and their application. This assessment shall:

d. Utilize the most current and appropriate guidelines for such a review, which may include but not be limited to Council on Environmental Quality and Environment Canada guidelines;
e. Give substantive consideration to climate change or other significant threats to Basin Waters and take into account the current state of scientific knowledge, or uncertainty, and appropriate Measures to exercise caution in cases of uncertainty, if serious damage may result;
f. Consider Adaptive Management principles and approaches recognizing, considering and providing adjustments for the uncertainties in, and evolution of, science concerning the

1 Quoted text taken from Article 209 of the Agreement. Section 4.15 of the Compact includes similar language.
2 As of 2013, the Great Lakes Commission, at the request of the Regional Body and Compact Council, includes an interim cumulative impact assessment as an appendix to annual water use reports. This scaled-down assessment compares a given year's water use data against Lake and River water budget data as included in the most recent 5-year assessment.

Basin's water resources, watersheds and ecosystems including potential changes to Basin-wide processes, such as lake level cycles and climate; and,

g. [The Regional Body shall] [i]nclude the evaluation of Article 201 [of the Agreement] concerning Exceptions. Based on the results of this assessment, the provisions in that Article may be maintained, made more restrictive or withdrawn…."

Furthermore, the review and potential revisions to Basin-wide water conservation and efficiency goals and objectives pursuant to Article 304 paragraph 3 of the Agreement and Section 4.2.3 of the Compact must be in part based on the cumulative impact assessment.

DEFINITIONS

The standard definitions set forth in Article 103 of the Agreement and Section 1.2 of the Compact shall apply to the cumulative impact assessment, including the following terms:

"Basin or Great Lakes—St. Lawrence River Basin" means the watershed of the Great Lakes and the St. Lawrence River upstream from Trois-Rivières, Québec within the jurisdiction of the Parties.

"Consumptive Use" means that portion of Water Withdrawn or withheld from the Basin that is lost or otherwise not returned to the Basin due to evaporation, incorporation into Products, or other processes.

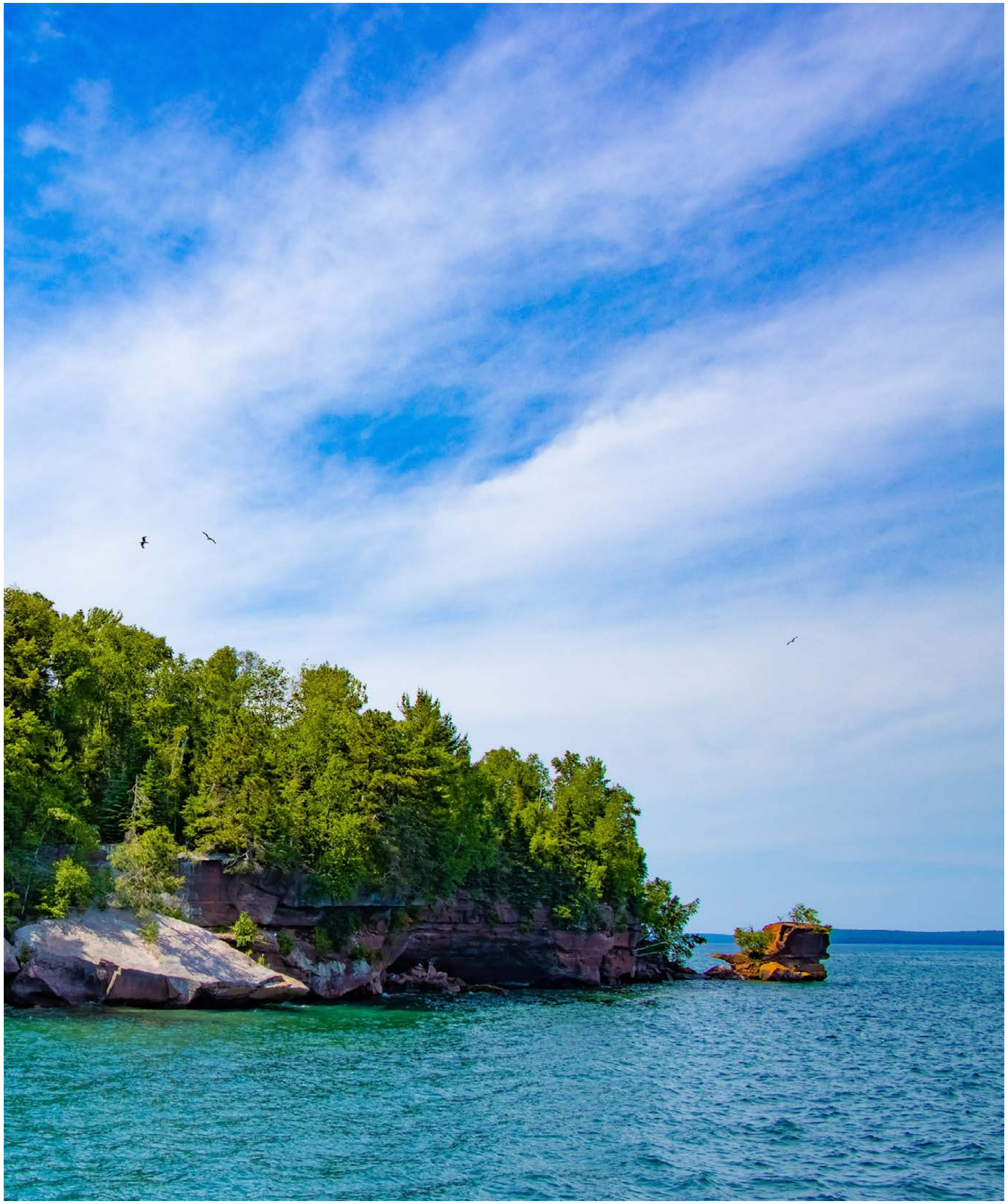
"Cumulative impacts" mean the impact on the Great Lakes—St. Lawrence River Basin Ecosystem that results from incremental effects of all aspects of a Withdrawal, Diversion or Consumptive Use in addition to other past, present, and reasonably foreseeable future Withdrawals, Diversions and Consumptive Uses regardless of who undertakes the other Withdrawals, Diversions and Consumptive Uses. Cumulative impacts can result from individually minor but collectively significant Withdrawals, Diversions and Consumptive Uses taking place over a period of time.

"Diversions" means a transfer of Water from the Basin into another watershed, or from the watershed of one of the Great Lakes into that of another by any means of transfer, including but not limited to a pipeline, canal, tunnel, aqueduct, channel, modification of the direction of a watercourse, a tanker ship, tanker truck or rail tanker but does not apply to Water that is used in the Basin or Great Lakes watershed to manufacture or produce a Product that is then transferred out of the Basin or watershed.

"Source Watershed" means the watershed from which a Withdrawal originates. If Water is Withdrawn directly from a Great Lake or from the St. Lawrence River, then the Source Watershed shall be considered to be the watershed of that Great Lake or the watershed of the St. Lawrence River, respectively. If Water is Withdrawn from the watershed of a stream that is a direct tributary to a Great Lake or a direct tributary to the St. Lawrence River, then the Source Watershed shall be considered to be the watershed of that Great Lake of the watershed of the St. Lawrence River, respectively, with a preference to the direct tributary stream watershed from which it was Withdrawn.

"Withdrawal" means the taking of Water from surface Water or groundwater. **"Withdraw"** has a corresponding meaning.

APPROACH *to* ASSESSING CUMULATIVE IMPACTS



The approach to assessing cumulative impacts for the period 2016-2020 is identical to that used in the first two 5-year assessments for 2006-2010 and 2011-2015. The assessment focuses on the hydrologic effects of Withdrawals, Consumptive Uses and Diversions on water supply and flow at Watershed and Basin scales. These hydrologic effects are presented in the context of Watershed and Basin water budgets: that is, the flows into and out of each Watershed and the Basin.

This assessment presents water budgets for the entire Basin and for each of the individual Watersheds. These include the watersheds for Lake Superior, Lakes Michigan-Huron, Lake Erie, Lake Ontario (collectively, Lakes) and the St. Lawrence River (River).

In the future, information may be developed through research and monitoring that would enable consideration of impacts other than hydrologic, such as economic and environmental, for the Basin, Lake, and River Watersheds.

The timeframe for this assessment is 2016-2020. For comparative purposes, longer data sets for flows are presented to provide a historical context for 2016-2020 data. The longer data sets for natural flows and Diversions are 1950-2015 For consumptive use, data for 2016-2020 are compared to those from the previous five-year reports. Future assessments may take a different approach as data and information improve. To that end, in 2011 the Parties adopted new water use reporting protocols that improved the timeliness, consistency and comparability of water use data. In 2013, the Parties developed new metadata protocols that track differences in reported values from one year to another. This metadata has greatly improved the quality of water use data reported by the Parties. The Parties further reviewed and revised these protocols in 2016.

The Basin water budget is an accounting of water flows into and out of the Basin. Some of these flows are natural and some are constructed or affected by humans. Withdrawals, Consumptive Uses and Diversions are part of the water budget. Each of these flows vary from year to year, either due to climate variability or due to human activities.

Inflows include precipitation on the surface of the Lake(s), surface water runoff to the Lake(s) or River, Diversions into some Lakes, and connecting channel flows into each of the Lakes or River, except for Lake Superior which does not have an inflowing connecting channel. Outflows include evaporation from the surface of the Lake(s), Diversions from some Lakes, and connecting channels flows out of each of the Lakes and Consumptive Uses. The St. Lawrence River at Trois Rivieres, Quebec is the outflow for the entire Basin. Although Withdrawals are a component of water budgets, this assessment considers only the hydrologic effect of Withdrawals, which is Consumptive Use.

Some Great Lakes have interbasin Diversions, which are Diversions into or out of the Basin. Some Great Lakes have intrabasin Diversions, which are Diversions within the Basin from one Watershed to another Watershed.

Only the intrabasin Diversion at the Welland Canal from Lake Erie to Lake Ontario is considered in this report. The Parties report Consumptive Uses and Diversions (interbasin and intrabasin) by Watershed on an annual basis.

Separately, groundwater seeps into and out of each Lake and the River through the Lake and River bottoms. In this assessment, however, **groundwater seepage into the Lakes and the River is not included, for three reasons.** First, there are limited data and computer models regarding seepage. The only computer model for the entire Basin is by Xu et al (2021). Second, the available data and computer model indicate that groundwater seepage is a relatively small component of the Lake(s) water budget, ranging from 0.6 percent for Lake Ontario to 1.3 percent for Lake Michigan. Third, scientists generally ignore groundwater seepage in water budget calculations for the Lake(s), so historical and current data are not available. As data and information improve, this approach can be reconsidered.

The water budgets presented in the assessment are focused on inflows and outflows. Clearly, if a Lake has an inflow greater than outflow, water levels in the Lake will rise, and vice versa. The effects of one particular inflow or outflow cannot be used to determine effects on water levels of a given Lake in a given year. Rather, **the sum of all inflows and all outflows determines Lake levels.** Historical water-level data for the Lake(s) is available for the time period covered in this assessment, 1950-2010. It is difficult, however, to directly relate annual water level changes on the Lake(s) to specific amounts of annual water flow change. The specific contribution made by Diversions and Consumptive Uses to water level changes, apart from natural variability, is uncertain given the complex hydrology, geographic and temporal variability of uses, and other factors (see section on Consideration of Uncertainty).

Lake Superior and Lake Ontario connecting channel outflows--the St. Marys River and St. Lawrence River--are regulated by control structures at Sault St. Marie and Cornwall, respectively. Decisions about operation of these control structures affect historical and current water budgets for the affected Lake(s) and connecting channels and must be considered in any budget calculations. Additional information about these operations may be accessed through the International Joint Commission, http://www.ijc.org/.

Consistent datasets for all inflows and outflows, except Consumptive Uses, are available from 1950-2010. Although data for some flows date back to the late 19th century, this assessment requires data on all flows and the most consistent data for the Basin begins in 1950. This data consists of monthly computations of each of the inflows and outflows for the Great Lakes and the St. Lawrence River, not including Consumptive Uses and smaller Diversions. Information in this assessment on Consumptive Use and all Diversions is reported for 2016-2020. This information is reported by the Parties. For historical context, however, the reported data on Diversions is compared against historical data gathered by the U.S. Army Corps of Engineers.

For the Basin and each Lake Watershed, individual Diversions are aggregated and presented as a single value by the Parties. Data for some Diversions in the States is collected separately by federal agencies and available from the U.S. Army Corps of Engineers. Consumptive Uses are reported by the Parties by Watershed to the Great Lakes Water Use Database Repository on an annual basis.

Flows are complex and can be difficult to relate to water supply. Therefore, the information is presented in text, graphic and tabular forms. Following standard scientific procedures, inflows are presented as positive numbers and outflows are presented as negative numbers. This convention is used to help relate different flows to one another and to supply. It is not intended to communicate a value judgment on whether these flows are good or bad for the Basin. All flows are given in cubic feet per second (cfs). Sources of all data are included in Appendix, rather than being cited in the text, figures and tables of this report.

HYDROLOGIC EFFECTS *of* CONSUMPTIVE USES & DIVERSIONS

The following sections discuss the hydrologic effects of Consumptive Uses and Diversions for the Basin, Lakes and River. In each section, water budgets for the reporting period, 2016-2020, are presented and compared to long-term water budgets for 1950-2015 to provide a relative hydrologic context for the reporting period. Consumptive Uses and Diversions are then compared to natural inflows (connecting channel, precipitation on the Lake(s), and runoff).

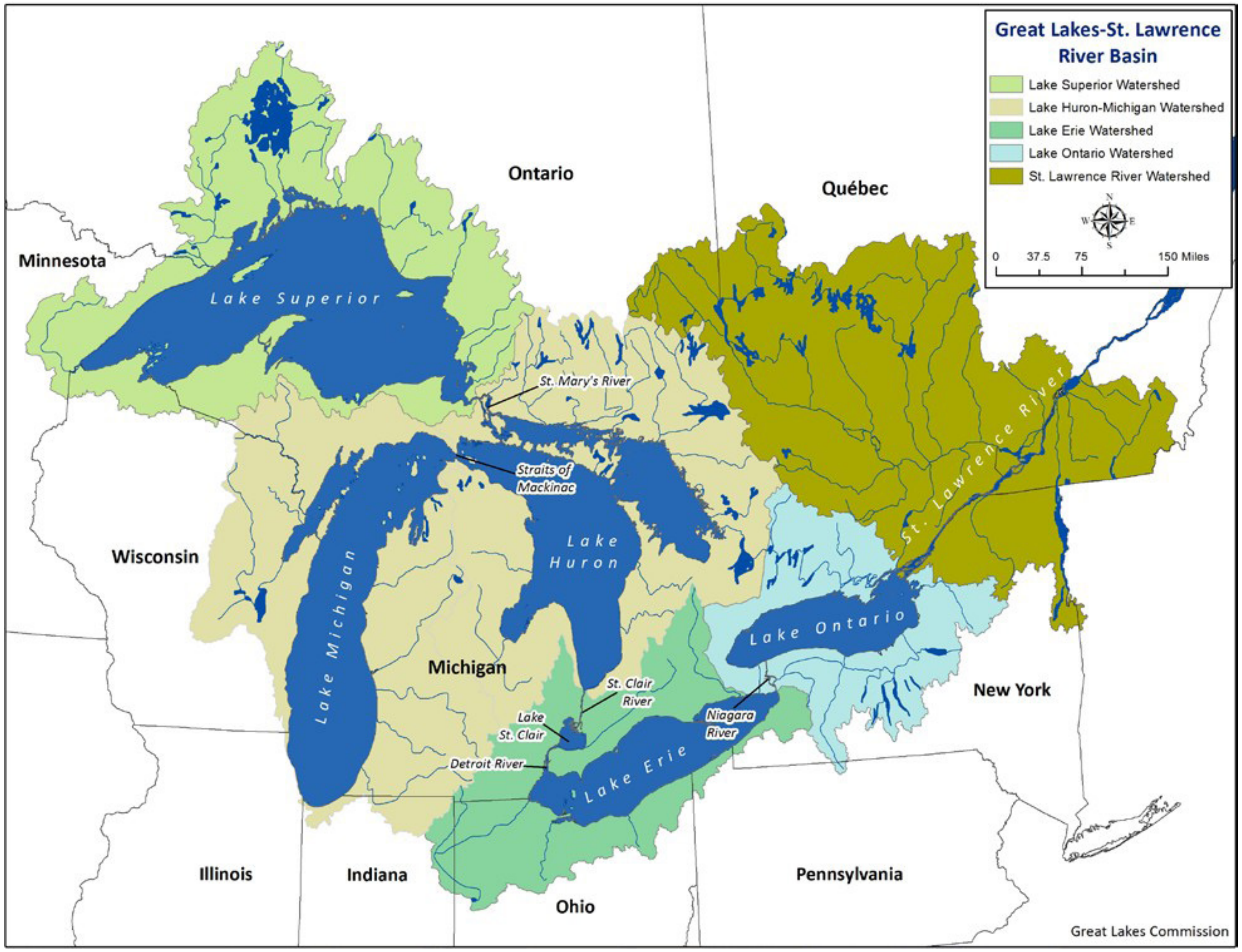


Figure 1. *Great Lakes-St. Lawrence River Basin*

Figure 1 shows the Basin and the Watersheds as defined by the Compact and Agreement. Upstream connecting channels are included in each Lake Watershed. Figure 2 and Table A present a comparison of five-year reporting period averages and 65-year historical period averages in water budget data for the Basin. As illustrated in Figure 2 and Table A, the largest outflow for the Basin is the St. Lawrence River and the smallest is Consumptive Use. The average Basin water flow components are variable when comparing components during these time periods. All the natural flows in the Basin—runoff, precipitation on the Lakes, evaporation from the Lakes, and St. Lawrence River—are greater during the five-year period compared to the 65-year period. Figure 2 and Table A show that the natural inflows and outflows dominate the water budget. Figure 2 and Table A also illustrate that inflows do not always equal outflows, which is attributable to the imprecisions inherent in the techniques used to estimate average flows and to changes in storage over time. Many of these flows are imprecisely estimated and therefore have significant uncertainties associated with them. However, this is the best available data.

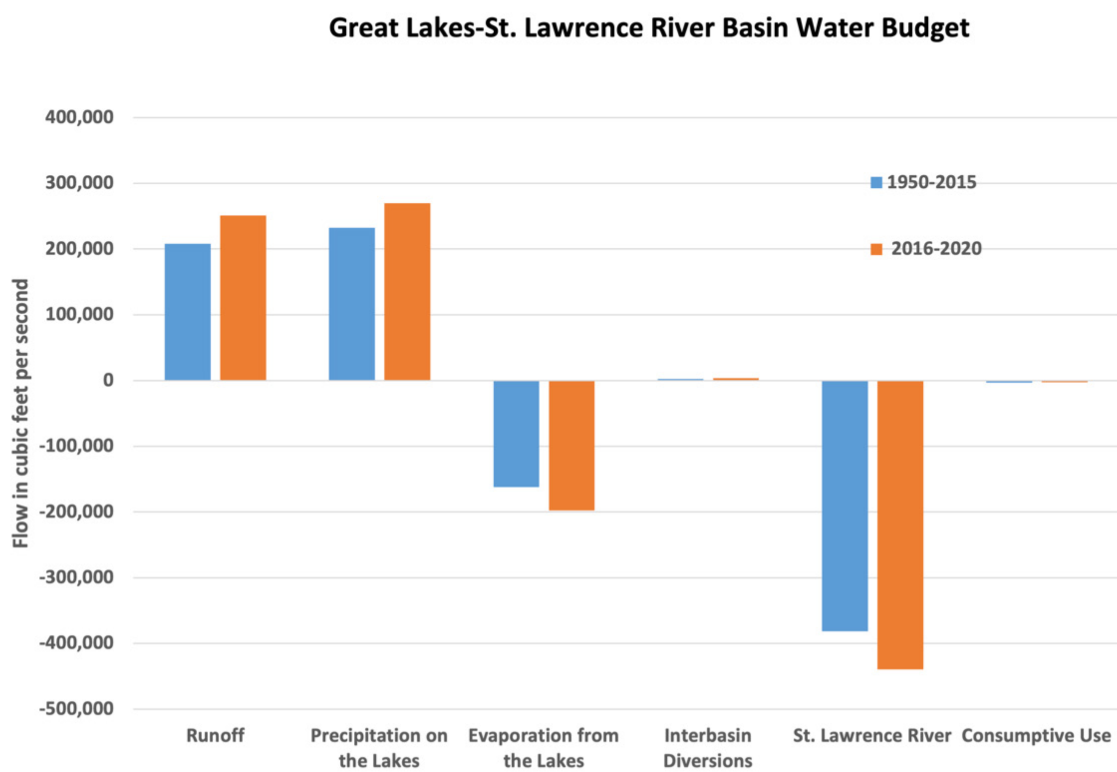


Figure 2. *Great Lakes-St. Lawrence River Basin water budget using average annual flows, comparing a five-year period (2016-2020) to a historical 65-year period (1950-2015).*

The cumulative hydrologic effect of Consumptive Uses and Diversions as compared to natural inflow for 2016-2020 is shown for the Basin in Figure 3. Table B includes the flow values used to construct Figure 3 and shows the amount of Consumptive Uses and Diversions compared to runoff and precipitation.

Water Budget Component	5-year Flow (cfs)	65-year Flow (cfs)
Runoff	250,971	207,924
Precipitation	269,928	232,404
Evaporation	-197,574	-162,033
St. Lawrence River	-439,754	-381,526
Interbasin Diversions	3541	2619
Consumptive Uses	-2,710	-3,283*

Table A. *Water budget average flow values for the Great Lakes-St. Lawrence River Basin, comparing 5-year period (2016-2020) to a historical 65-year period (1950-2015). * Average consumptive use for 2006-2015.*

As illustrated in Table B, the cumulative hydrologic effect of Consumptive Uses and Diversions (annual averages) for the Basin are small relative to inflows (runoff plus precipitation). The cumulative hydrologic effect of Consumptive Uses and Diversions is positive for 2016-2019 and negative for 2020. A positive number means more water is diverted into the Basin than the total amount of water diverted out of the

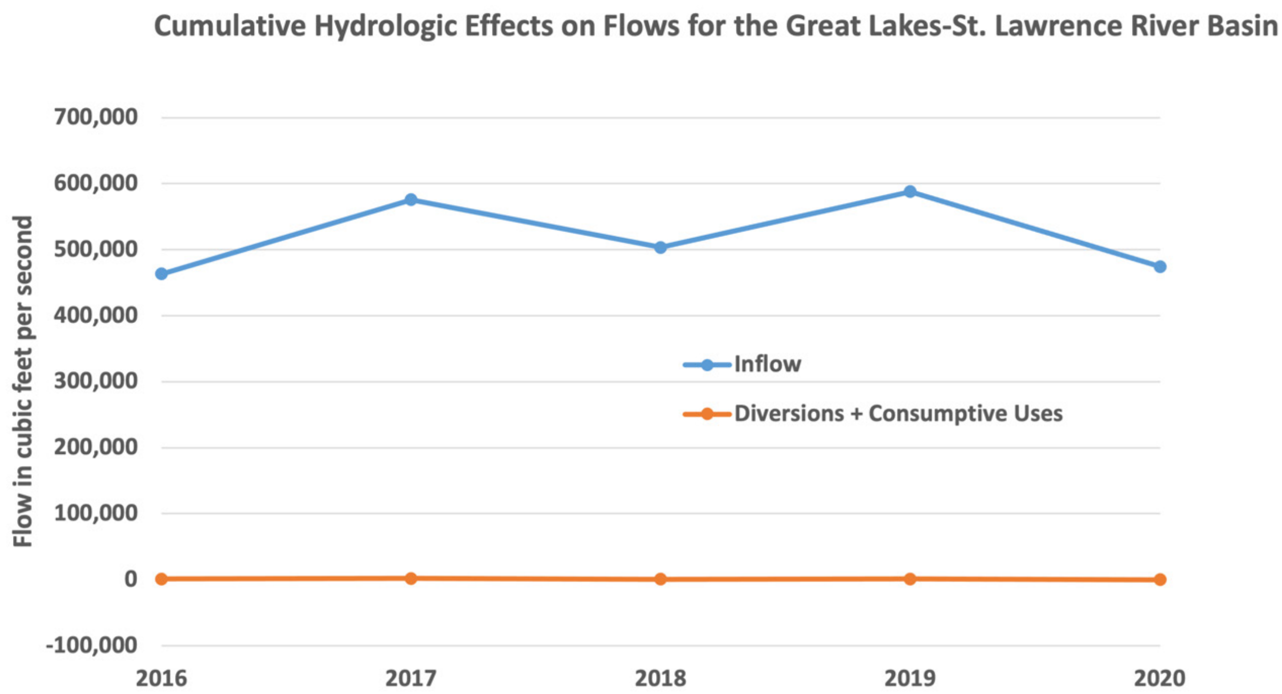


Figure 3. *Cumulative hydrologic effects on flows for the Great Lakes-St. Lawrence River Basin, 2016-2020.*

Year	Runoff + Precipitation (cfs)	Consumptive Uses + Diversions (cfs)
2016	463,342	908
2017	575,703	1806
2018	503,392	621
2019	587,864	1056
2020	474,197	-217

Table B. *Water budget values in cubic feet per second for the Great Lakes-St. Lawrence River Basin, 2016-2020.*

The significance of changes to Basin flow or Lake water levels may differ depending on the temporal and geographic scales used or issues of concern related to a particular water use or water user. **Assessments conducted at the Basin or Lake Watershed scale by design do not focus on potential impacts at smaller scales, nor on a particular water use or user.** For example, higher water levels or river flow may generally improve boating opportunities or shipping carrying capacities, but also may increase flooding and erosion potential in particular areas. Similarly, certain plants and animals thrive at high water levels or flows, while others thrive at low water levels or flows.

The International Upper Great Lakes Study concludes fluctuating water levels – which provide for optimal conditions for different species in different years – support the most diverse and resilient aquatic ecosystems.

For the Basin, the Lake and River Watersheds have unique varieties of Consumptive Uses and Diversions that are described in each of the sections below. For example, the cumulative hydrologic effect of Consumptive Uses and Diversions on the Lake Superior watershed (as for the entire Basin) is an increase in flow. Diversions into the Lake Superior watershed exceed Consumptive Uses, resulting in an increase in connecting channel outflow as compared to the natural baseline.

LAKE SUPERIOR WATERSHED

Inflows to Lake Superior include runoff, precipitation on the surface of Lake Superior, and Diversions. Outflows include evaporation from the surface of Lake Superior, outflow from the St. Marys River, and Consumptive Uses throughout the Watershed. Figure 4 shows the watershed.

Figure 5 and Table C present a comparison of the 5-year period and 65-year period averages in water budget data for Lake Superior. As illustrated in Figure 5 and Table C, the largest outflow for the Lake Superior Watershed is the St. Marys River and the smallest is Consumptive Use. All natural flows—runoff, precipitation on the Lake, evaporation from the Lake, and St Marys River are greater for the 5-year reporting period than the 65-year period. Specifically, inflows of runoff and precipitation for the 5-year period were 26,442 cfs more than the historical average. Outflows of evaporation from the surface of Lake Superior and the St. Marys River for the 5-year period were 31,544 cfs greater than the historical average.

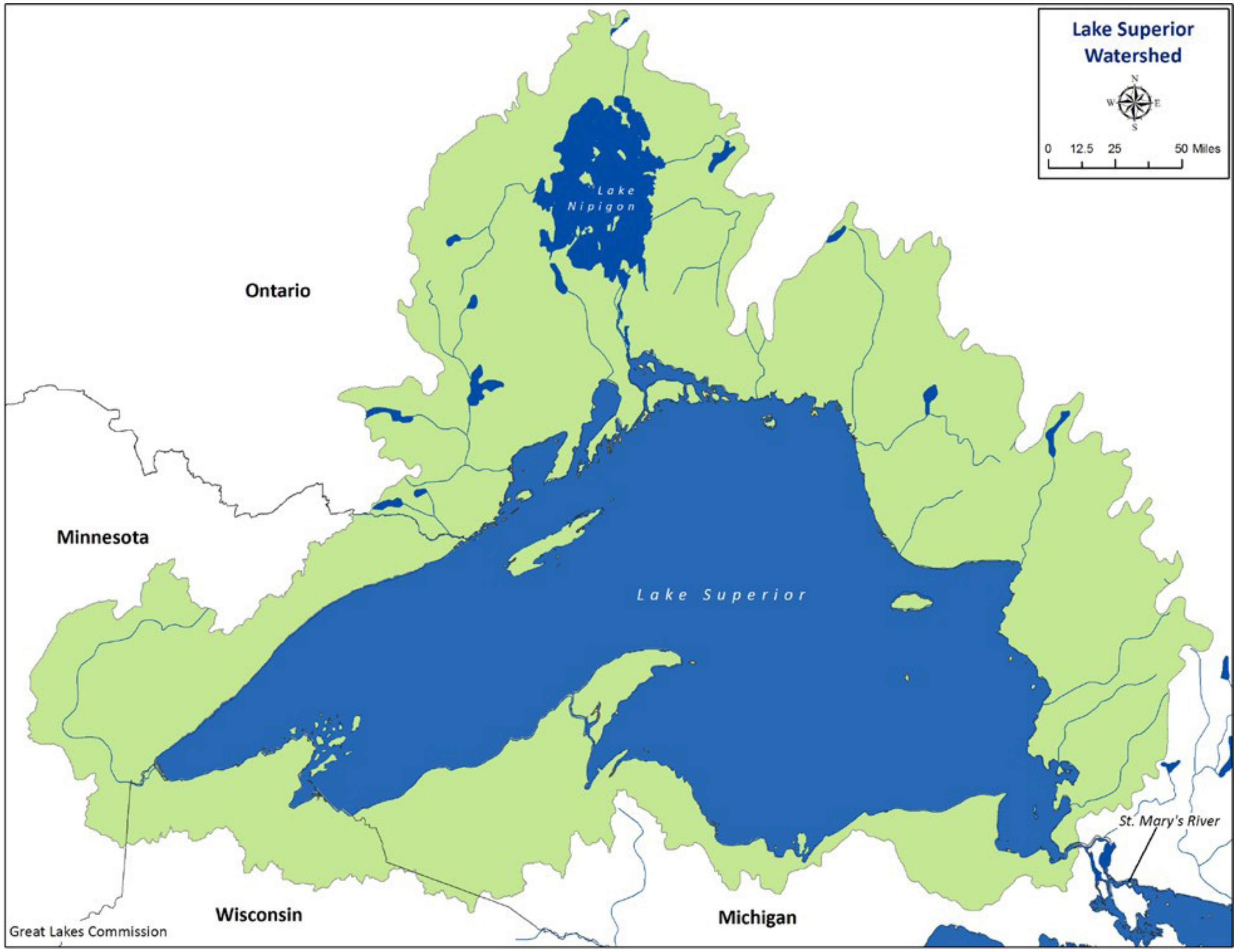


Figure 4. *Lake Superior Watershed*

Data in Table C and used in Figure 5 indicate that inflows do not equal outflows. In some years outflows may exceed inflows while in other years inflows may exceed outflows. This is due in part to changes in storage in Lake Superior and in part to a lack of accuracy or uncertainties in measurements or estimates of the flows. This inequality of inflow and outflow is true for each of the Lakes and the River. Issues of uncertainty are discussed in the next main section.

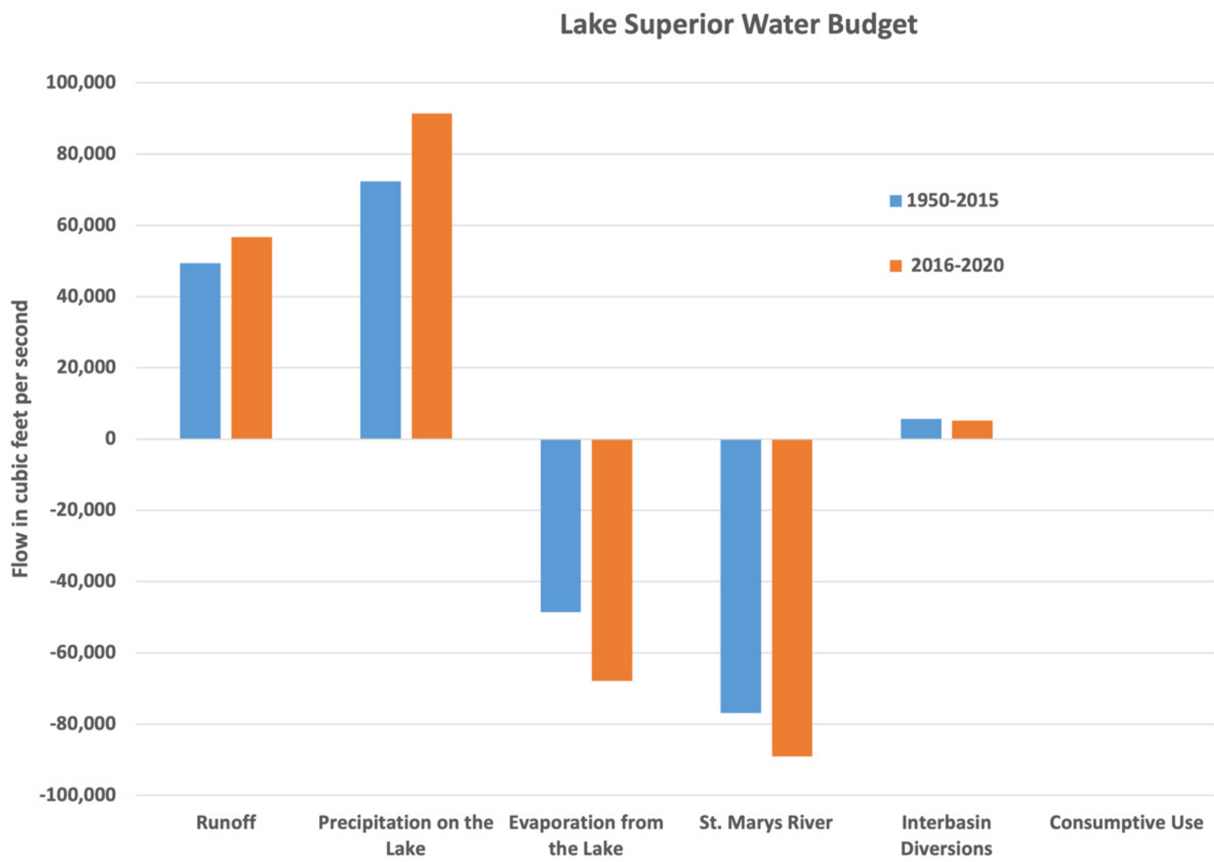


Figure 5. *Water budget average flow values for Lake Superior using average annual flows, comparing a 5-year period (2016-2020) to a historical 65-year period (1950-2015).*

Water Budget Component	5-year Flow (cfs)	65-year Flow (cfs)
Runoff	56,753	49,410
Precipitation	91,409	72,301
Evaporation	-67,879	-48,595
St. Marys River	-89,087	-76,827
Interbasin Diversions	5,201	5,648
Consumptive Uses	-62	-93*

Table C. *Water budget average flows for Lake Superior, comparing a 5-year period (2016-2020) to a historical 65-year period (1950-2015). *Average consumptive use for 2006-2015.*

The hydrologic effect of Consumptive Uses and Diversions as compared to natural inflows for 2016-2020 is shown for the Lake Superior Watershed in Figure 6 and Table D. As described previously, this assessment defines a hydrologic effect as the Consumptive Uses plus Diversions compared to the inflows (connecting channel flow plus precipitation and runoff). Note that the net effect of Consumptive Uses and Diversions for Lake Superior is an increased average flow of 5,108 cfs during the 5-year reporting period. As with similar information described previously in this assessment, each data point has significant uncertainty associated with it, and is based on averages on a 5-year timescale. Future assessments may take a different approach as data and information improve.

As illustrated in Table D, for the Lake Superior Watershed the hydrologic effect of Consumptive Uses and Diversions (annual averages) are small relative to inflows. Further, while inflows fluctuate from 2016-2020, the cumulative hydrologic effect of Consumptive Uses and Diversions is fairly constant for these annual averages. The net effect of Consumptive Uses and Diversions is positive for the Lake Superior Watershed.

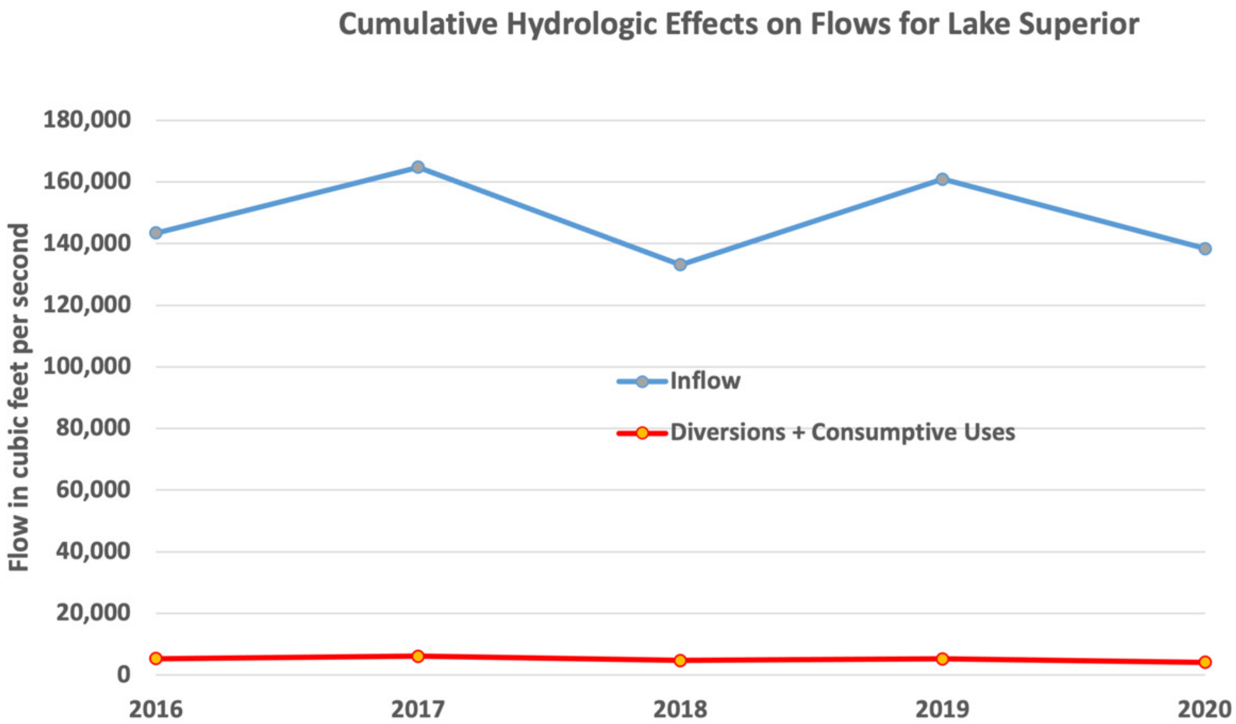


Figure 6. *Cumulative hydrologic effects on flows for Lake Superior, 2016-2020.*

Year	Total Inflow	Estimated net volume of consumptive uses and diversions	Consumptive uses and diversions as a percentage of total inflow
2016	143,455	5,307	3.70%
2017	164,802	6,141	3.73%
2018	133.161	4,716	3.54%
2019	160,960	5,260	3.27%
2020	138,430	4,115	2.97%

Table D. *Water budget values in cubic feet per second for Lake Superior, 2016-2020.*

While the water budgets presented in this assessment focus on flow, water supply can either be described in volumetric terms (e.g. quadrillion of gallons) or in terms of water levels for the individual Lakes. Water level data is available both on an historical and current basis. When compared to this baseline data, water levels can help characterize how flow changes affect supply.

Accordingly, below are graphic presentations for Lake Superior levels, both historically and for the period of 2016-2020. The historical water levels in Figure 7 show natural cyclical variability. As illustrated in figure 8, water levels during 2016-2020 also show this variability with an overall range of about .52 feet. Both figures present average data. The specific contribution made by Diversions and Consumptive Uses at any given point in time or space, separate and apart from natural variability, is uncertain given the complex hydrologic, geographic and temporal variability of uses, and other factors. Since Diversions and Consumptive Uses are small compared to natural flows, their cumulative hydrologic effect on water levels is likewise small.[3]

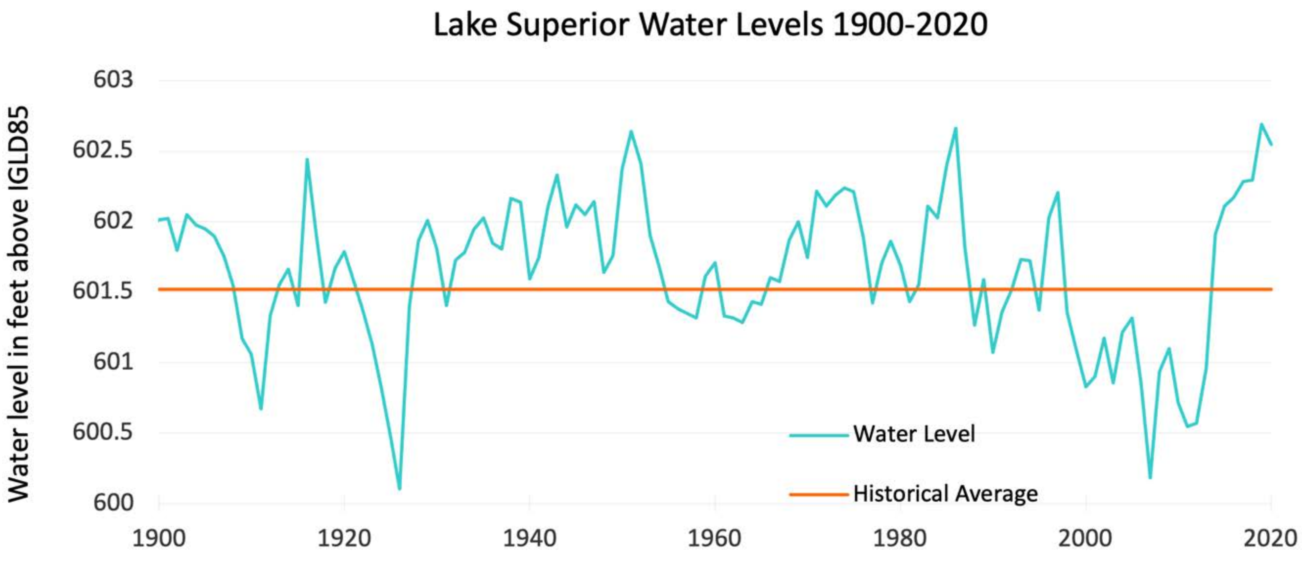


Figure 7. *Historical water levels for Lake Superior, 1900-20203*

3 Water levels presented throughout this assessment are compared against International Great Lakes Datum (IGLD) 1985. IGLD is the reference system by which Great Lakes-St. Lawrence River Basin water levels are measured. It consists of benchmarks at various locations on the Lakes and St. Lawrence River that roughly coincide with sea level. All water levels are measured in feet or meters above this point. Movements in the earth's crust necessitate updating this datum every 25-30 years. The first IGLD was based upon measurements and bench marks that centered on the year 1955. The most recently updated datum uses calculations that center on 1985.

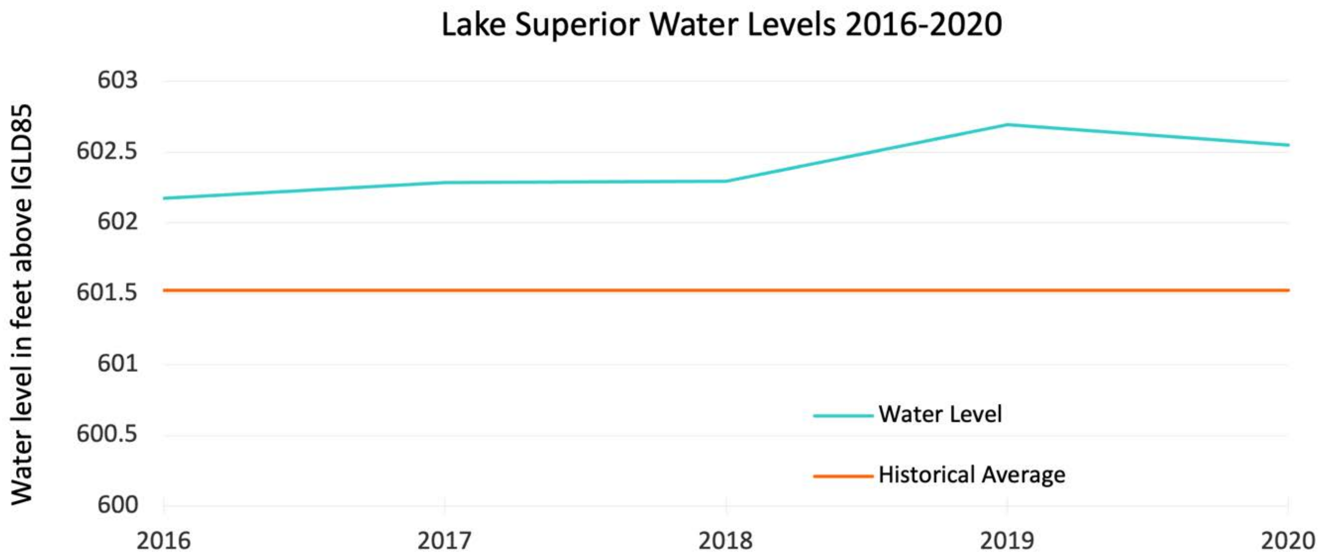


Figure 8. *Water levels for Lake Superior, 2016-2020.*

LAKES MICHIGAN-HURON WATERSHED

Inflows to Lakes Michigan-Huron include the St. Marys River, runoff, and precipitation on the surface of the Lakes. Outflows for the Watershed include the St. Clair River, evaporation from the surface of the Lakes, a Diversion and Consumptive Uses throughout the Watershed. Figure 9 shows the watershed.

Figure 10 and Table E present a comparison of the 5-year period and 65-year period averages in water budget data for Lakes Michigan-Huron. As illustrated in Figure 10 and Table E, the largest outflow for the Lakes Michigan-Huron Watershed is the St. Clair River and the smallest is Consumptive Use. All natural flows—runoff, precipitation on the Lake, St Marys River, evaporation from the Lake, and St. Clair River are greater for the 5-year reporting period than the 65-year period. Specifically, inflows of runoff, precipitation, and St. Marys River were 49,560 cfs greater for the 5-year period, and outflows of evaporation from the surface of Lakes Michigan-Huron and the St. Clair River were 49,127 cfs greater for the 5-year period than the historical average.

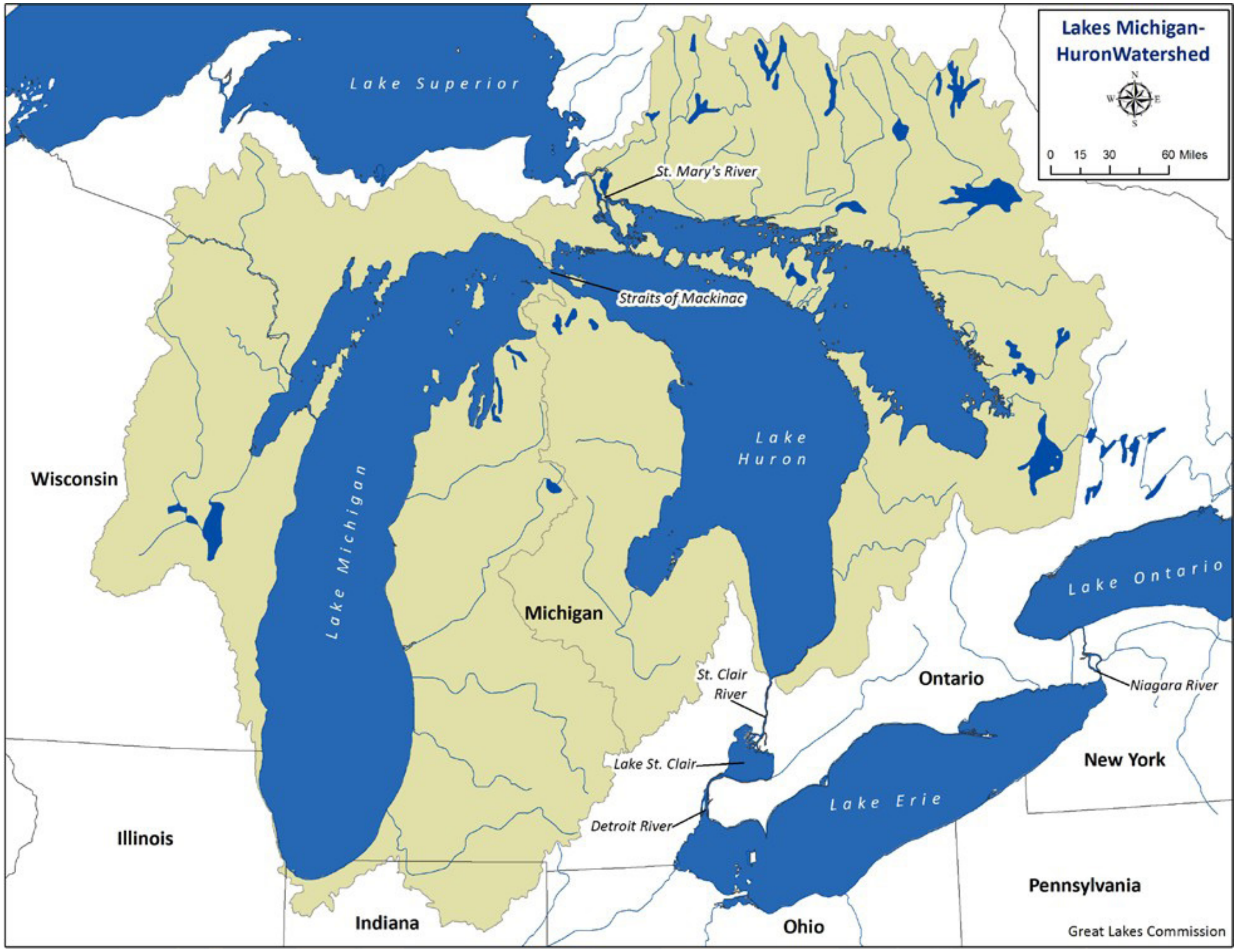


Figure 9. *Lakes Michigan-Huron Watershed*

Data in Table E and used in Figure 10 indicate that inflows do not equal outflows. In some years outflows may exceed inflows while in other years inflows may exceed outflows. This is due in part to changes in storage in Lakes Michigan-Huron and in part to a lack of accuracy or uncertainties in measurements or estimates of the flows. This inequality of inflow and outflow is true for all of the Lake(s) and the River. Issues of uncertainty are discussed in the next main section.

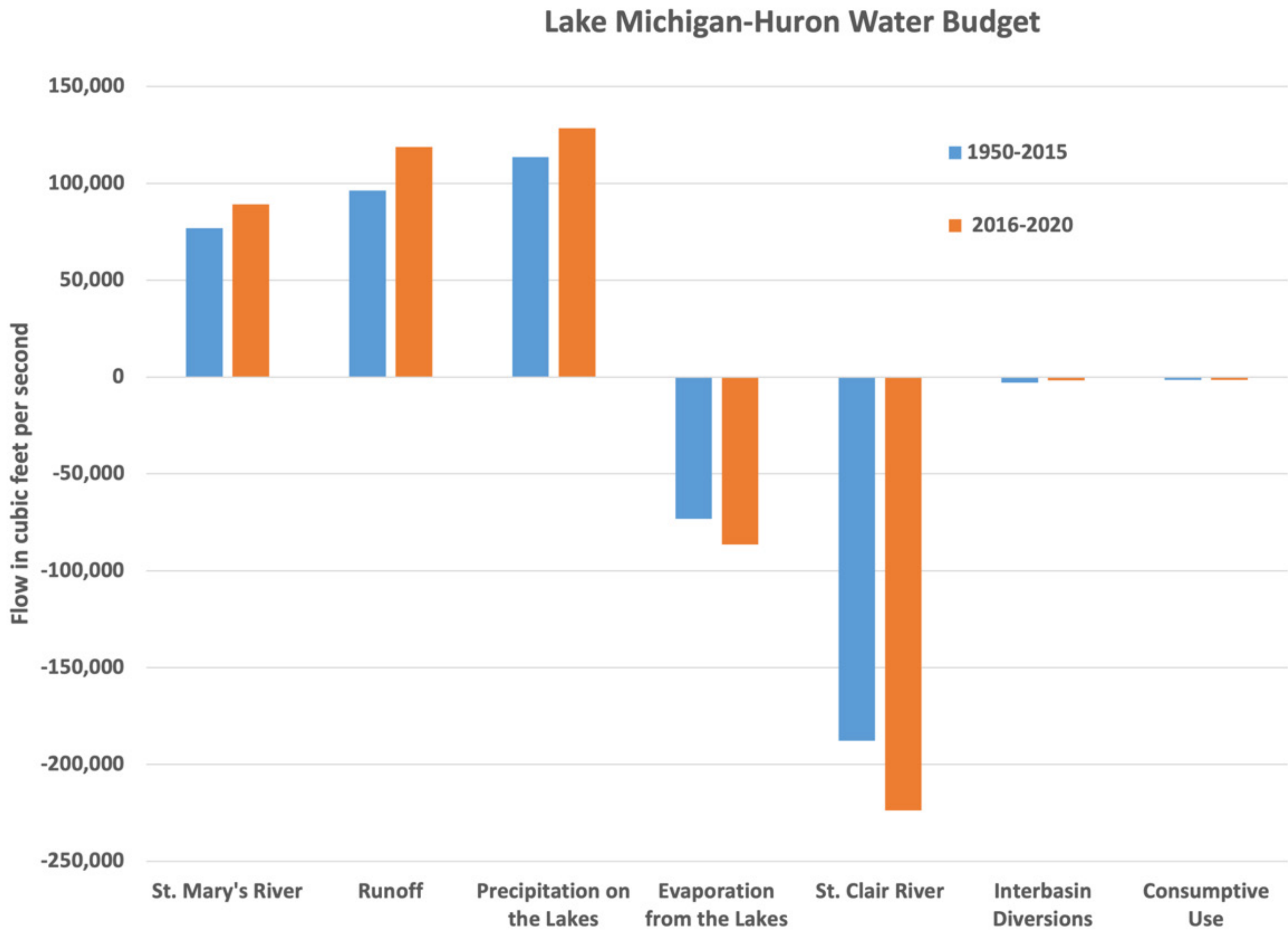


Figure 10. *Water budget average flow values for Lakes Michigan-Huron using average annual flows, comparing a 5-year period (2016-2020) to a historical 65-year period (1950-2015).*

Water Budget Component	5-year Flow (cfs)	65-year Flow (cfs)
St. Marys River	89,087	76,827
Runoff	118,785	96,253
Precipitation	128,332	113,564
Evaporation	-86,452	-73,136
St. Clair River	-223,695	-187,884
Interbasin Diversions	-1,660	-3,029
Consumptive Uses	-1,428	-1,423*

Table E. *Water budget average flows for Lakes Michigan-Huron, comparing a 5-year period (2016-2020) to a historical 65-year period (1950-2015). *Average consumptive use for 2006-2015.*

The hydrologic effect of Consumptive Uses and Diversions as compared to natural inflows for 2016-2020 is shown for the Lakes Michigan-Huron Watershed in Figure 11. As previously described, this assessment defines a hydrologic effect as the Consumptive Uses plus Diversions compared to the inflows (connecting channel flow plus precipitation and runoff). Table F includes the flow values used to construct Figure 11 and shows the volume of Consumptive Uses and Diversions compared to runoff and precipitation. As with similar information previously described in this assessment, each data point has significant uncertainty associated with it, and is based on averages on a 5-year timescale. Future assessments may take a different approach as data and information improve.

As illustrated in Table F, for the Lakes Michigan-Huron Watershed the hydrologic effect of Consumptive Uses and Diversions (annual averages) are small relative to inflows. The net effect of Diversions and Consumptive Uses is an increased outflow of 3,088 cfs for the 5-year reporting period. Further, while inflows fluctuate from 2016-2020, the hydrologic effect of Consumptive Uses and Diversions is fairly constant for these annual averages.

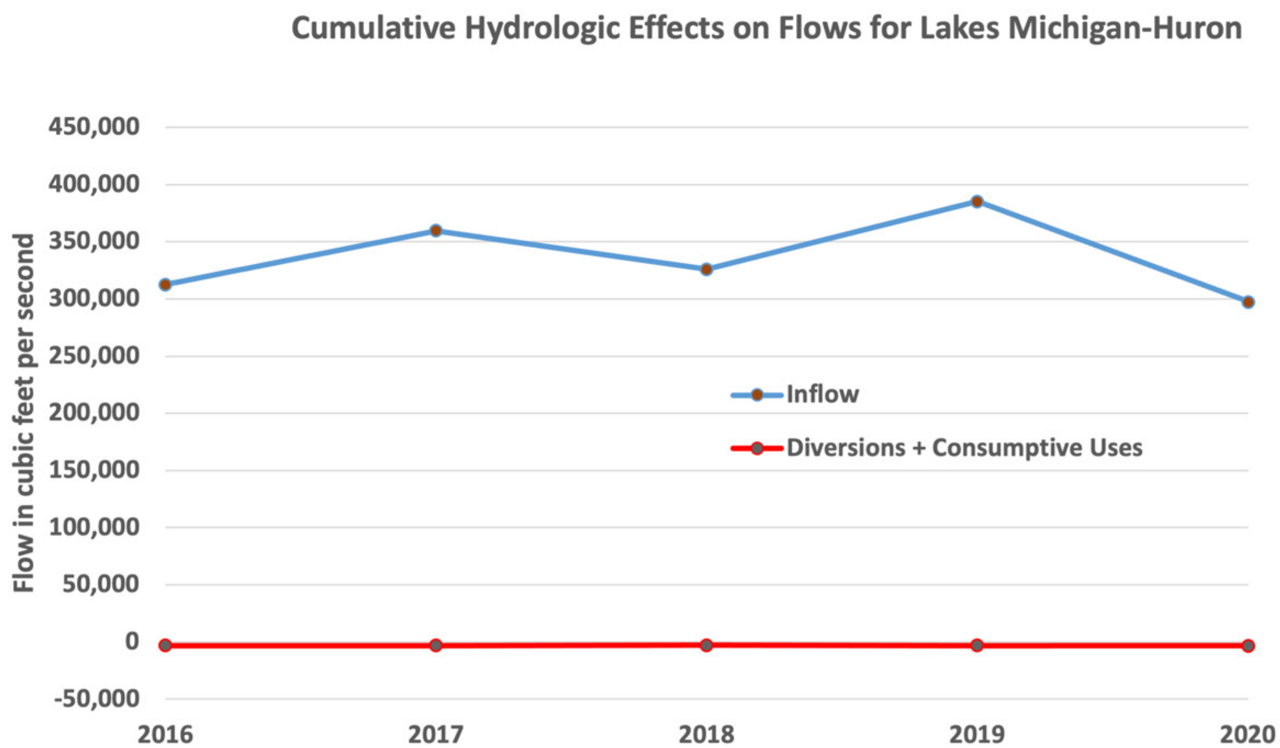


Figure 11. *Cumulative hydrologic effects on flows for Lakes Michigan-Huron, 2016-2020.*

Year	Total Inflow	Estimated net volume of consumptive uses and diversions	Consumptive uses and diversions as a percentage of total inflow
2016	312,559	-3,161	1.01%
2017	359,665	-3,142	0.87%
2018	325,859	-2,902	0.89%
2019	385,145	-3,048	0.79%
2020	297,803	-3,187	1.07%

Table F. *Water budget values in cubic feet per second for Lakes Michigan-Huron, 2016-2020.*

While the water budgets presented in this assessment focus on flow, water supply can either be described in volumetric terms (e.g., quadrillion of gallons) or in terms of water levels for the individual Lakes. Water level data is available both on an historical and current basis. When compared to this baseline data, water levels can help characterize how flow changes affected supply. Accordingly, below are graphic presentations for Lakes Michigan-Huron water levels, both historically and for the period of 2016-2020. The historical water levels in Figure 12 show natural cyclical variability. As illustrated in Figure 13, water levels during 2016-2020 also show this variability with an overall range of 2.0 feet. Both figures present average data. The specific contribution made by Diversions and Consumptive Uses at any given point in time or space, separate and apart from natural variability, is uncertain given the complex hydrologic, geographic and temporal variability of uses, and other factors. Since Diversions and Consumptive Uses are small compared to natural flows, their hydrologic effect on water levels is likewise small.

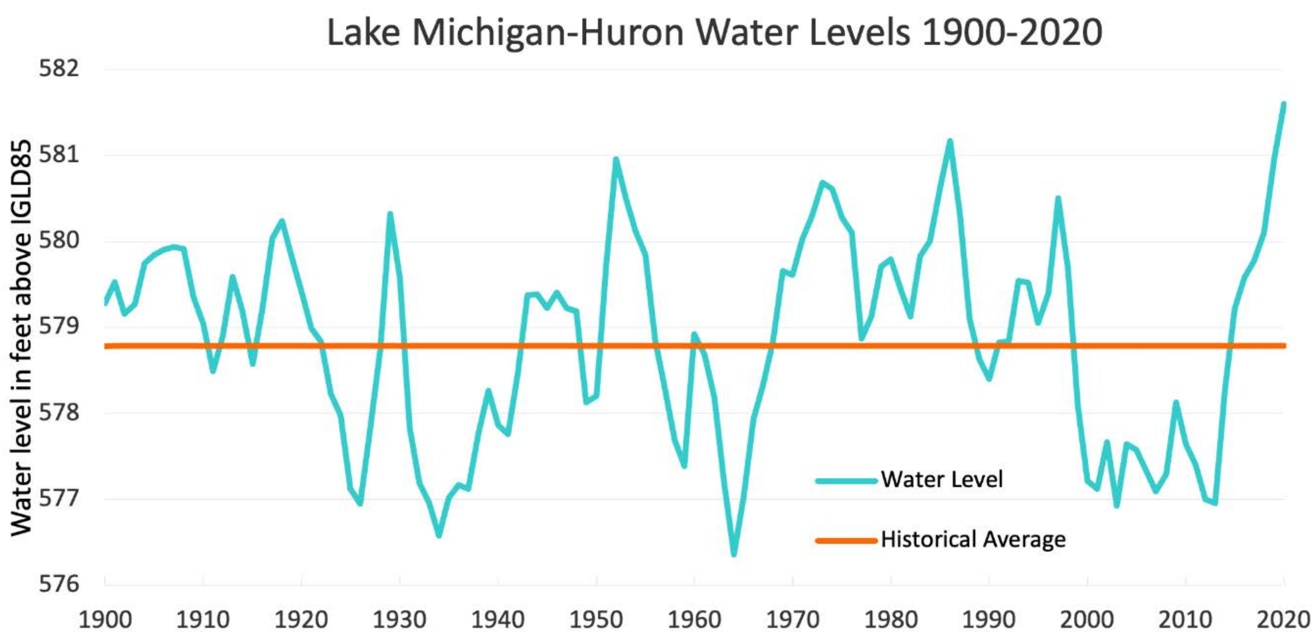


Figure 12. *Historical water levels for Lakes Michigan-Huron, 1900-2020.*

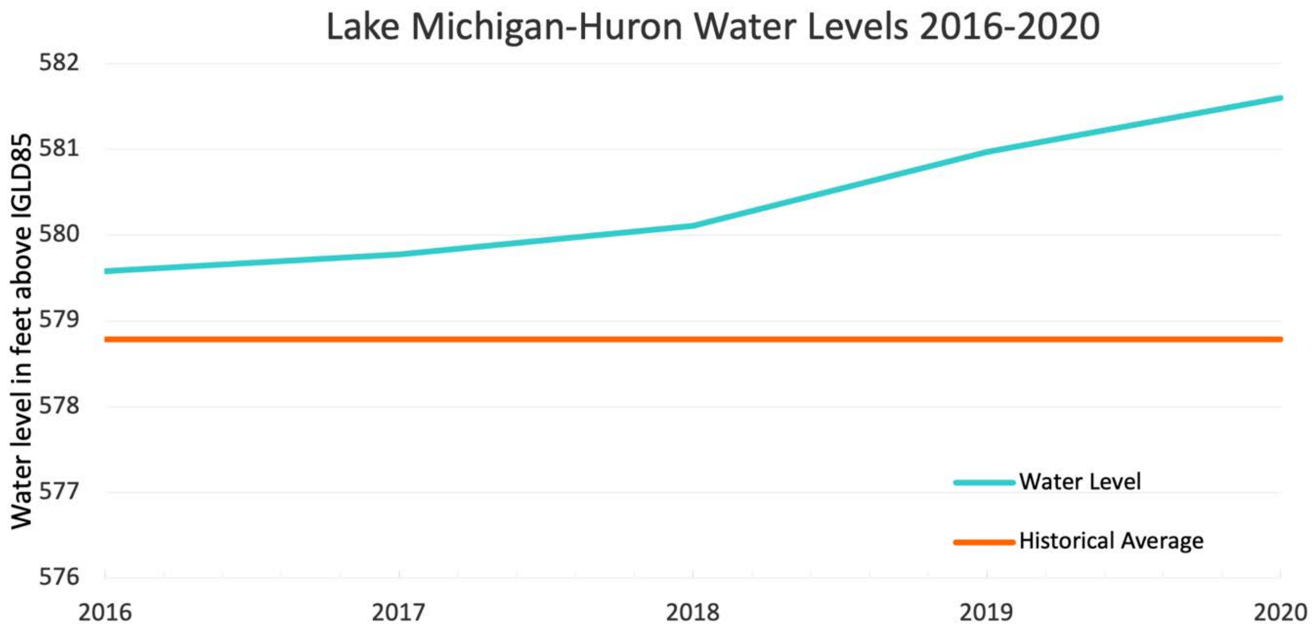


Figure 13. *Water levels for Lakes Michigan-Huron, 2016-2020.*

LAKE ERIE WATERSHED

Inflows to Lake Erie include the Detroit River, runoff, and precipitation on the surface of the Lake. The Detroit River inflow incorporates runoff from the area between the Detroit River measurement site and the St. Clair River measurement site, as well as precipitation on and evaporation from Lake St. Clair. Outflows include the Niagara River, evaporation from the surface of the Lake, Diversions and Consumptive Uses throughout the Watershed.[4] Figure 14 shows the watershed.

Figure 15 and Table G present a comparison of the 5-year period and 65-year period averages in water budget data for Lake Erie. As illustrated in Figure 15 and Table G, the largest outflow for the Lake Erie Watershed is the Niagara River and the smallest is Consumptive Use. All natural flows—runoff, precipitation on the Lake, Detroit River, evaporation from the Lake, and Niagara River are greater for the 5-year reporting period than the 65-year period. Specifically, inflows of runoff, precipitation on the surface of Lake Erie, and the Detroit River

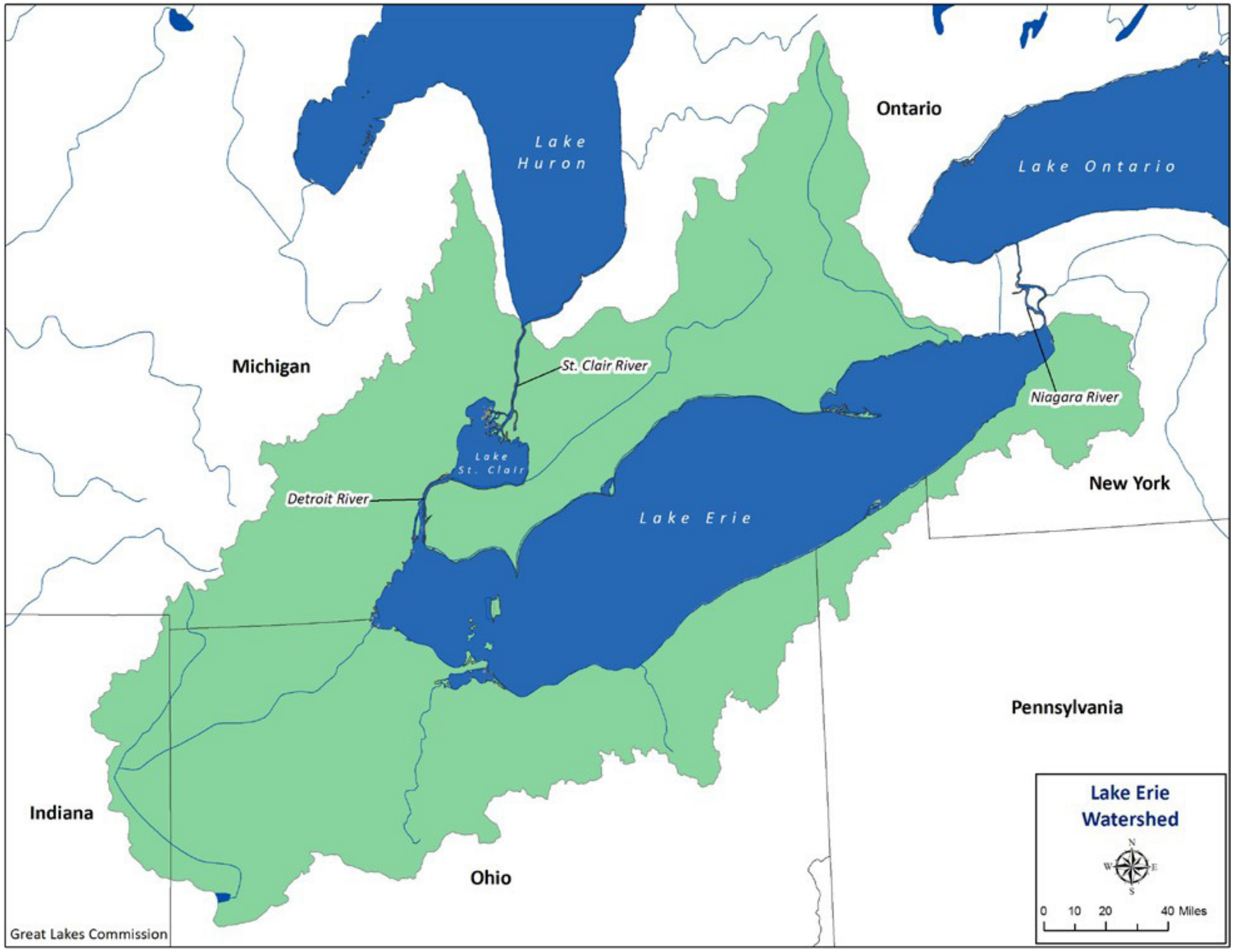


Figure 14. *Lake Erie Watershed*

4 Diversion data for the Lake Erie Watershed include an intrabasin diversion at Welland Canal.

were 43,861cfs during the 5-year period. Outflows of evaporation from the surface of Lake Erie, the Niagara River, and intrabasin diversions were 83,468 cfs more during the 5-year period.

Data in Table G and used in Figure 15 indicate that inflows do not equal outflows. In some years outflows may exceed inflows while in other years inflows may exceed outflows. This is due in part to changes in storage in Lake Erie and in part to a lack of accuracy or uncertainties in measurements or estimates of the flows. This inequality of inflow and outflow is true for each of the Lake(s) and the River. Issues of uncertainty are discussed in the next main section.

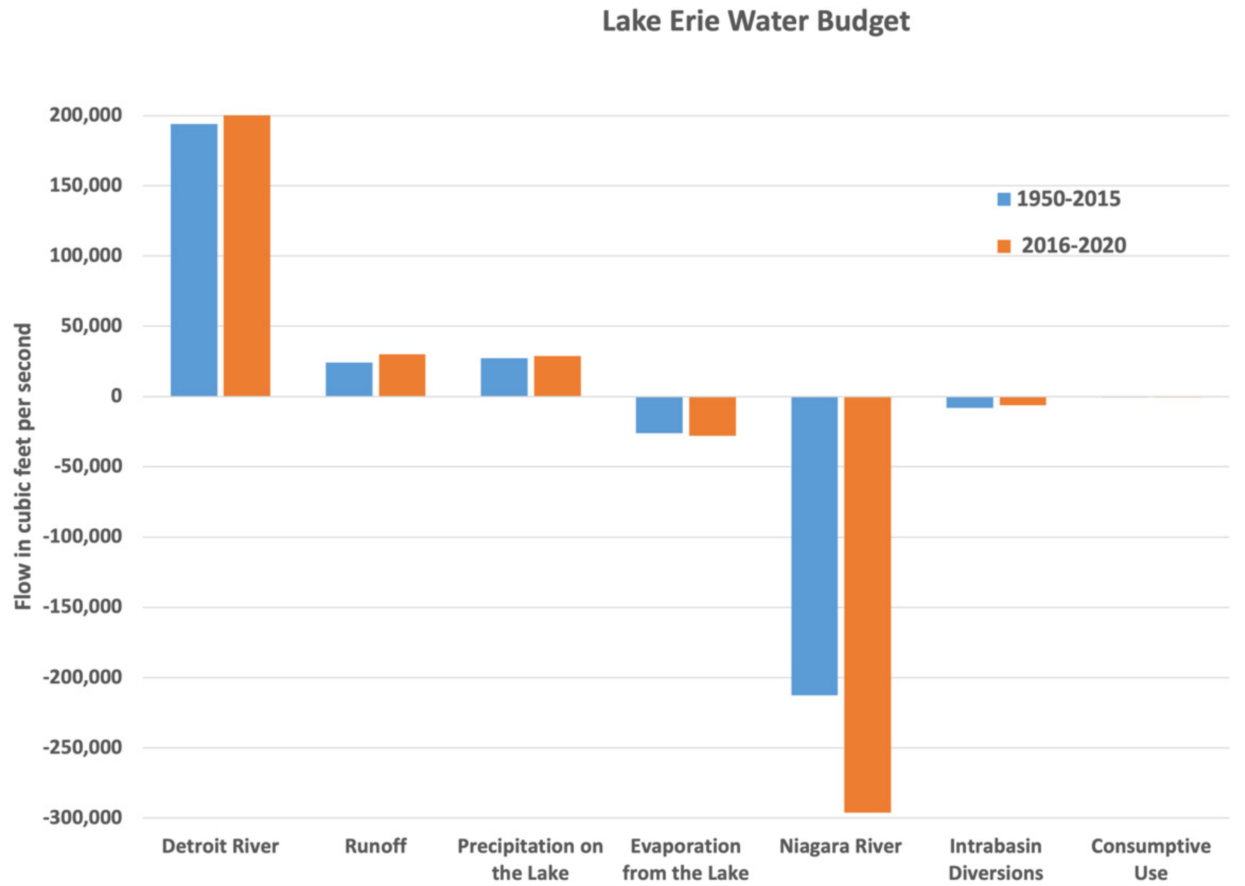


Figure 15. *Water budget average flow values for Lake Erie using average annual flows, comparing a 5-year period (2016-2020) to a historical 65-year period (1950-2015).*

Water Budget Component	5-year Flow (cfs)	65-year Flow (cfs)
Detroit River	230,575	194,182
Runoff	30,148	24,251
Precipitation	28,941	27,370
Evaporation	-27,818	-26,120
Niagara River	-296,178	-212,579
Intrabasin Diversion	-6,336	-8,165
Consumptive Uses	-664	-716*

Table G. *Water budget average flows for Lake Erie, comparing a 5-year period (2016-2020) to a historical 65-year period (1950-2015). * Average consumptive use for 2006-2015.*

The hydrologic effect of Consumptive Uses and Diversions as compared to natural inflows for 2016-2020 is shown for the Lake Erie Watershed in Figure 16. As previously described, this assessment defines a hydrologic effect as the Consumptive Uses plus Diversions compared to the inflows (connecting channel flow plus precipitation and runoff). Table H includes the flow values used to construct Figure 16 and shows the volume of Consumptive Uses and Diversions compared to runoff and precipitation. As with similar information described previously in this assessment, each data point has significant uncertainty associated with it, and is based on averages on a 5-year timescale. Future assessments may take a different approach as data and information improve.

As illustrated in Table H, for the Lake Erie Watershed the cumulative hydrologic effect of Consumptive Uses and Diversions (annual averages) are small relative to inflows. The net effect of Diversions and Consumptive Uses is an increased outflow of 7,001 cfs for the 5-year reporting period. Further, while inflows fluctuate from 2016-2020, the hydrologic effect of Consumptive Uses and Diversions is fairly constant for these annual averages.

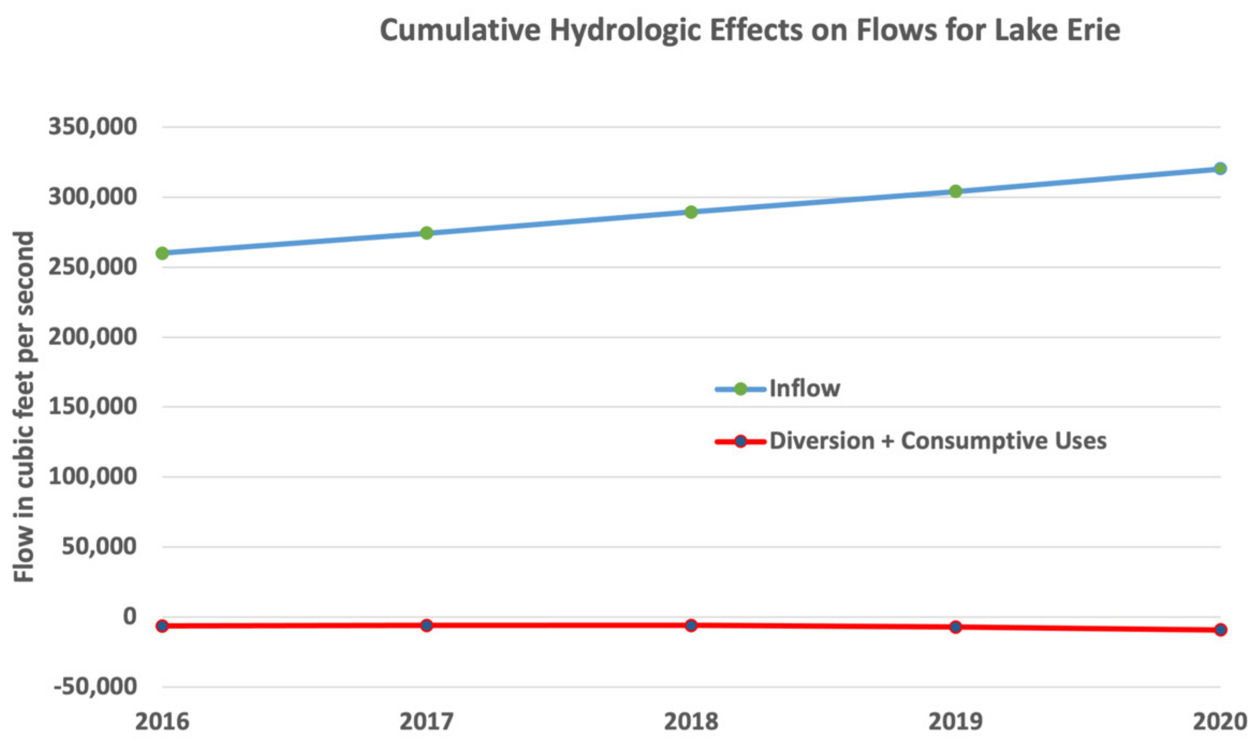


Figure 16. *Cumulative hydrologic effects on flows for Lake Erie, 2016-2020.*

Year	Total Inflow	Estimated net volume of consumptive uses and diversions	Consumptive uses and diversions as a percentage of total inflow
2016	260,121	-6,328	2.43%
2017	274,310	-6,073	2.21%
2018	289,519	-6,037	2.09%
2019	304,126	-7,186	2.36%
2020	320,246	-9,379	2.93%

Table H. *Water budget values in cubic feet per second for Lake Erie, 2016-2020.*

While the water budgets presented in this assessment focus on flow, water supply can either be described in volumetric terms (e.g., quadrillion of gallons) or in terms of water levels for the individual Lakes. Water level data is available both on an historical and current basis. When compared to this baseline data, water levels can help characterize how flow changes affect supply Accordingly, below are graphic presentations for Lake Erie water levels, both historically and for the period of 2016-2020. The historical water levels in Figure 17 show natural cyclical variability. As illustrated in Figure 18, water levels during 2016-2020 also show this variability with an overall range of about 1.6 feet. Both figures present average data. The specific contribution made by Diversions and Consumptive uses at any given point in time or space, separate and apart from natural variability, is uncertain given the complex hydrologic, geographic and temporal variability of uses, and other factors. Since Diversions and Consumptive uses are small compared to natural flows, their cumulative hydrologic effect on water levels is likewise small.

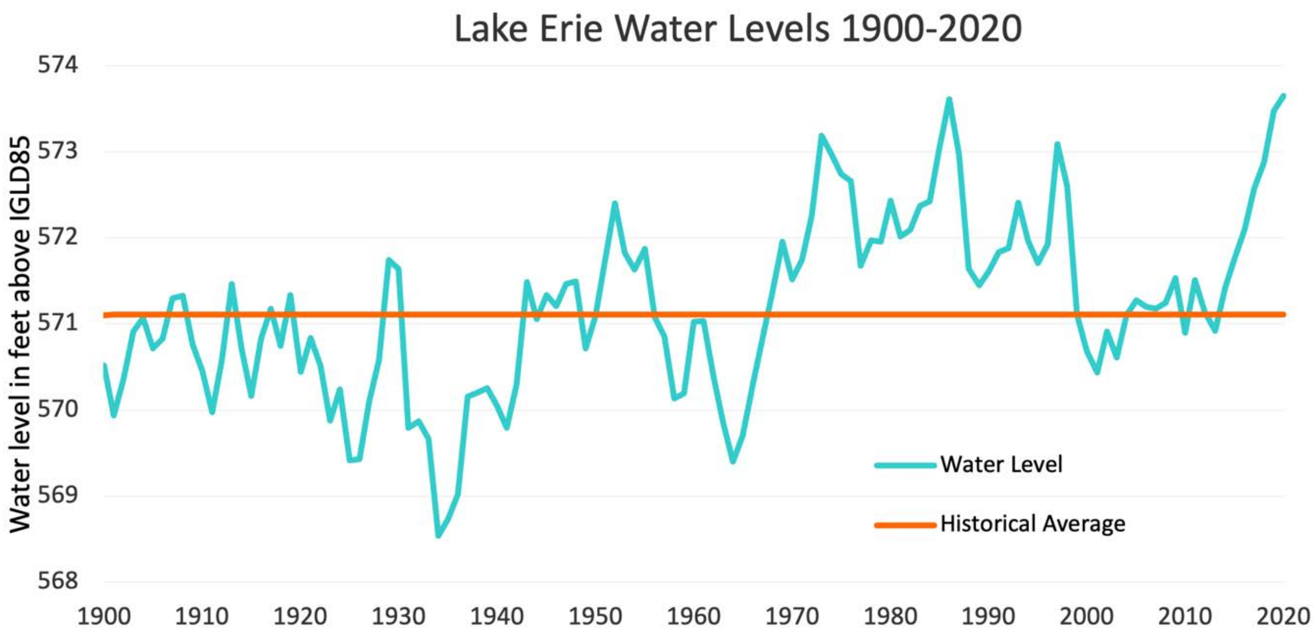


Figure 17. *Historical water levels for Lake Erie, 1900-2020.*

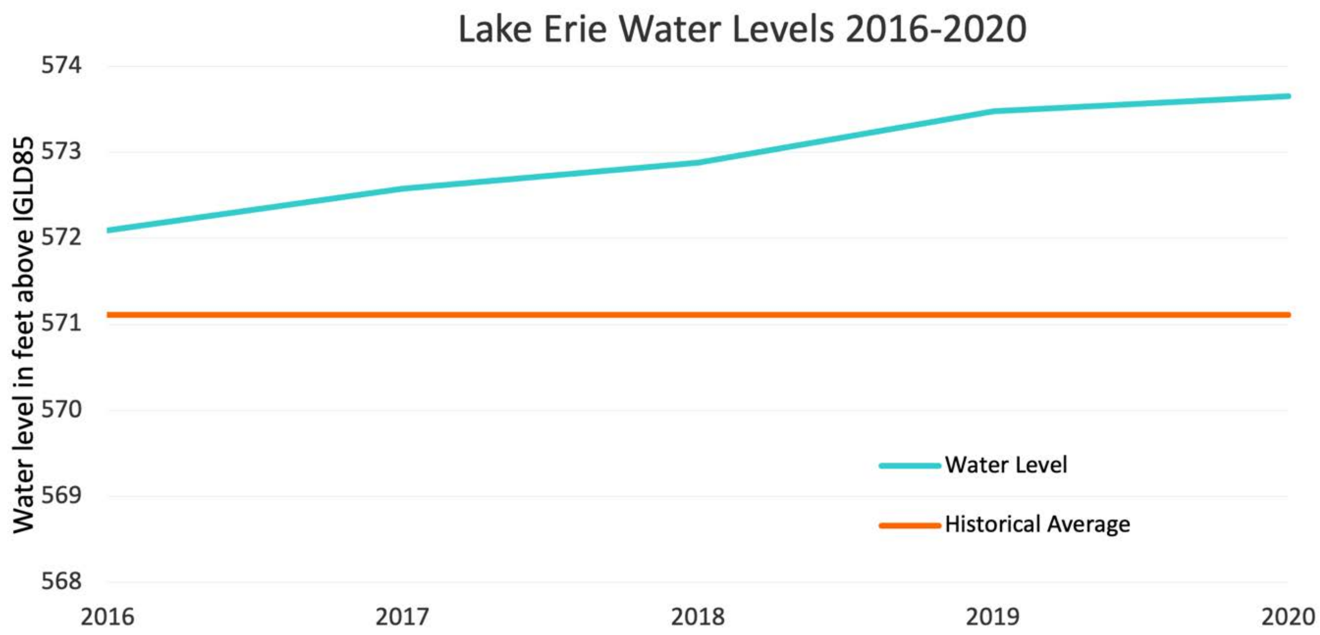


Figure 18. *Water levels for Lake Erie, 2016-2020.*

LAKE ONTARIO WATERSHED

Inflows to Lake Ontario include the Niagara River, runoff, precipitation on the surface of the Lake and Diversions. Outflows for the Watershed include the St. Lawrence River, evaporation from the surface of the Lake, and Consumptive Uses throughout the Watershed.

Figure 19 shows the watershed. The measuring location for the St. Lawrence River is downstream from the Watershed as shown in figure 19. Thus, some of the St. Lawrence River outflow reported in this section is not from the Lake Ontario Watershed but from the St. Lawrence River Watershed.

Figure 20 and Table I present a comparison of the 5-year period and 65-year period averages in water budget data for Lake Ontario. As illustrated in Figure 20 and Table I, the largest outflow for the Lake Ontario Watershed is the St. Lawrence River and the smallest is Consumptive Use. All natural flows—runoff, precipitation on the Lake, Niagara River, evaporation from the Lake, and St. Lawrence River are greater for the 5-year reporting period than the 65-year

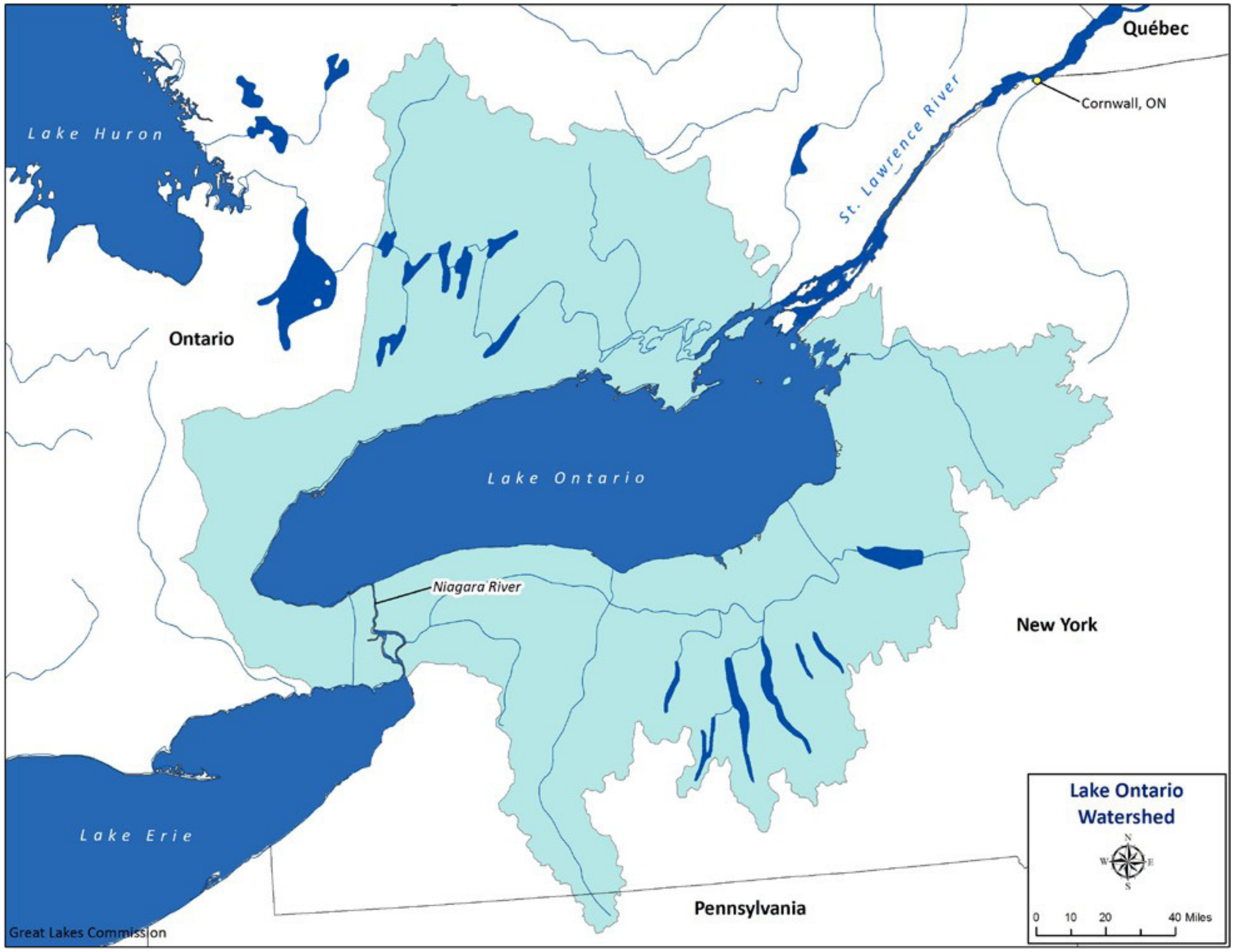


Figure 19. *Lake Ontario Watershed.*

period. Specifically, inflows of runoff, precipitation on the surface of Lake Ontario, intrabasin diversion, and Niagara River were 41,571 cfs more during the 5-year period. Outflows of evaporation from the Lake and St. Lawrence were 40,460 cfs more during the 5-year period.

Data in Table I and used in Figure 20 indicate that inflows do not equal outflows. In some years outflows may exceed inflows while in other years inflows may exceed outflows. This is due in part to changes in storage in Lake Ontario, as well as regulation of outflows by the International Lake Ontario – St. Lawrence River Board to meet the International Joint Commission's Orders of Approval, and in part to a lack of accuracy or uncertainties in measurements or estimates of the flows. This inequality of inflow and outflow is true for all of the Lake(s) and the River. Issues of uncertainty are discussed in the next main section.

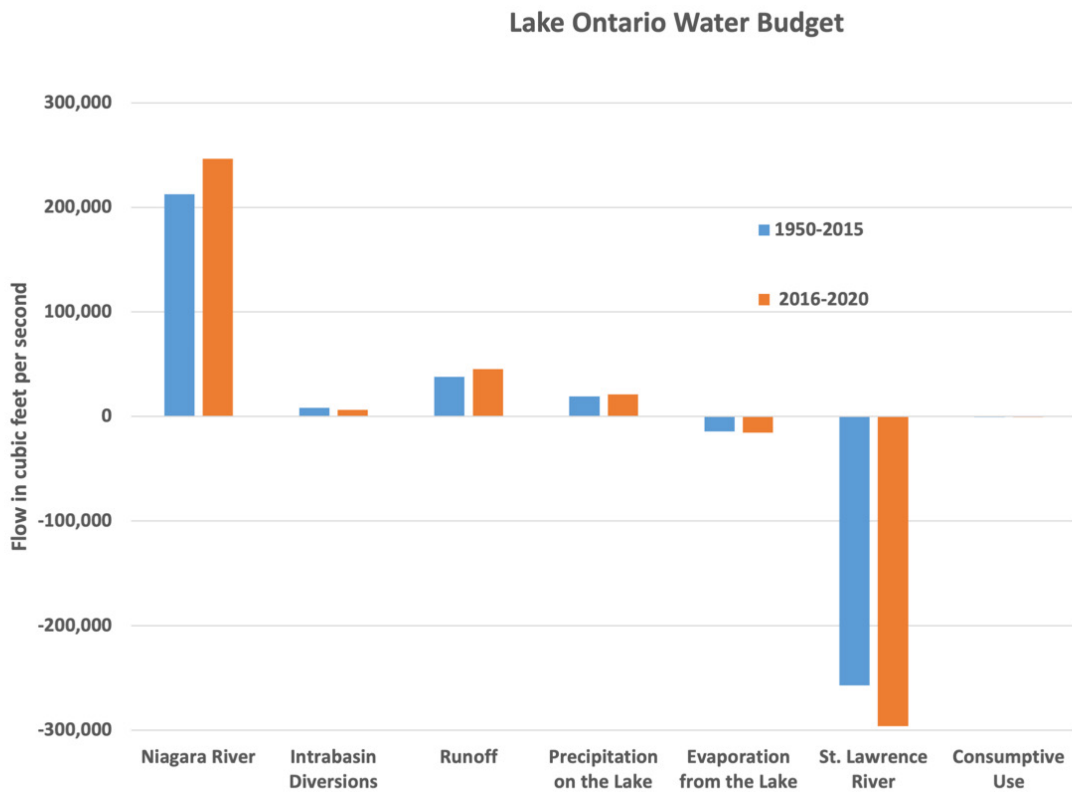


Figure 20. *Water budget average flow values for Lake Ontario using average annual flows, comparing a 5-year period (2016-2020) to a historical 65-year period (1950-2015).*

Water Budget Component	5-year Flow (cfs)	65-year Flow (cfs)
Niagara River	246,626	212,579
Runoff	45,286	38,010
Precipitation	21,246	19,169
Evaporation	-15,425	-14,182
St. Lawrence River	-296,178	-256,961
Intrabasin Diversion	6,336	8,165
Consumptive Uses	-556	-591*

Table I. *Water budget average flows for Lake Ontario, comparing a 5-year period (2016-2020) to a historical 65-year period (1950-2015). * Average consumptive use for 2006-2015*

The hydrologic effect of Consumptive Uses and Diversions as compared to natural inflows for 2016-2020 is shown for the Lake Ontario Watershed in Figure 21. The net effect is an increased inflow of 5,779 cfs for the 5-year reporting period. As previously described, this assessment defines a hydrologic effect as the Consumptive Uses plus Diversions compared to the inflows (connecting channel flow plus precipitation and runoff). Table J includes the flow values used to construct Figure 21 and shows the volume of Consumptive Uses and Diversions compared to runoff and precipitation. As with similar information described previously in this assessment, each data point has significant uncertainty associated with it, and is based on averages on a 5-year timescale. Future assessments may take a different approach as data and information improve.

As illustrated in Table J, for the Lake Ontario Watershed the cumulative hydrologic effect of Consumptive Uses and Diversions (annual averages) are small relative to inflows. Further, while inflows fluctuate from 2016-2020, the cumulative hydrologic effect of Consumptive Uses and Diversions is fairly constant for these annual averages.

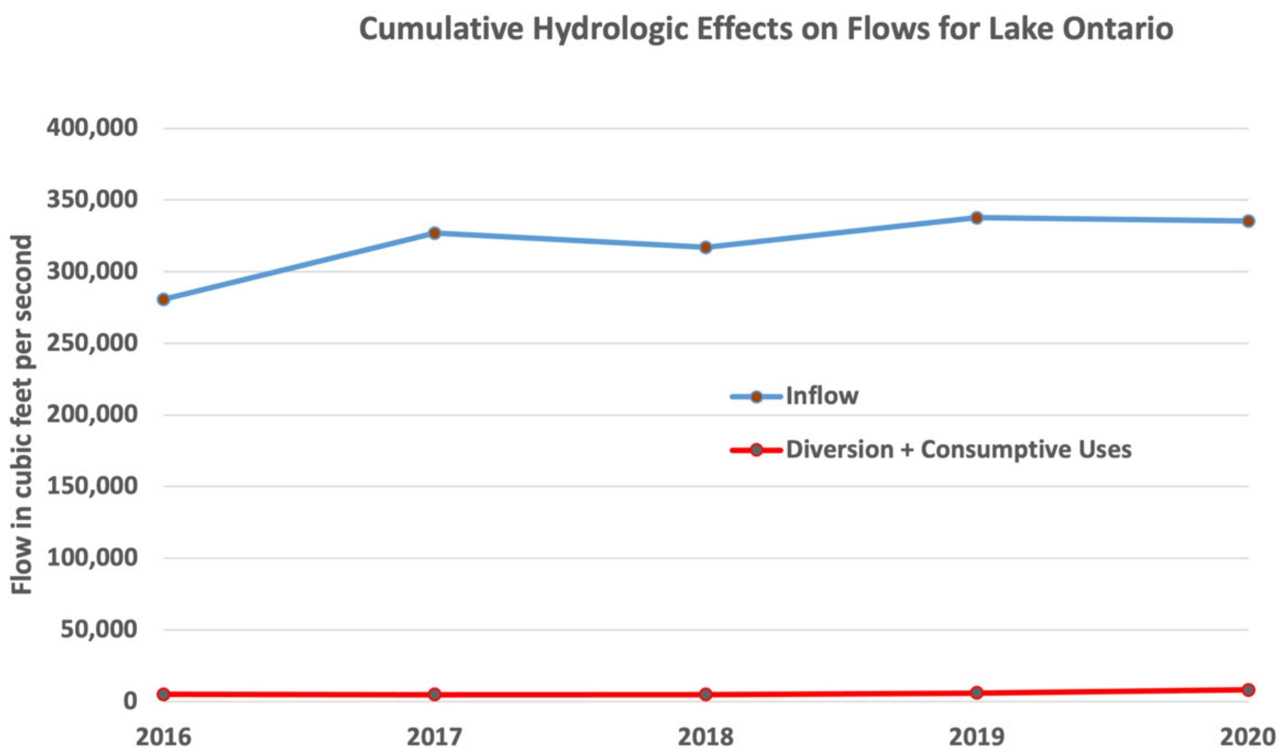


Figure 21. *Cumulative hydrologic effects on flows for Lake Ontario, 2016-2020.*

Year	Total Inflow	Estimated net volume of consumptive uses and diversions	Consumptive uses and diversions as a percentage of total inflow
2016	280,739	5,042	1.80%
2017	326,861	4,846	1.48%
2018	316,893	4,821	1.52%
2019	337,668	5,997	1.78%
2020	335,309	8,187	2.44%

Table J. *Water budget values in cubic feet per second for Lake Ontario, 2016-2020.*

While the water budgets presented in this assessment focus on flow, water supply can either be described in volumetric terms (e.g., quadrillion of gallons) or in terms of water levels for the individual Lakes. Water level data is available both on an historical and current basis. When compared to this baseline data, water levels can help characterize how flow changes affect supply. Accordingly, below are graphic presentations for Lake Ontario water levels, both historically and for the period of 2011- 2015. The historical water levels in Figure 22 show natural cyclical variability. As illustrated in figure 23, water levels during 2016-2020 also show this variability with an overall range of about 1.5 feet.

Both figures present average data. The specific contribution made by Diversions and Consumptive Uses at any given point in time or space, separate and apart from natural variability, is uncertain given the complex hydrologic, geographic and temporal variability of uses, and other factors. Since Diversions and Consumptive Uses are small compared to natural flows, their cumulative hydrologic effect on water levels is likewise small.

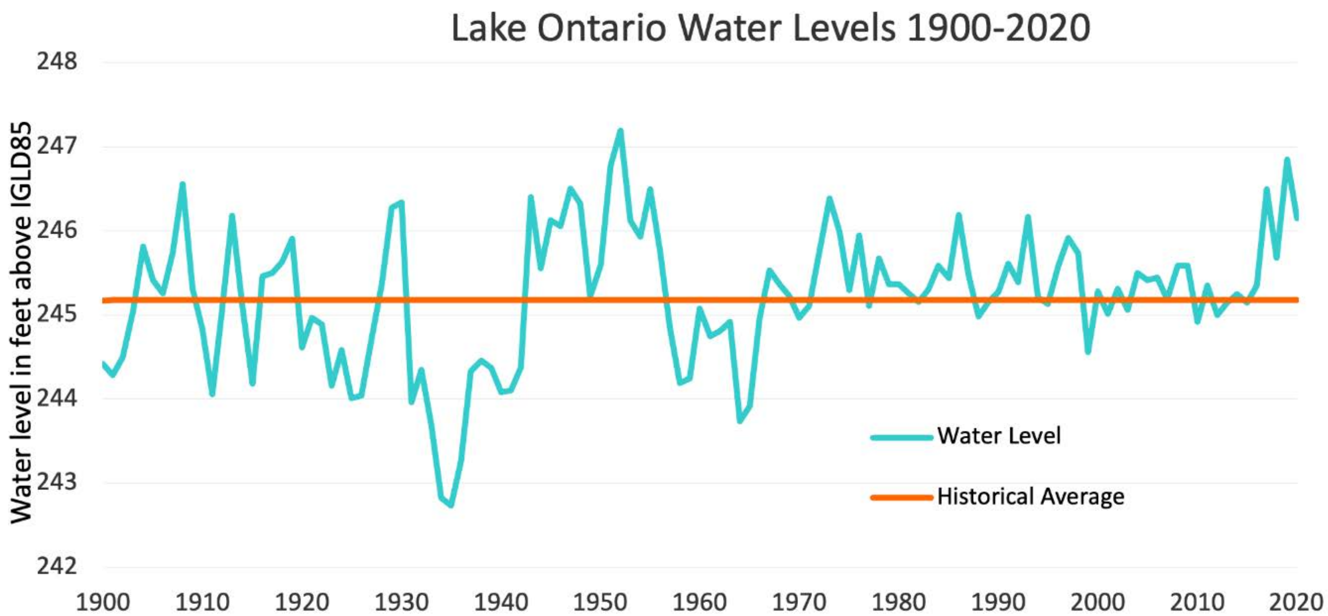


Figure 22. *Historical water levels for Lake Ontario, 1900-2020.*

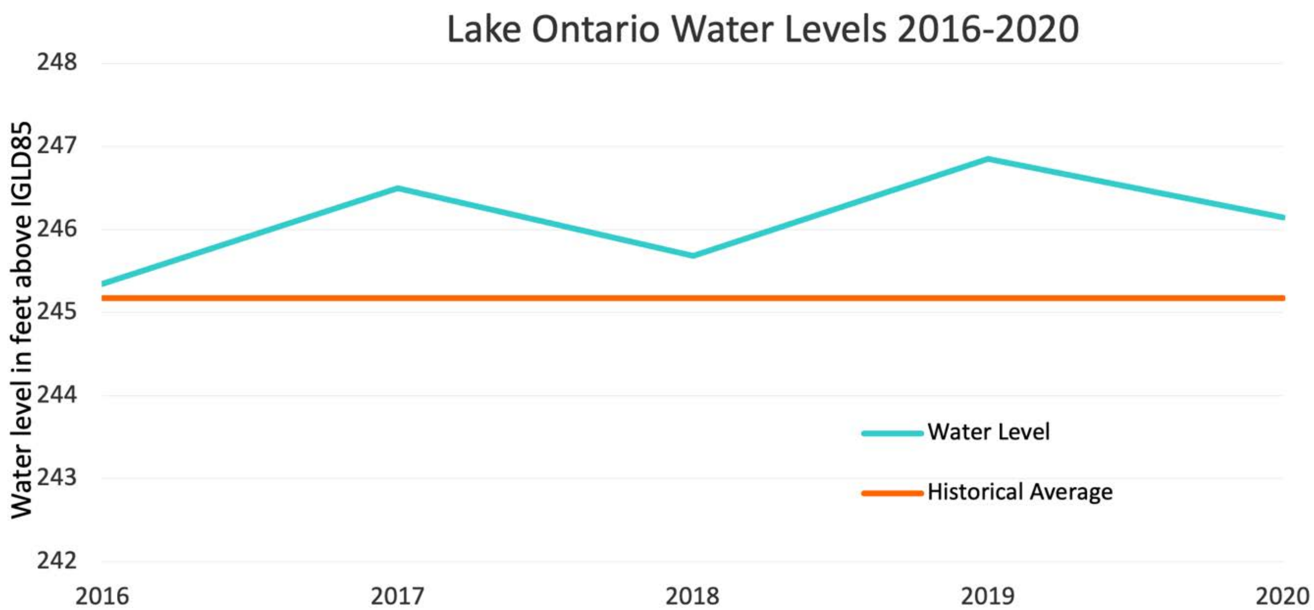


Figure 23. *Water levels for Lake Ontario, 2016-2020.*

ST. LAWRENCE RIVER WATERSHED

The St. Lawrence River Watershed in the Compact and Agreement is shown in Figure 24. The measuring location for the St. Lawrence River at Cornwall, Ontario is downstream from the western part of the watershed shown in figure 24. Thus, some of the St. Lawrence River inflow reported in this section is not only from the Lake Ontario Watershed, but from the western part of the St. Lawrence River Watershed.

Precipitation on and evaporation from the River are not included in the water budget for the River because they contain a very small surface area compared to the Watershed and no data for these components are available. Runoff is also not reported since it is simply the difference between flow measurements for the River at Cornwall, Ontario and modeled or estimated flow at Trois Rivières, Québec. Additionally, no Diversions are reported by the Parties for the River Watershed prior to 2011. Accordingly, the water budget for the St. Lawrence River Watershed is different than those for the Lakes. Inflow consists of the St. Lawrence River flow measured at Cornwall, Ontario.

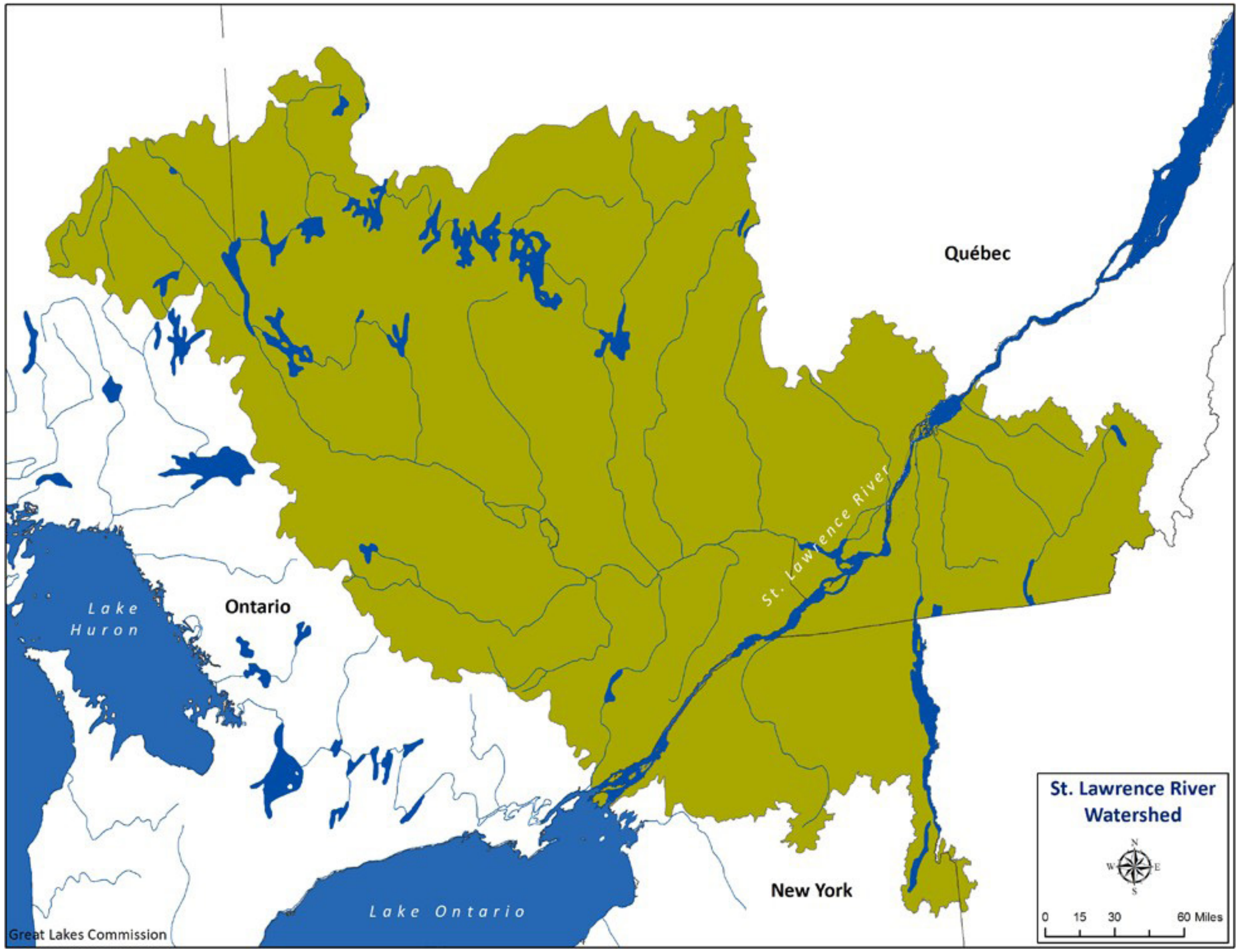


Figure 24. St. Lawrence River Watershed.

Outflow consists of the River's flow modeled at Trois Rivieres, Québec and Consumptive Uses throughout the Watershed.

Figure 25 shows water budget data for 2016-2020. As illustrated in Table K, for the St. Lawrence River Watershed the hydrologic effect of Consumptive Use is small relative to inflows. Further, while inflows fluctuate from 2016-2020, the hydrologic effect of Consumptive Use is fairly constant for these annual averages.

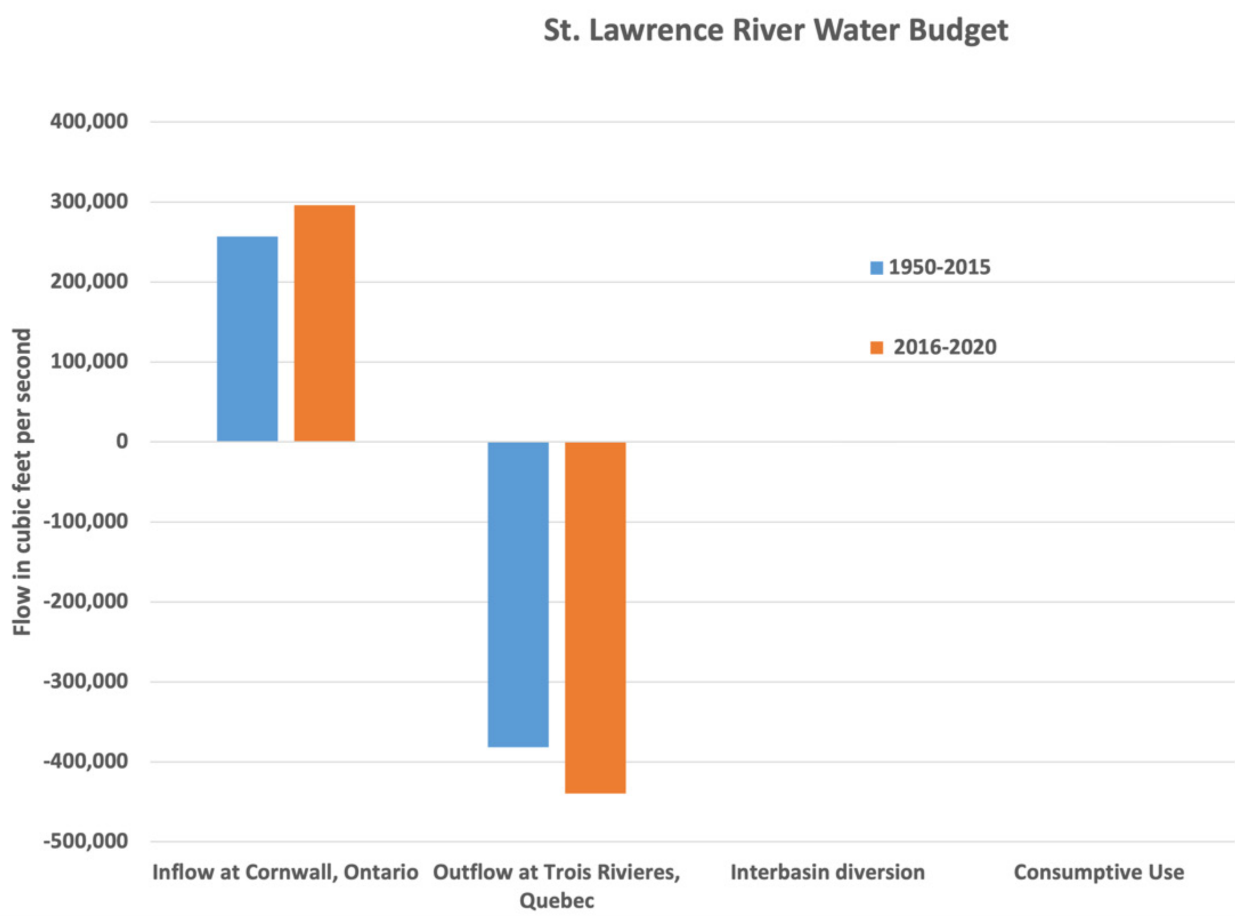


Figure 25. *Water budget average flow values for the St. Lawrence River using average annual flows, comparing a 5-year period (2016-2020) to a historical 65-year period (1950-2015).*

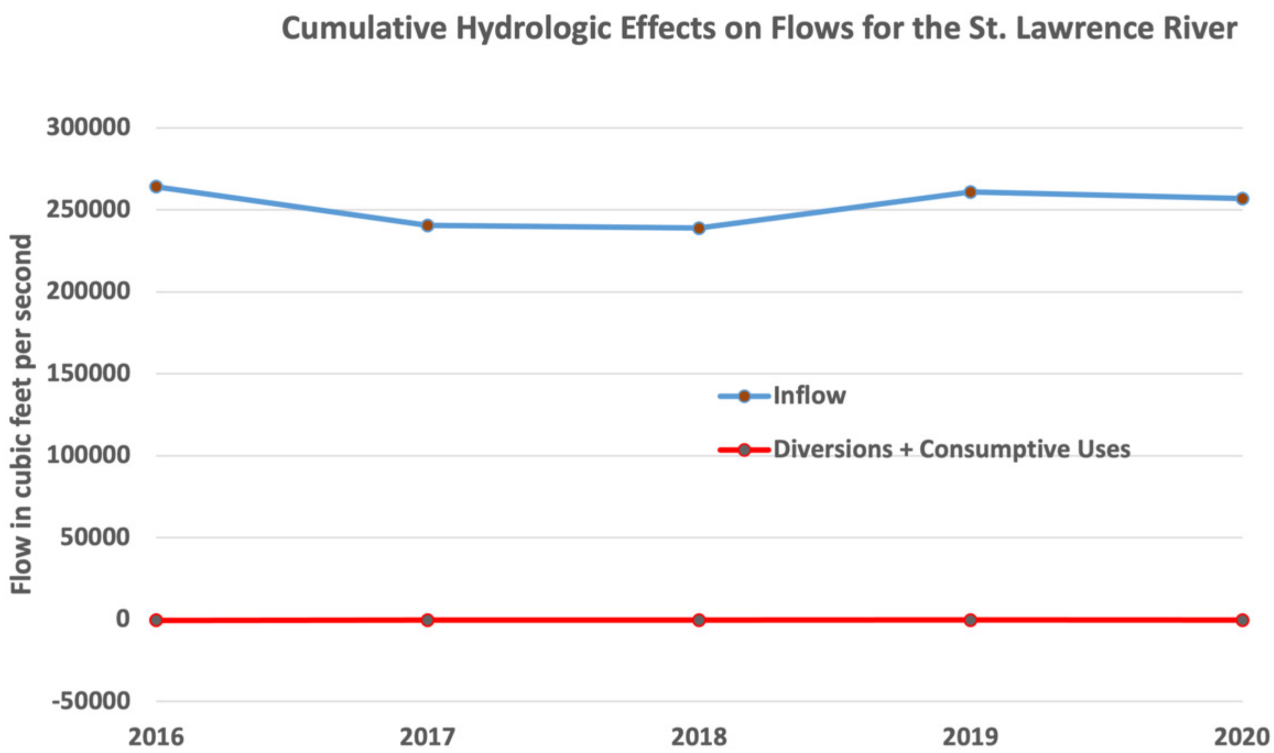


Figure 26. *Cumulative hydrologic effects on flows for the St. Lawrence River, 2016-2020.*

Year	Total Inflow	Estimated net volume of consumptive uses and diversions	Consumptive uses and diversions as a percentage of total inflow
2016	260,262	-432	0.17%
2017	298,438	-353	0.12%
2018	295,083	-382	0.13%
2019	312,417	-316	0.10%
2020	314,330	-322	0.10%

Table K. *Water budget values in cubic feet per second for the St. Lawrence River, 2016-2020*

CONSIDERATION *of* UNCERTAINTY

Estimates of components of the Basin water budget used in this Cumulative Impact Assessment report have significant uncertainty. More specifically, the estimates of runoff, evaporation from the Lake surfaces, and precipitation on the Lake surfaces used in this Report (and in previous reports) are all calculated using models that compute watershed values from point data. No data exists, however, for many areas within the Basin and each Watershed. For instance,

34 percent of the Lake Huron watershed has no streamflow gauges, and runoff from this area is estimated from nearby gauges. Additionally, precipitation on the surfaces of the Lakes is calculated almost entirely from precipitation gauges that are near, but not on, the Lakes.

The amount of uncertainty associated with various components of the water budget is difficult to quantify, but, as referenced in Table 1 of the Supplementary Report, scientists have historically estimated that it may range from 15-35 percent for runoff, 15-45 percent for precipitation on the Lake surfaces, and 10-35 percent for evaporation from the Lake surfaces. The International Upper Great Lakes Study (IUGLS) resulted in increased emphasis and research regarding uncertainty and the Great Lakes water budget. The Supplementary Report includes references to recent technical publications associated with uncertainty in the Basin water budget.

One of the most important consequences of historical uncertainty in the Basin water budget is an inability for researchers to “close the water budget.” That is, if one computes the differences in inflow and outflows, one should be able to calculate the resulting water level change on a Lake; however, this has not been done until recently. Gronewold and others (2016, see Appendix), used a statistical method that accounts for uncertainty in the water budget to calculate the historically large increase in water levels on Lake Superior and Lakes Michigan-Huron during 2013-2014, thus closing the water budget. To support this Cumulative Impact Assessment, this approach was recently applied to all of the Great lakes (see Supplementary Report).

Consumptive Use data also includes significant uncertainty. Consumptive Use is seldom measured directly. In most cases, Consumptive Use is calculated using a coefficient that represents a percentage of water consumed for a given category, such as domestic use, industrial use or irrigation. Each category has a wide range of reported values in the literature, and an average value for a category is generally used. Each of the Parties reports Consumptive Use by Watershed to the Great Lakes Commission annually for input to the water use database, and the Parties make independent decisions regarding the application of Consumptive Use coefficients. In 2011, under the Agreement, the Parties adopted new water use reporting protocols that have improved the timeliness, consistency and comparability of water use data. In 2016, the Parties reviewed and revised these reporting protocols. Appendix includes information about the regional water use database and includes references to recent technical publications associated with Consumptive Use.

Conventional approaches to quantifying uncertainty in the Basin water budget components lead to water balance component uncertainty estimates that are much larger than total Consumptive Uses. For example, total runoff to the Basin in 2020 was 227,163 cfs. Assuming a 15 percent uncertainty, the amount of calculated runoff may be off by over 34,074 cfs. In comparison, Consumptive Use in 2020 was only 2,768 cfs. Therefore, the hydrologic effects of Consumptive Uses on flows and water levels are masked by uncertainties in the natural inflows and outflow.

To address these significant uncertainties in the Basin water balance, the University of Michigan (UM) developed the Large Lake Statistical Water Balance Model (L2SWBM) This model allows the input of numerous datasets of historical values for the water balance components, then runs those values through a supercomputer for thousands or even millions of iterations. In the model, each component value depends on every other value in the water balance, and in each of its iterations, it validates and adjusts each value, eventually settling on the most likely estimate of each value with much lower uncertainty. This allows the overall water balance to be much more accurate in terms of overall water levels, and individual hydrologic components. This model operates using historical data, or existing data, rather than projections of future data.

The UM work shows that: (1) the L2SWBM can be used to significantly reduce uncertainty in the water balance (see Table 1 in Supplementary Report) and close the water balance over various time scales; and (2) as more iterations occur and more data sources are reconciled, the uncertainty will shrink further. In short—the use of these new models will result in ever decreasing uncertainty in future iterations of the Cumulative Impact Assessment.

CONSIDERATION *of* CLIMATE CHANGE, ADAPTIVE MANAGEMENT & FUTURE WORK

CLIMATE CHANGE

UM also compared trends in the historical data to some existing climate change scenarios in the academic literature. As part of that comparison, the past impacts of climate change on the water balance and the likely future impacts were examined, resulting in a review of both long-term averages and seasonal variation.

A series of statistical methods were used to analyze the outputs of the L2SWBM model in order to attempt to find trends in the historical record for precipitation, evaporation, runoff, and outflow between the Great Lakes. Using methods like segmented regression and smooth moving averages, the team was able to filter out some extreme values and highlight long-term trends, as well as more recent short-term deviations. For example, there has been a dramatic increase in precipitation in Lake Superior over the last two decades, especially since 2013. All the Great Lakes showed change points, or markers of a shift upwards in mean, for precipitation around the year 2010.

The UM review had several conclusions. First, climate change signals might already exist in the historical record, especially in precipitation. For instance, precipitation patterns on Lake Superior follow a hockey stick shape, an emblematic trait of climate change where values dramatically increase at the end of a time scale. Second, in the future, precipitation and evaporation are likely to increase, leading to a wetter and hotter climate in the region. Third, increases in precipitation and evaporation may result in a "tug-of-war", where rapid changes in water levels occur when either water-balance component changes significantly for a period.

Note, however, that the increases in precipitation and evaporation have opposite effects and thus do not significantly change average long-term water levels.

ADAPTIVE MANAGEMENT

Adaptive management has various definitions, but under the Agreement and Compact is defined as "a water resources management system that provides a systematic process for evaluation, monitoring and learning from the outcomes of operational programs and adjustment of policies, plans and programs based on experience and the evolution of scientific knowledge concerning water resources and water-dependent resources." In other words, **adaptive management essentially is a decision-making**

process that seeks, in the face of uncertainty, to improve resource management by learning from previously employed policies and practices. Adaptive management requires monitoring of the resource and benefits from modeling. As more is understood about the hydrologic effects of Diversions and Consumptive Uses, adaptive management will be an even more increasingly useful tool in addressing these effects. As noted in the Introduction, the review and potential revisions to Basin-wide water conservation and efficiency goals and objectives pursuant to Article 304 paragraph 3 of the Agreement and Section 4.2.3 of the Compact, and other future work, must be in part based on the cumulative impact assessment. Additionally, the Parties will promote an adaptive management approach to the conservation and management of Basin Water resources pursuant to Article 100 of the Agreement and Section 1.3.2h of the Compact.

FUTURE WORK

In preparation for this Cumulative Impact Assessment, consideration was given as to whether forecasting of future water demands and their impact on the water budget could be taken into consideration. In particular, with the potential for changes in the growing season due to changes in the climate, the forecasting of the demand by the agricultural sector may be of particular interest as the region's water managers work to ensure that water is available for such uses. However, it was determined that the tools necessary to complete such a forecast are not available at this point in time.

Cumulative impact assessments require reliable data and information regarding the Basin water budget and Consumptive Uses. **While work is needed in many areas to improve Basin water budget data and reduce uncertainty, several specific areas stand out for near-term action:**

1. Research is needed to improve estimates of Consumptive Use and to improve consistency in application of Consumptive Use coefficients by the Parties.
2. Further work is needed to improve understanding of the impacts of new or increased withdrawals on flows, associated chemical and biological conditions, as well as on other water uses at scales from local to regional to Basin.
3. Changes to methods to improve calculations of runoff, evaporation from the Lakes, and precipitation on the Lakes are ongoing at Provincial and federal agencies, and universities. This research is vital to understanding the natural variability of the Basin water balance and to assessing potential changes in the future.
4. For future assessments, consider using data from Large Lake Statistical Water Balance Model, which has less uncertainty than data used for the Cumulative Impact Assessment section of this and earlier reports.

APPENDIX

SOURCES OF DATA AND INFORMATION

Numbers in this assessment, in text, graphs and tables, are all derived from the following sources.

Runoff

Monthly values from 1950-2020 are calculated by National Oceanic Atmospheric Administration's Great Lakes Environmental Laboratory (GLERL). The data are updated periodically and are in spreadsheets that can be downloaded from GLERL's web site. Values were converted from millimeters over the lake surface area to cubic feet per second using coordinated lake areas. For 2020, data were not available for October-December, so the average for 9 months was used.

For Lake Superior, GLERL's runoff figure includes the Ogoki Diversion. In this assessment, the Ogoki Diversion was subtracted from GLERL's runoff using the Binational Coordinating Committee on Basic Hydrologic and Hydraulic Data (Coordinating Committee) Ogoki Diversion flow estimates, since Diversions are considered separately from runoff.

Evaporation

Monthly values from 1950-2020 are calculated by GLERL. The data are updated periodically and are in spreadsheets that can be downloaded from GLERL's web site. Values were converted from millimeters over the lake surface area to cubic feet per second using coordinated lake areas.

Precipitation

Monthly values from 1950-2020 are calculated by GLERL. The data are updated periodically and are in spreadsheets that can be downloaded from GLERL's web site. Values were converted from millimeters over the lake surface area to cubic feet per second using coordinated lake areas.

Connecting Channel flows

Monthly values from 1950-2020 for the St. Marys, St. Clair, Detroit, Niagara, and St. Lawrence (at Cornwall, Ontario) Rivers were downloaded from the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data website.

Annual flows from 1950-2015 for the St. Lawrence River at Trois Rivieres, Québec were provided by Environment Canada. Data for 2016-2020 were estimated using percent differences in flow for each year at Cornwall/Massena compared to the long-term average, and then applying that percent difference to flows at Trois Rivieres.

Diversions and Consumptive Uses

Diversions and Consumptive Uses are reported annually by each Party by Watershed to the Great Lakes Commission. The Great Lakes Commission maintains the Great Lakes Water Use Database Repository on behalf of the Parties. This database includes data from 1998-2020. Earlier data is available only in paper or PDF format. In this assessment, only data from 2006-2020 are reported due to quality and consistency issues with earlier data.

For historical comparison purposes, this assessment uses Diversion data from 1950-2010 provided by the U.S. Army Corps of Engineers, as the GLC database does not include earlier data on diversions. While these data may differ from those included in the Great Lakes Water Use Database Repository, they provide a historical context for Diversions.

Further information on individual diversions is reported by the Parties to the Great Lakes Water Use Database Repository. Information on some of these diversions in the States is separately collected by federal agencies and is available from the U.S. Army Corps of Engineers.

Water levels

Lakes levels were downloaded from the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data website. These are an average annual lake level for each lake in meters using the IGLD85 datum.

Other water budget assessments have estimated the effect of Diversions and Consumptive Uses on water levels. For further information on this effect, see for example the International Joint Commission's Great Lakes Study Water Use Report and Water Uses Reference Study.

RELEVANT PUBLICATIONS

Information in the following publications assisted in the writing of this assessment.

DeMarchi, C., Dai, Q., Mello, M.E., Hunter, T.S., 2012, Estimation of Overlake Precipitation and Basin Runoff Uncertainty, IUGLS Technical Working Group report, p. 51 (available on IUGLS web site)

Feinstein, D.T., Hunt, R.J., and Reeves, H.W., 2010, Regional groundwater-flow model of the Lake Michigan Basin in support of Great Lakes Basin water availability and use studies: U.S. Geological Survey Scientific Investigations Report 2010–5109, p. 379

Filatova, N.N., and Vyruchalkinaa, T.Y, 2017, Many-Year Level Variations in the Great Lakes of Eurasia and North America, Water Resources, Vol. 44 No. 5, pp 685-696.

Gronewold, A. D., J. Bruxer, D. Durnford, J. P. Smith, A. H. Clites, F. Seglenieks, S. S. Qian, T.S. Hunter, and V. Fortin , 2016, Hydrological drivers of record-setting water level rise on Earth's largest lake system, Water Resour. Res., 52.

IUGLS, 2012, Addressing uncertainty in Great Lakes water levels, Summary of findings and recommendations, p. 14

IUGLS Hydroclimatic Work Group, 2012, Hydroclimatic Conditions: Past, Present and Future, p. 83 (available on IUGLS web site)

Lofgren, B.M. and Rouhana, J., 2016, Physically Plausible Methods for Projecting Changes in Great Lakes Water Levels under Climate Change Scenarios, Journal of Hydrometeorology, v. 17, pp. 2209-2223.

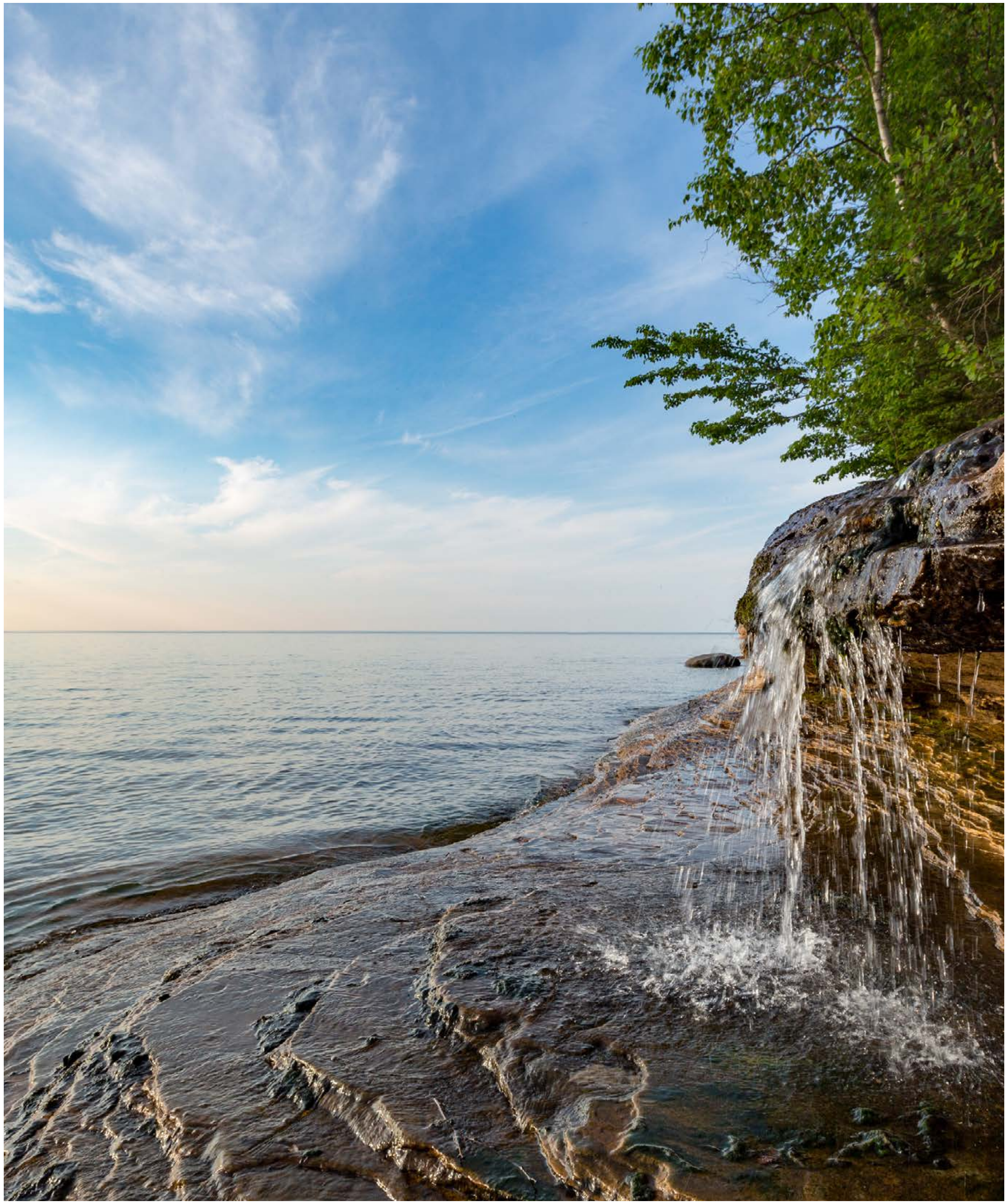
Neff, B.P., and Nicholas, J.R., 2005, Uncertainty in the Great Lakes water balance, U.S. Geological Survey Scientific Investigations Report 2004-5100, p. 42

Notaro, M., Bennington, V., and Lofgren, B., 2015, Dynamical Downscaling–Based Projections of Great Lakes Water Levels, Journal of Climate, v. 28, pp. 9721-9745.

Xu, S., S.K. Frey, A.R. Erler, O. Khader, S.J. Berg, H.T. Hwang, M.V. Callaghan, J.H. Davison, E.A. Sudicky, 2021. Investigating groundwater-lake interactions in the Laurentian Great Lakes with a fully-integrated surface water-groundwater model, Journal of Hydrology, p. 594

APPENDIX

ANALYSIS OF GREAT LAKES WATER BALANCE COMPONENTS: UNCERTAINTY REDUCTION, TREND DETECTION & PROJECTIONS FOR THE FUTURE



Prepared for the Compact Council and Regional Body of the Great Lakes St. Lawrence Governors and Premiers as a supplement to the 2023 (2016-2020) Cumulative Impact Assessment

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EXECUTIVE SUMMARY

This report serves as a supplement to the current iteration (years 2016-2020) of the Great Lakes Cumulative Impact Assessment (CIA). The CIA is prepared every 4-5 years by the Compact Council and Regional Body of Great Lakes Governors and Premiers, and documents the magnitude of historical Great Lakes water balance components. Some of these components are impacted primarily by the regional climate (such as precipitation and evaporation) while others are more closely related to anthropogenic activity (such as consumptive use, withdrawals, and diversions of water within and across the Great Lakes basin boundary). A main objective of the CIA is to provide a basis for assessing whether or not there are changes in these water balance components over time, and to ensure that estimates of these components reflect current advancements in the state-of-the-art in hydrologic science.

To support these objectives, we prepared this Supplementary Report that focuses on three key tasks including 1) reducing uncertainty in historical Great Lakes water balance components, 2) assessing trends or other patterns in those components, and their potential connections to climate change, and 3) identifying future anticipated changes in water balance components. Data for previous CIA reports has typically been drawn from a single source (details are provided in the report narrative below). **Here, we utilize a relatively new data analysis tool known as the Large Lake**

Statistical Water Balance Model (L2SWBM) that aggregates multiple data sets, for each water balance component, from across the Great Lakes basin, and infers the most likely value of each water balance component along with an explicit representation of uncertainty.

Our findings indicate that the use of the L2SWBM leads to historical water balance component estimates that a) were consistent with multiple historical data sets, b) "closed" the Great Lakes water balance over time, and c) had uncertainty bounds that are considerably lower than those used historically.

The new water balance component estimates also provided insight into historical trends, and how they relate to potential future conditions under a changing climate.

INTRODUCTION

The Great Lakes and St. Lawrence Governors and Premiers have committed to administering the Great Lakes and St. Lawrence River Basin Sustainable Water Resources Agreement and Compact (Agreement/Compact). This administration is conducted through the Great Lakes - St. Lawrence Regional Body and Compact Council. Through collaborations with scientists and water resources decision-makers, the Compact Council and Regional Body have, to date, completed two 5-year Cumulative Impact Assessments (CIAs). In 2019, the Compact Council and Regional Body published a Science Strategy outlining expected challenges in carrying out the Agreement and Compact which underscored the need for continued investments in developing robust scientific data to support future iterations of the Cumulative Impact Assessment.

Specifically, the Science Strategy calls for more definitive projections of water budget components in the Great Lakes to prepare for impacts of climatic change, including implications for managing diversions, withdrawals and consumptive uses (*Great Lakes St. Lawrence Regional Body and Compact Council Science Strategy*, 2019). The following excerpt underscores those objectives:

> "As identified in the 2017 Cumulative Impact Assessment of Withdrawals, Consumptive Uses and Diversions (2011-2015), the assessment requires more reliable data and information regarding the Basin water budget and how consumptive uses are measured or estimated."

Here, we address that requirement by developing a new set of historical water balance components with a novel approach to quantifying (and reducing) uncertainty. We use that new record to improve understanding of climate change impacts on the historical record, and to provide context for plausible future water balance change scenarios.

UNDERSTANDING THE WATER BALANCE

The hydrologic cycle in any region of the world includes a set of co-occurring processes in which water transitions through different physical states. Using this principle in a defined spatial domain (e.g. a lake basin) we can apply the law of conservation of mass to account for all water entering and leaving that domain. **It is especially difficult to account for all the water moving through a large system like the Great Lakes where weather, land type variation, subsurface geology and the large surfaces areas of the lakes themselves affect water storage and flow rates between the lakes.**

A common tool for addressing this "accounting" problem is the conventional water balance equation (Figure 1) which represents major inputs and outputs of water, and can be adapted for the Great Lakes system. Water inputs to each of the Great Lakes include over-lake precipitation, over-land precipitation and its propagation into runoff, and connecting channel inflow from an upstream lake. Outputs from each Lake include over-lake evaporation and connecting channel outflow. **For a system as large as the Great Lakes, it is impractical to estimate these components without uncertainty; spatial variability**

$$\Delta S = P + R - E + Q_{in} - Q_{out} + \varepsilon$$

Where,

ΔS: Change in storage (i.e. change in water level)

P: Precipitation over the lake

R: Runoff

E: Evaporation over the lake

+Q_{in}: Connecting channel inflow

-Q_{out}: Connecting channel outflow

ε: Error

Figure 1-- Simplified conventional lake water balance equation. A similar version of this equation is used to calculate inflows and outflows of water to the Great Lakes system in the L2SWBM. Units are typically either in millimeters (mm) over a lake surface area for a given time step, or as an average flow in cubic feet per second (cfs) over a given time step. In this version of the equation, groundwater flows, and other small water balance components, are assumed to be included in the error term.

in monitoring platforms, limited modeling capabilities, and limited historical data availability all contribute to this uncertainty. Aside from uncertainty in individual water balance components, there is also an expression of error (in a lake water balance model that represents other potential sources of uncertainty in the water balance. In the conventional Great Lakes water balance model, this error term typically represents groundwater flow, changes in water level due to isostatic rebound, consumptive uses, and thermal expansion.

Measurements of various components of the Great Lakes hydrologic system have been collected as far back as the late 1800's. For decades (starting in the 1980s and early 1990s), the most-readily accessible aggregation of these measurements was a database known as the North American Great Lakes basin-scale monthly hydrometeorological database (GLM-HMD) maintained by NOAA's Great Lakes Environmental Laboratory (NOAA-GLERL). The GLM-HMD has been considered by many regional scientists and practitioners to be the only comprehensive database of its kind for this region that documents all Great Lakes water budget variables across the U.S. and Canadian portions of the North American Great Lakes, and has customarily been used as the basis for previous Cumulative Impact Assessments (Hunter et al., 2015).

UNCERTAINTY

> "Action Item: Focus discussion and identify more immediate actions to improve the 2023 Cumulative Impact Assessment: Reconsider how the uncertainty associated with the water budget parameters is reported, for example by reporting water budget parameters as a range or by expanding the uncertainty section of the Cumulative Impact Assessment. "
>
> Great Lakes St. Lawrence Regional Body Compact Council *Science Strategy, 2019 (pg.12)*

Uncertainties in historical data can occur when there are limitations on the temporal or spatial extent of monitoring infrastructure, or if there is high variation for a data point among data sets. **In previous research, uncertainty was quantified using professional scientific judgment based on water balance estimates that preceded the L2SWBM (i.e. primarily from the GLM-HMD). Those historical uncertainty estimates ranged between 15-45% for over-lake precipitation, 15-35% for runoff, 10-35% for evaporation, and 5-15% for outflow (Table 1).** Groundwater has, in most previous basin-scale studies, been considered negligible relative to other major components of the

Great Lakes water balance (Figure 2). It is informative to note that while groundwater fluxes may indeed be smaller than other water balance components, **we find there are few comprehensive state-of-the-art groundwater flow data sets across the entire Great Lakes basin to fully support this claim, and believe that improving an understanding of regional basin-scale groundwater flux into and out of the Great Lakes is an important area for continued research.** For more information on historical quantification of uncertainty, we refer readers to the 2011-2015 Cumulative Impact Assessment and the section on 'Consideration of Uncertainty' (page 6).

Table 1 – Comparison between conventional uncertainty estimates in water balance components (adapted from Neff & Nicholas, 2005) and uncertainty estimates calculated from the new L2SWBM results. Note that calculations of percent uncertainty for evaporation and runoff in the L2SWBM are inflated in months when evaporation and runoff are very monthly flows of evaporation and runoff can be very low (i.e. close to zero) at certain times of the year. The uncertainties in these months increase the estimates of long-term uncertainty. For reference, see Figure 3.

Water balance component	Upper range of uncertainty (%) in conventional (from Neff & Nicholas, 2005) monthly water balance component estimates				Upper range (upper bound of 95% confidence interval) of uncertainty from the L2SWBM			
	Superior	MH	Erie	Ontario	Superior	MH	Erie	Ontario
Over-lake precipitation	45	45	45	45	22	13	27	15
Evaporation	35	35	35	35	30	28	28	21
Runoff	35	35	35	45	28	17	46	23
Connecting channel outflow	15	15	10	2	4	3	3	3

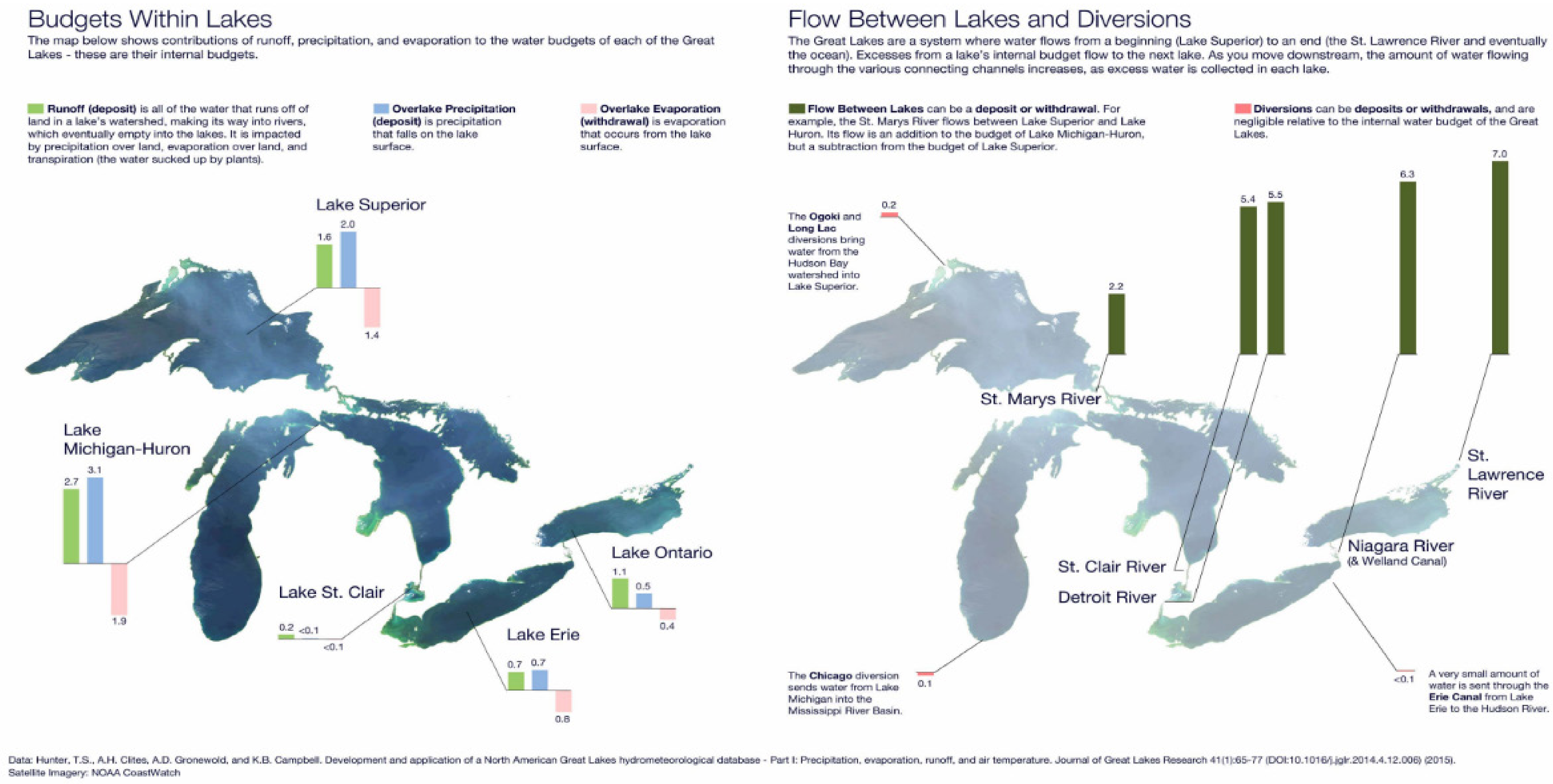

Figure 2 – Graphical summary (from NOAA-GLERL) of historical long-term average Great Lakes water balance component values. The height of each vertical bar reflects the relative magnitude of each component, and numbers at the top of each bar are long-term average flows in units of thousands of cubic meters per second. Groundwater fluxes and consumptive uses are not represented, and are often considered negligible relative to other water balance components.

THE LARGE LAKE STATISTICAL WATER BALANCE MODEL

The large lake statistical water balance model (L2SWBM) is a statistical model that assimilates multiple historical water balance component estimates over time, and executes millions of calculations to estimate what the "true" value of each water balance component must be that is both consistent with those measurements, and with the water balance (via equation in Figure 2). **The L2SWBM is, to our knowledge, the most effective way to quantify and potentially reduce uncertainty across all components of the Great Lakes water budget over time.**

The L2SWBM is built within a framework that employs a unique formulation of the lake water balance model (Figure 2) in which historical monthly water balance components are estimated through Bayesian inference (for further details, see Gronewold et al., 2020). **The L2SWBM is currently used by the U.S. Army Corps of Engineers and Environment and Climate Change Canada through a binational data coordination process to continuously update the most recent ten years of water balance data, and to use that data for regional water resources management planning.**

The L2SWBM can assimilate multiple estimates of each water balance component (from either historical model simulations or interpolated *in situ* monitoring data), and it can accommodate those estimates even if they span different time periods (Gronewold et al., 2020). The L2SWBM can also be executed if data for a particular water balance component is unavailable. Each water balance component or "true" value of a variable is estimated by combining (following standard Bayesian statistical procedures) a prior probability distribution and likelihood functions parameterized from multiple independent data sources.

Table 2 – Summary of legacy data sets incorporated into the L2SWBM for this report. It is informative to note that the GLM-HMD (see below) has been used as the sole basis for previous CIA reports, and that none of the data sets listed below close the Great Lakes water balance (the L2SWBM does). Furthermore, to our knowledge, none of the data sets below have been documented with explicit expressions of uncertainty.

Water Balance Component(s)	Data Source
Beginning of Month Water Levels Interbasin diversions Lake St. Clair net basin supply	Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (CCGLBHHD)
Over-lake precipitation	NOAA GLERL GLM-HMD AHPS (Advanced Hydrologic Prediction System) • Including both USACE and GLERL output ECCC WCPS (Water Cycle Prediction System) Inchcape (Canadian Precipitation Analysis) National Weather Service Multisensor Precipitation Estimate (NWS-MPE) Historical CCGLBHHD coordinated values USACE Thiessen polygon interpolation MPE-CaPA merged product
Over-lake evaporation	NOAA GLERL GLM-HMD AHPS (Advanced Hydrologic Prediction System) • Including both USACE and GLERL output ECCC WCPS (Water Cycle Prediction System) NOAA GLERL FVCOM simulations
Runoff	NOAA GLERL GLM-HMD AHPS (Advanced Hydrologic Prediction System) • Including both USACE and GLERL output ECCC WCPS (Water Cycle Prediction System) ECCC WATFLOOD (hydrologic model)

Outflow	Acoustic Doppler Velocity Meters located near International Gauging Stations (IGS): • St. Marys River Monthly Mean flow • St. Clair River • Detroit River St. Clair Monthly Mean Flow: from IGS Detroit Monthly Mean Flow: from IGS Niagara Monthly Mean Flow: from IGS St. Lawrence Monthly Mean Flow

Table 3 – Acronyms for commonly-referenced databases or federal agencies (or similar organizations).

Acronym	Related database(s)	Related agency or organization
CCGLBHHD	Water levels and other components	Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data
GLM-HMD	Great Lakes Monthly Hydrometeorological Database	NOAA Great Lakes Environmental Laboratory
AHPS	Advanced Hydrologic Prediction System	NOAA Great Lakes Environmental Laboratory
IGS	International Gauging Station	U.S. Geological Survey Water Survey Canada
ADVM	Acoustic Doppler Velocity Meter	U.S. Geological Survey
GEM-MESH	Canadian Global Environmental Multiscale-Modelisation Environmentale-Surface et Hydrologie	Environment and Climate Change Canada
CaPA	Canadian Precipitation Analysis	Environment and Climate Change Canada

L2SWBM OUTPUT: RESULTS AND ANALYSIS

UNCERTAINTY REDUCTION

A comparison (for representative years 2015 to 2019) between historical (i.e. Neff & Nicholas, 2005) quantification of uncertainty (purple bands, Figure 4) and uncertainty estimates from our recent run of the L2SWBM (thin yellow band representing 95% credible intervals) indicates that **our new L2SWBM results significantly reduce uncertainty in all Great Lakes water balance components.** The new estimates we developed using the L2SWBM (median values presented as red lines in Figure 4), along with their estimates of uncertainty, provide a robust basis for interpreting patterns and trends in the historical record, and for potentially detecting climate change, which we describe further in the following section.

HISTORICAL TRENDS AND CLIMATE CHANGE DETECTION

According to the sixth IPCC report (AR6), climate change can be characterized as a statistically measurable phenomenon based on assessment of specific indices or metrics (i.e. variables). **A recent IPCC report states specifically that climate change is defined as "…a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/ or the variability of its properties and that persists for an extended period, typically decades or longer".**

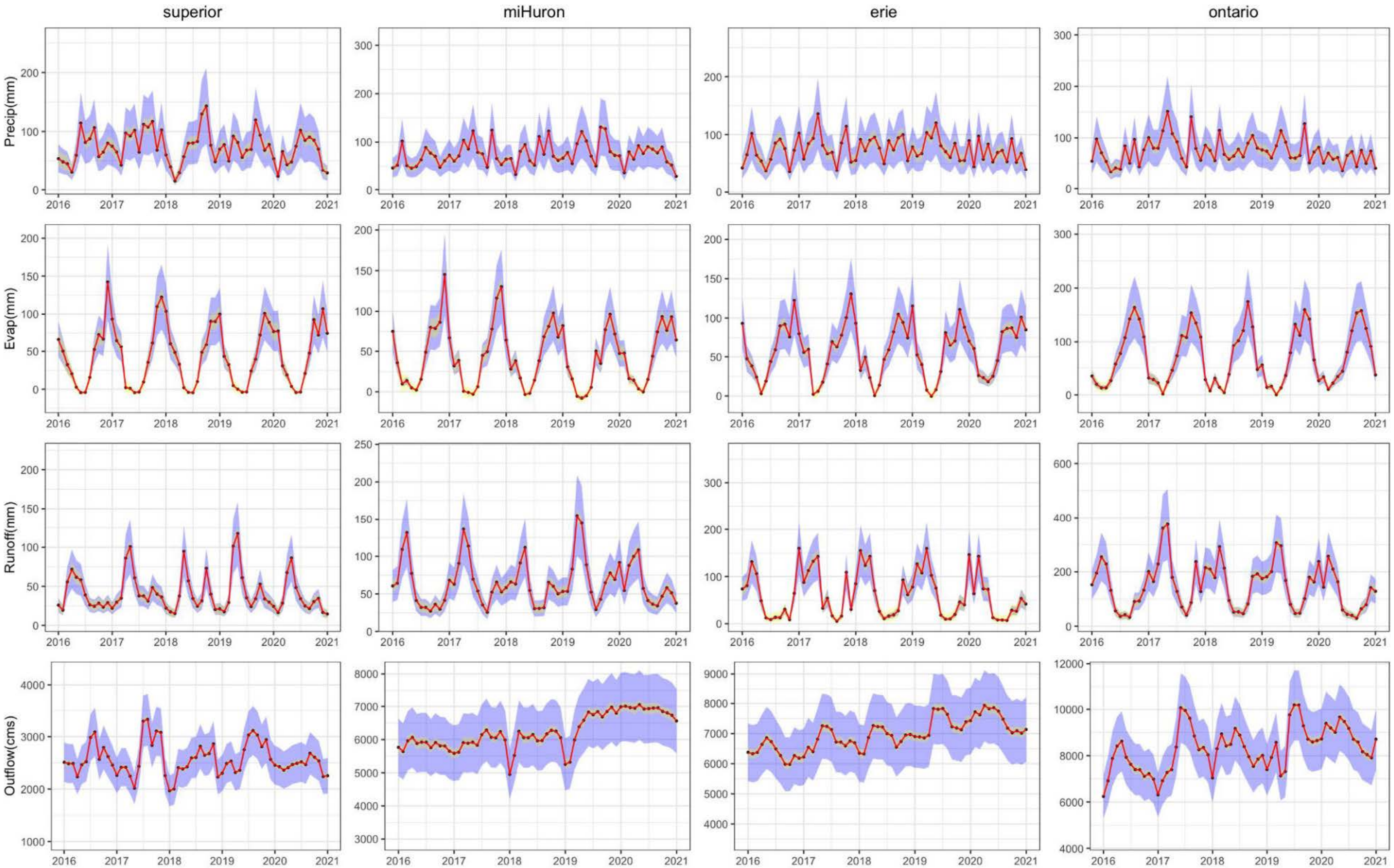

Figure 3 - New representative monthly estimates of the Great Lakes water balance (using the L2SWBM) from 2015 to 2019. Median values are shown as red lines. Purple bands represent uncertainty bounds adapted from Neff & Nicholas (2005). Yellow bands represent uncertainty 95% credible intervals from the new L2SWBM results.

Following this guidance, we assess patterns in the historical Great Lakes water balance record using the following four general statistical methods:

- Method 1 - Linear regression (one regression model applied across the entire record)
- Method 2 - Fixed change-point in 1980 with:
    - Comparison of means (Method 2a)
    - Segmented linear regression (Method 2b)
- Method 3 - Empirical (data-driven) change-point with:
    - Comparison of means (Method 3a)
    - Segmented linear regression (Method 3b)
- Method 4 - Rolling average

All methods were implemented using the R statistical analysis software package.

METHOD 1: LINEAR REGRESSION

A relatively simple and conventional method to assess trends in data over time is linear regression. However, adopting this approach assumes that a linear relationship is in fact the best explanation for changes in data over time. When applied across the historical record (using our new L2SWBM data) for Lake Superior over-lake precipitation, for example (top left panel in Figure 5), this method implies an increasing trend. However, this method is not nuanced enough to capture the persistent decrease in Lake Superior over-lake precipitation from 1970 to 2010, or the drastic increase in precipitation from 2013 to 2019, neither of which are represented by a single linear trend. More generally, **we find that the linear regression method (though often used in regional studies) is not particularly well-suited to detect important signals of climate change in the historical record such as a regime shift or change points that may better describe observed patterns in the data.**

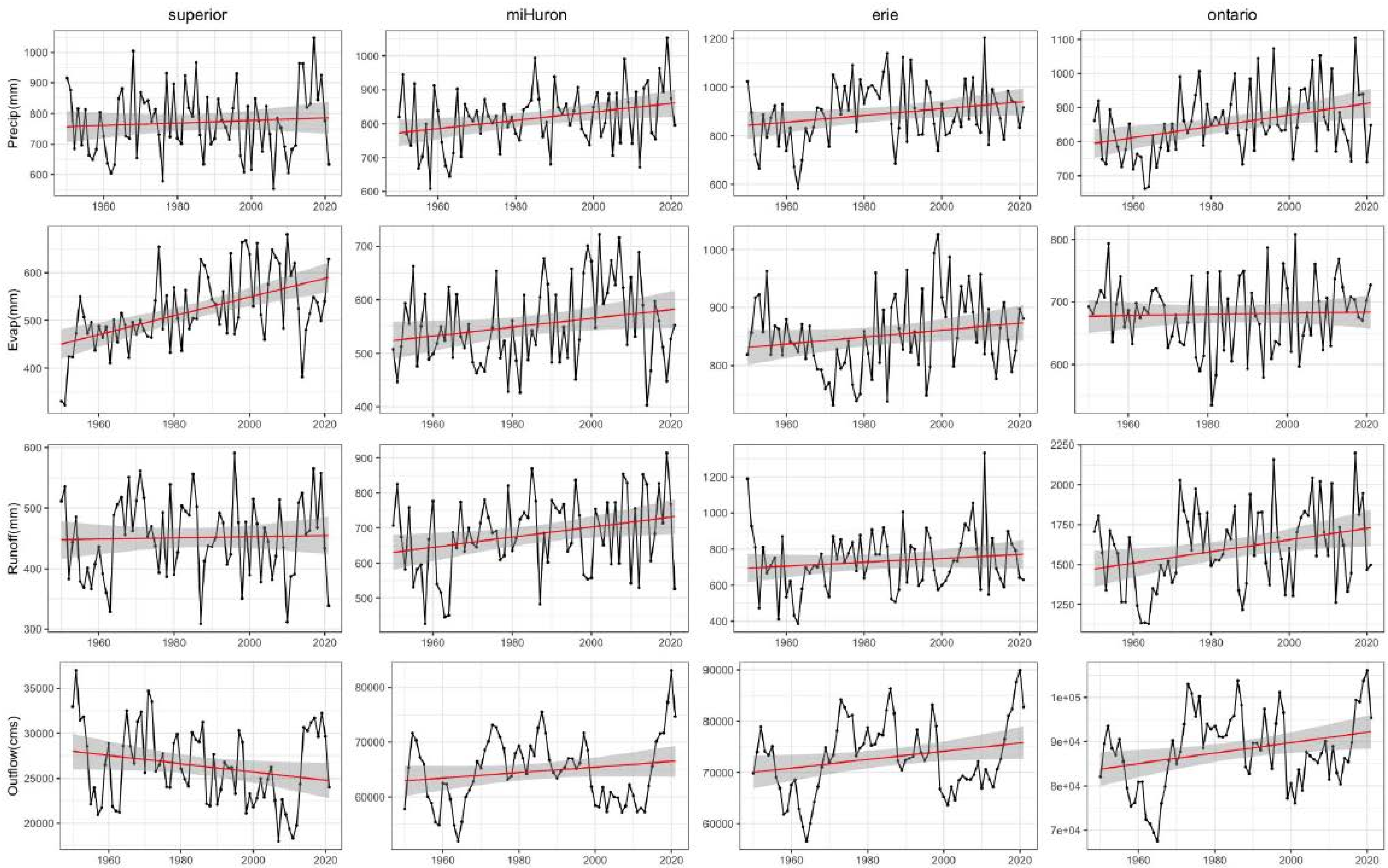

Figure 4 – New historical water balance record from the L2SWBM and application of a linear regression model (analysis method 1). The linear regression mean is represented by a red line, and the 95% confidence interval in the mean is the grey shaded region.

OVERVIEW OF CHANGE POINT METHODS (METHODS 2A AND 2B)

A "change point" can be defined as a point in a time where a shift in patterns occurs between a previous and subsequent time period. The presence of a change point suggests that it may not be appropriate to represent all of the data in a historical record with a single summary statistic, such as a mean or trend. **Change points, from an environmental perspective, can be categorized as "regime shifts"; often defined as large, persistent, and nonlinear changes in the function and structure of a complex system** (Scheffer et al., 2009; Beaulieu et al., 2012; Ospina et al., 2019).

It may be useful to view patterns in Great Lakes hydrological data through the theoretical lens of a regime shift because the hydrological processes are driven by both external drivers (e.g., global and regional climate patterns) and internal feedback processes (e.g. local weather). These internal processes can both insulate the system from, or exacerbate the effects of, dramatic changes in external conditions on the internal system. **Change point methodology has been used to describe other Great Lakes hydrological processes including trends in seasonal ice cover duration (Mason et al., 2016).**

METHOD 2A: FIXED CHANGE POINT WITH PRE- AND POST-1980 REFERENCE PERIODS

We employed a fixed change point method in two ways (Methods 2a and 2b). First (2a) we applied a fixed change point in the historical record at 1979 to determine whether there is a statistically significant difference in mean precipitation, evaporation, runoff, and outflow between 1950-1979 and 1980-2020 (Figure 6). This approach is based on the idea of using a 'reference' or 'baseline' period that can be helpful in determining climatic scale changes (Houghton & Intergovernmental Panel on Climate Change, 2001; Intergovernmental Panel on Climate Change, 2014a; United Nations, 2012). It is worth noting that **a regional climate is typically defined using patterns across periods of at least 30 years** (Intergovernmental Panel on Climate Change, 2014b). Here, we use the period from 1950-1979 as a reference period following a precedent set by previous climate studies (Hansen et al., 2012; Smith & Pitts, 1997). It is also worth noting that the World Meteorological Organization Guidelines on the Calculation of Climate Normals has recently reported guidance suggesting an updated reference period of 1991-2020 as more data becomes widely available. Consideration of different reference periods is a potential area of study to be considered in future CIA reports (2017).

METHOD 2B: FIXED CHANGE POINT WITH SEGMENTED REGRESSION

We then applied a variation of Method 2a known as segmented regression (also known as piecewise regression or broken-stick regression). This method (2b) uses the same fixed transition period to fit a trendline to each time period (Figure 7). **Segmented regression often leads to a "hockey stick" shape, an identifiable signal of climate shifts in other regions and across various natural processes (Mann et al., 1998; Wagner et al., 2002).**

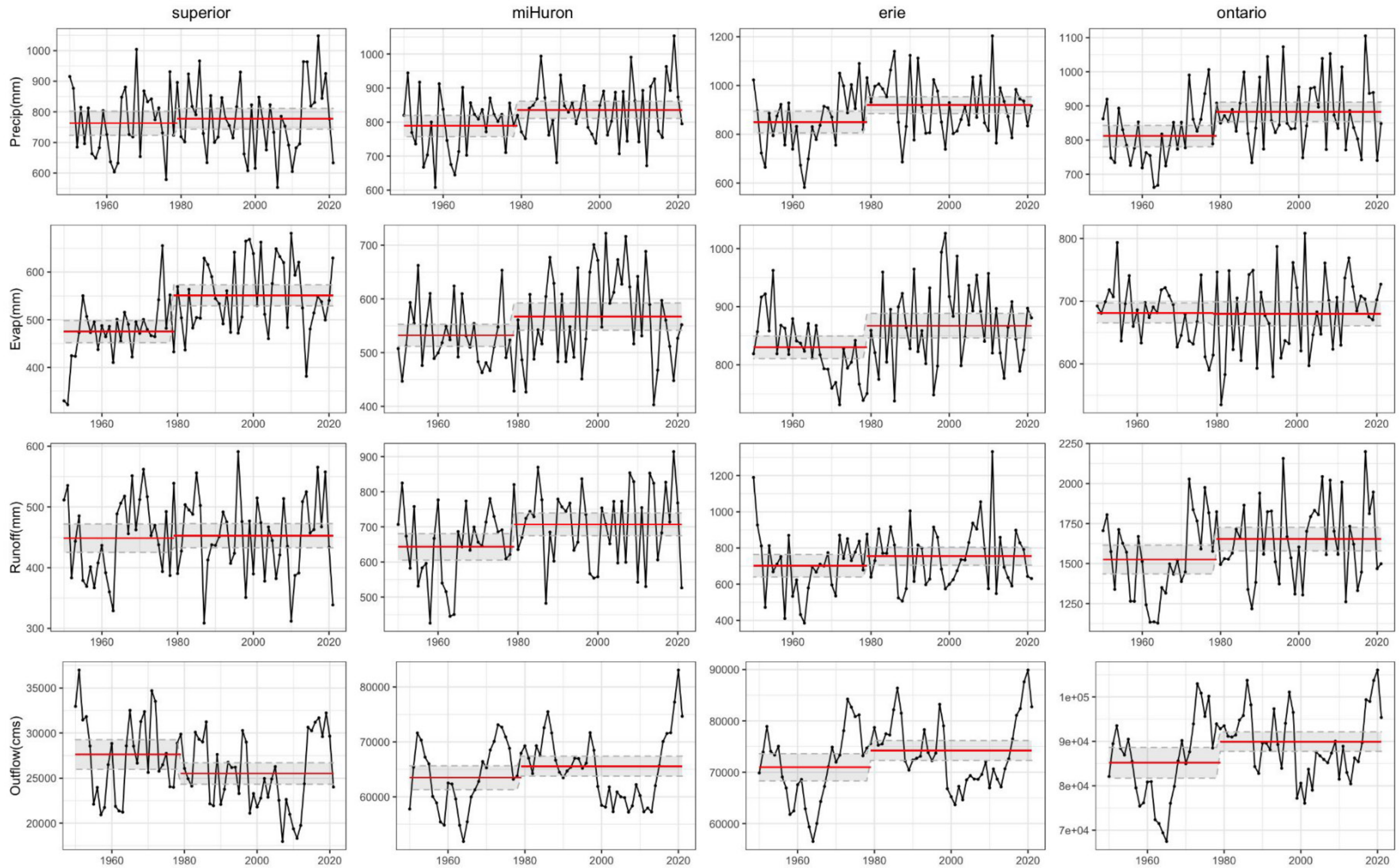

Figure 5 Figure 6 - Results of analyzing historical record with a fixed change point and comparison of long-term (i.e. multi-decadal) means before and after that change point (Method 2a). The long-term mean for each period is represented by a red line, and the 95% confidence interval in the mean is represented by the grey region. Note that overlapping grey regions (before and after the change point) suggest that the differences between them are not significant.

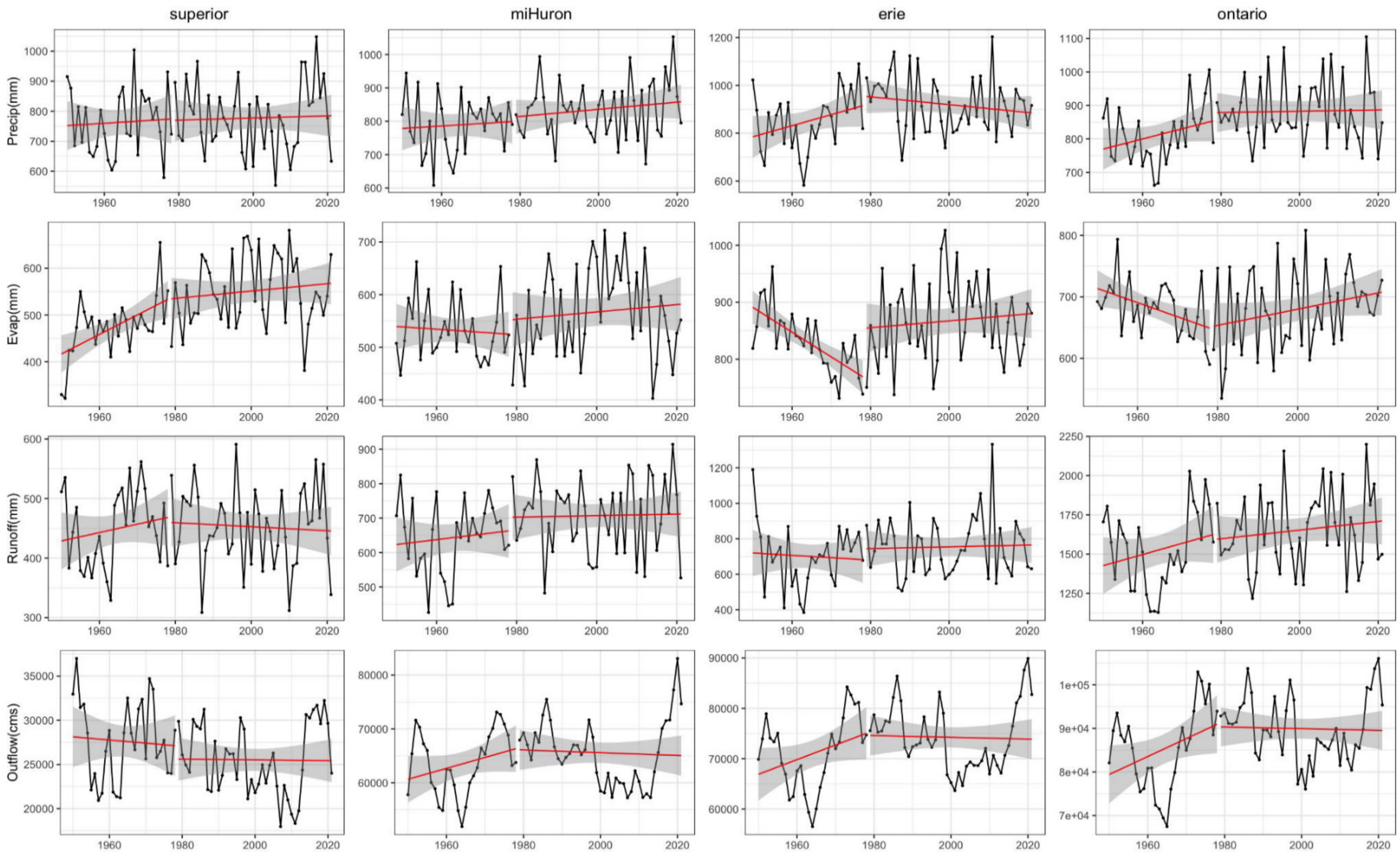

Figure 7 – Results of analysis using a fixed change point at 1979 with segmented regression (method 2b).

METHOD 3: AUTOMATED (OR EMPIRICAL) CHANGE-POINT DETECTION

Rather than assessing historical data with a fixed change point (as in method 2a and 2b) we can alternatively implement an automated or empirical (i.e. data-driven) change point detection method (Figures 8 and 9). Our implementation of this methodology involves using a computer algorithm to find a single change point in the data (using a function in the R statistical software package). We impose on this method a constraint that prevents a change point from being detected within the first or last 5 years of the data record. **This approach controls for what are referred to as "end effects", where unusually high or low values in the first or last year of a data record may impact the estimate of a change point.** As with method 2, we implement two versions of method 3, one designed to compare the long-term average mean before and after a change point (method 3a), and another designed to compare trends (via regression analysis) before and after a change point (method 3b).

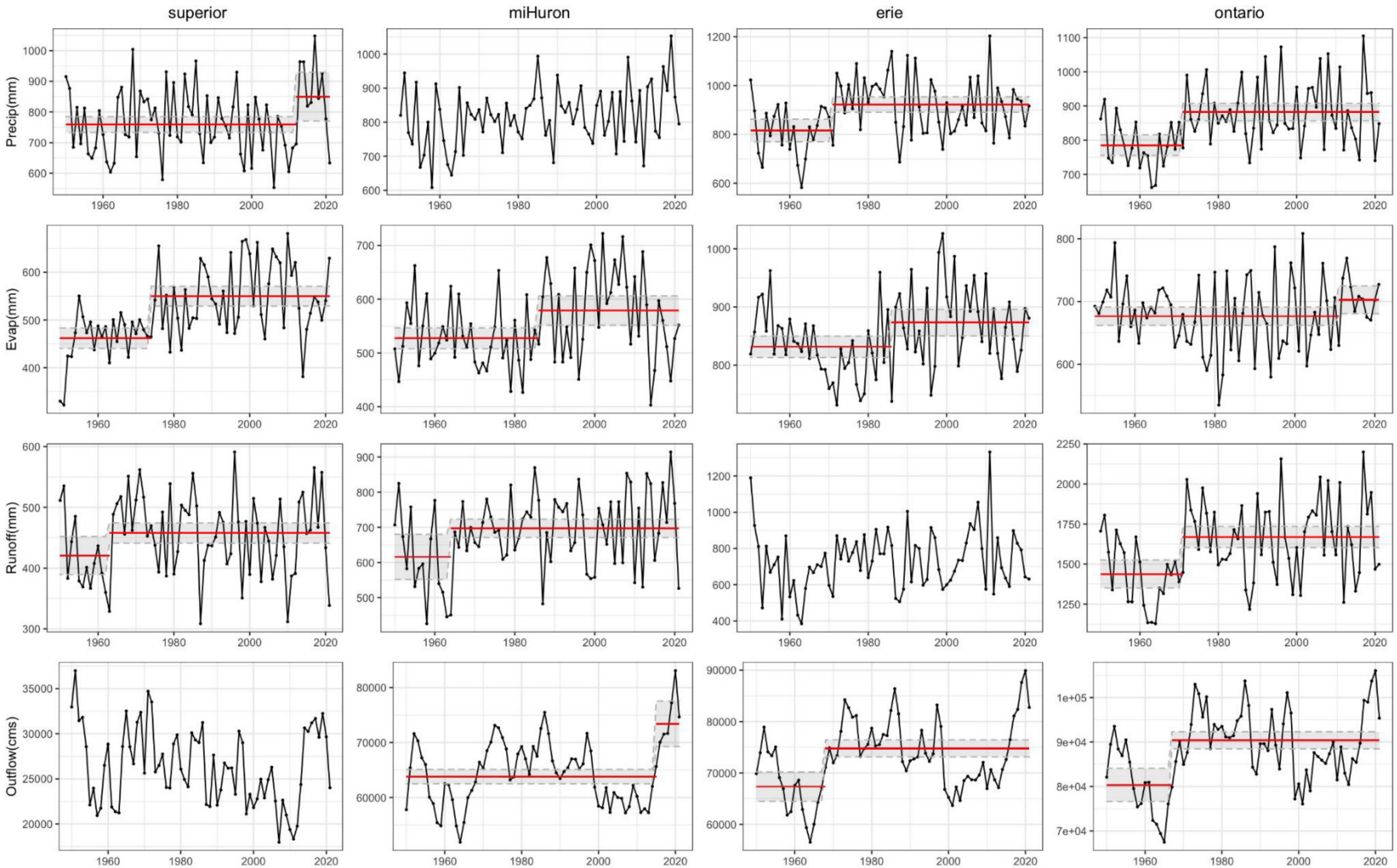

Figure 8 – Results of analysis using an empirical (automatically detected) changepoint with comparison between long-term mean (red line) before and after the changepoint (method 3a). If no line for the mean values is shown, a changepoint was either not detected, or it was detected in the first or last 5 years of the data set.

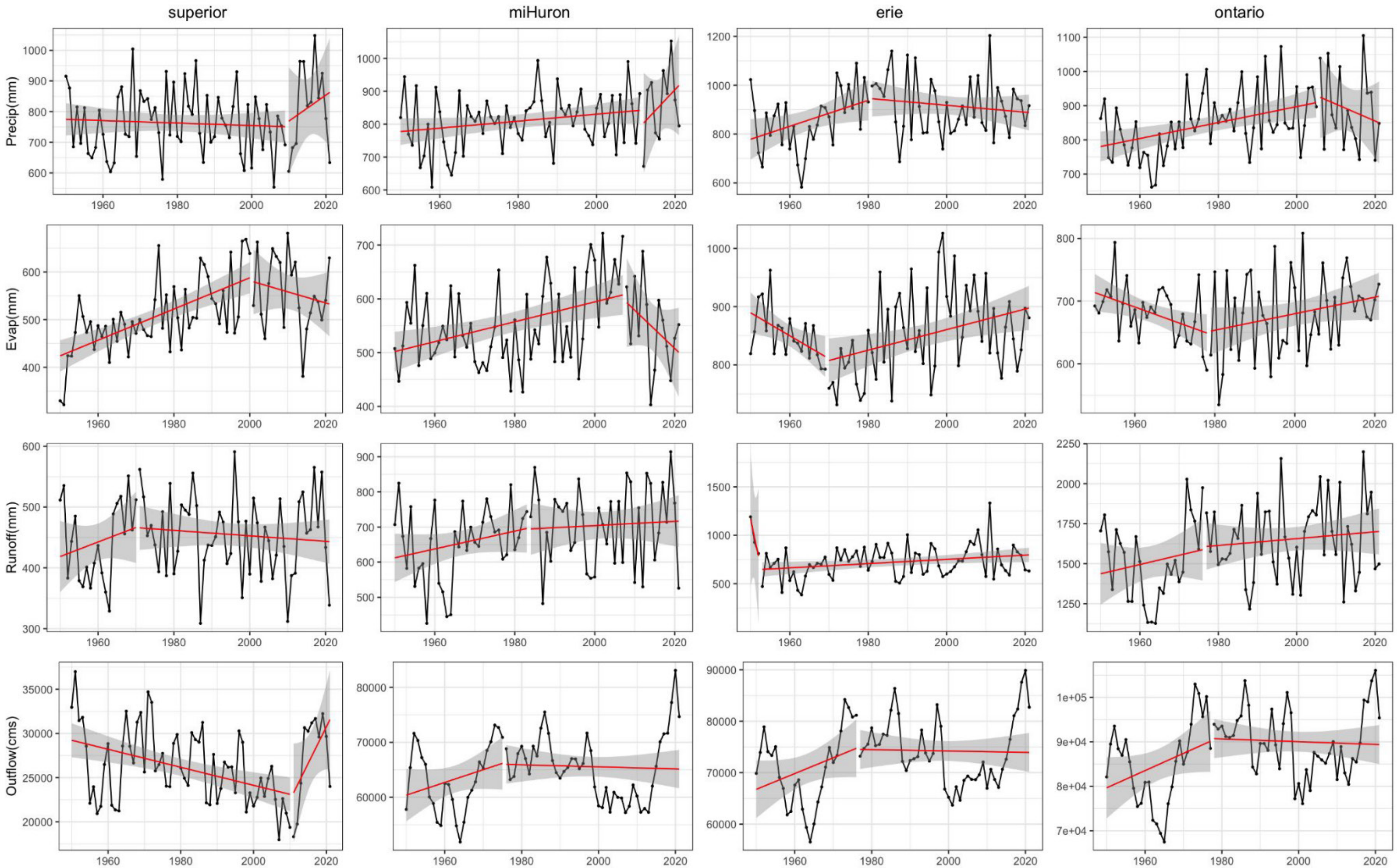

Figure 9 – Results of analysis using automated change point detection and a comparison of trends (using linear regression) before and after the changepoint (Method 3b).

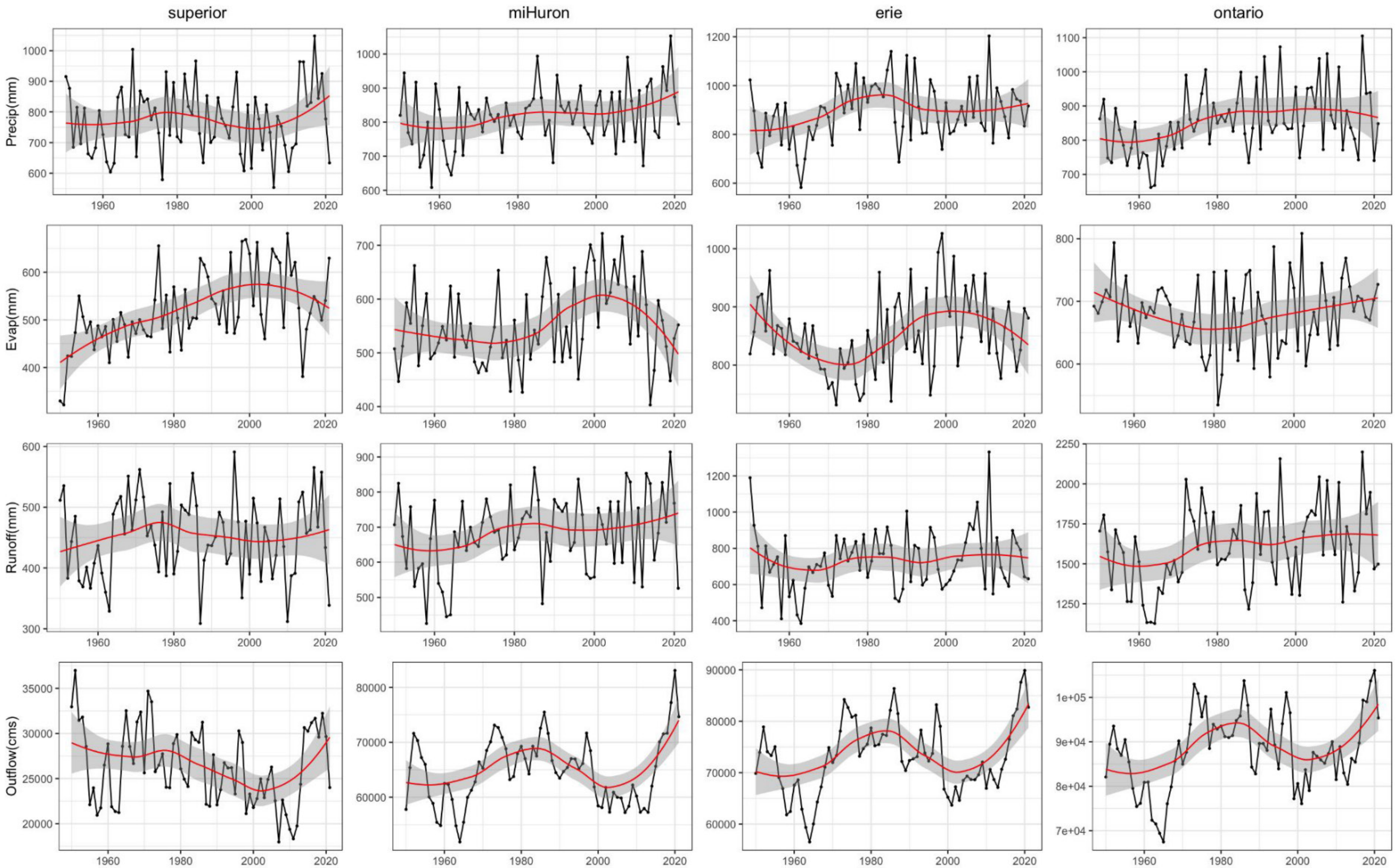

Figure 10 – Results of applying a smoothed trend line (or rolling average) to each lake and water balance component. Grey regions represent 95% confidence intervals.

METHOD 4: ROLLING AVERAGE

Our final analysis method employs a rolling average across the entire time period (Figure 10).

PLAUSIBLE FUTURE WATER BALANCE SCENARIOS

To understand potential climate change impacts on the future of the Great Lakes water balance, we present three plausible scenarios of climate change (representative results from Lake Superior in Figure 11). Each of these scenarios is based on either historical trends, or a synthesis of projected trends from the peer-reviewed literature. **Our first scenario (blue lines, Figure 11) represents a continuation of existing trends in water balance components since 1950.** We recognize that for many water balance components, a single trend may not be the best representation of long-term and short-term patterns. We employ it here, nonetheless, as a potentially helpful reference point.

Our second scenario (red lines, Figure 11) is similar to the first, but is based on a continuation of trends since 1980 (rather than 1950). This approach acknowledges the findings from our statistical analysis which indicates that some water balance components may continue to exhibit patterns more indicative of the post-1980 period than the 1950 to 1979 period. **Our third scenario (yellow lines, Figure 11) relies on previous research in Mailhot et al. (2019)runoff, evaporation and net basin supply (NBS, and uses the ensemble value of seven climate models they ran under a "high CO2 emissions scenario", quantified in climate studies with a representative concentration pathway (RCP) value of 8.5.** For all three scenarios, and for all water balance components, we fit a linear regression line to determine a trend for each calendar month.

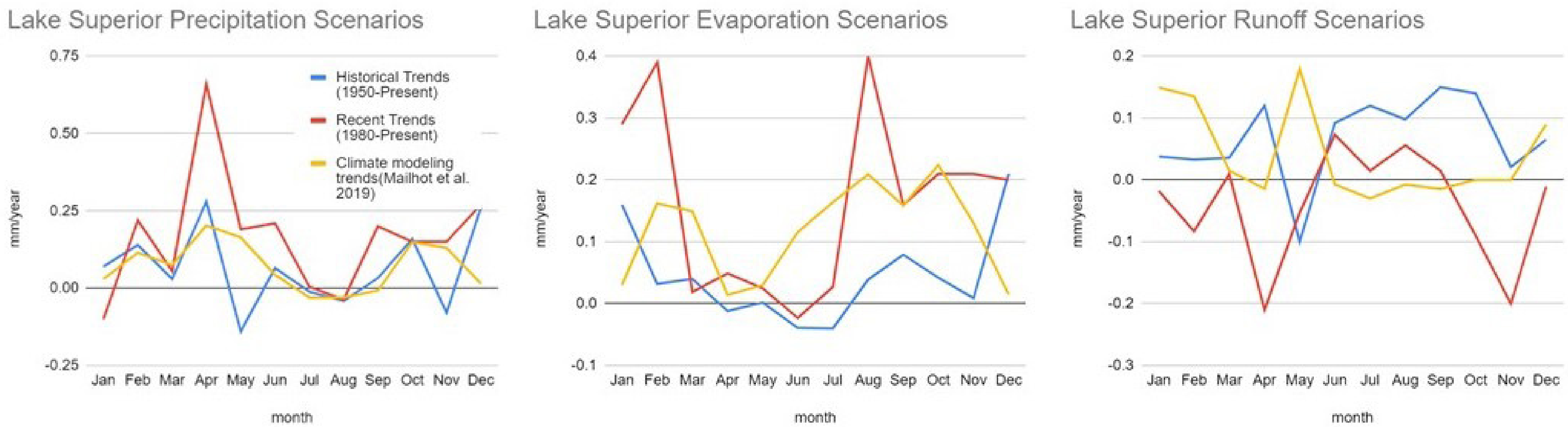

Figure 11 - Potential long-term trends (in mm/year) for monthly water balance components on Lake Superior (as a representative example; related data has been developed for the other Great Lakes).

Our analysis indicates that state-of-the-art climate models (yellow lines, Figure 11) are projecting increases in all three water balance components. This finding is consistent with related IPCC studies which suggest that some areas on Earth will experience an intensification of the hydrologic cycle (i.e. a future in which competing forces on the water balance are simultaneously getting larger, or "stronger"). It is informative to note that these patterns appear to be evident, and in some months amplified, in the period since 1980 (red lines, Figure 11). **For example, we find that Lake Superior precipitation has been increasing across all months since 1980, and that the rate of increase in the month of April has been roughly 3 times higher than the average projection from climate models. Similarly, Lake Superior evaporation has been much higher in the mid-winter and late summer months than climate models anticipate for the future.**

FINAL DISCUSSION AND CONCLUSIONS

This Supplemental Report, intended to complement the 2016-2020 Cumulative Impact Assessment report, presents a novel and robust consideration of uncertainty in historical water balance components, and the extent to which historical water balance components might have been impacted by climate change. It is important to note (as indicated in previous reports) that **not only is the magnitude of historical water balance components much greater than that of diversions and consumptive uses, but also that the uncertainties in historical water balance components are often greater than the cumulative effects of diversions and consumptive uses.** To address this challenge, this Report presents a new analysis framework for the Great Lakes basin that uses statistical methods to solve a basin-wide, lake-to-lake water balance model. **This new modeling framework led to water balance component estimates with significantly reduced uncertainty.**

The additional assessment of climate change impacts indicates that precipitation and evaporation are both likely to increase over the coming decades. Historical records indicate that long-term average precipitation is already increasing across the Great Lakes basin, and that both precipitation and evaporation (while increasing) have exhibited periods of increased interannual variability. These historical patterns, along with projected trends from climate models, suggest that **future long-term average (i.e. over multiple decades) water levels on the Great Lakes are unlikely to be significantly higher or lower than the historical long-term average.** It is possible, however, that water level variability over shorter time periods could be exacerbated, as observed during the rapid water level rise from 2013 (a period of record lows) to 2020 (a period of record highs).

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