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Water Balance of the Laurentian Great Lakes

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Without Abstract

Introduction

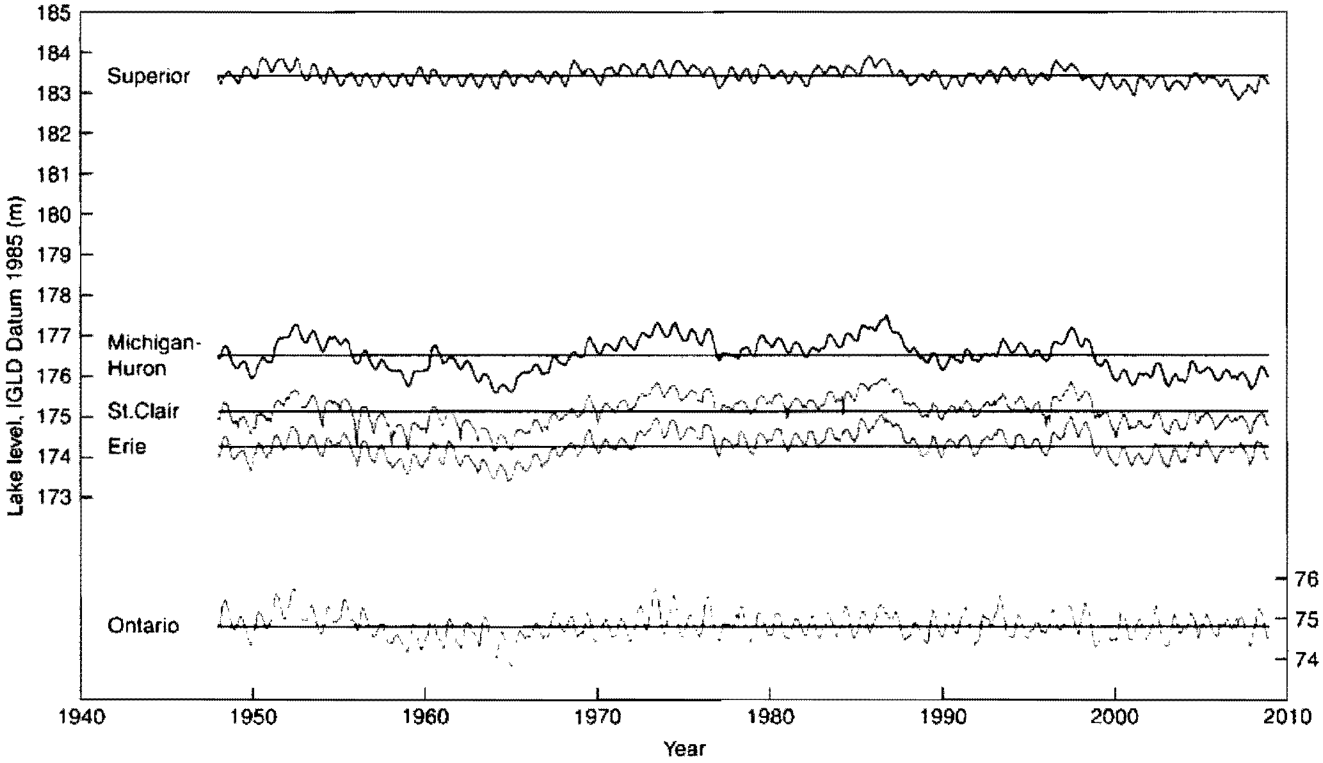
Surface water elevation dynamics of the Laurentian Great Lakes exhibit long-term persistence on decadal time scales, and the changes in surface water elevation over these time scales are driven mainly by climate dynamics. Understanding Great Lakes water elevation dynamics on shorter time scales (such as monthly and annual scales) is commonly based on a cumulative assessment of the individual components of the net supply of water (i.e., precipitation, evaporation, and runoff) within the Great Lakes basin.

Great lakes water levels

The surface water elevations (hereafter referred to as “water levels”) of the Great Lakes are closely monitored by both the United States (through NOAA’s National Ocean Service) and Canada (through the Canadian Hydrographic Service). Monthly mean lake-wide levels, obtained by averaging a subset of US and Canadian gauges from around the lakes, can be obtained from the US Army Corps of Engineers:

http://www.lre.usace.army.mil/greatlakes/hh/greatlakeswaterlevels/

Figure 1 illustrates how lake levels have changed over time from 1948 to 2008. Water level data is available prior to 1948; however, we focus here on the 1948–2008 time period because it is the only period for which water levels *and* estimates for all components of net basin supply are readily available. Lake Michigan and Lake Huron have the same mean water level, as the lakes are connected at the Straits of Mackinac. Note that in Figure 1, we use a separate vertical axis for Lake Ontario, which is on average approximately 100 m lower than Lake Erie (due primarily to the drop in elevation over Niagara Falls). The thin, gray horizontal lines in Figure 1 indicate the long-term average water level for each lake from 1948 to 2008.



Water Balance of the Laurentian Great Lakes, Figure 1 Time series of Great Lakes monthly average lake-wide water levels, 1948–2008.

In general, water levels over the past decade were lower than the 1948–2008 average for all lakes but Lake Ontario. Long-term persistence on decadal time scales is also seen for all lakes, although more pronounced cycles are apparent for Lake Michigan-Huron. Lag-1 autocorrelation of mean annual levels ranges from 0.5 for Lake Ontario to 0.8 for Lake Michigan-Huron. Autocorrelation is in fact significantly larger than zero at the 95% level from lag-1 to lag-5 for Lake Michigan-Huron over this time period. These results collectively suggest a persistent, non-randam pattern of annual water level on the Great Lakes.

Net basin supply

As with most lakes, the lake-wide average water level (*H*) of each of the Laurentian Great Lakes increases if the net total supply (*NTS*) of water to the entire basin (including the lake itself) is larger than the flow at the outlet of the lake (*O*). However, water level also varies with the temperature of the lake, which affects its density and, therefore, its volume. The change in water levels can therefore be expressed as follows (note that each term in the following expression, is in units of millimeter):

$$\Delta H = NTS - O + \Delta H_T$$

where ΔH_T reflects the impact of thermal expansion.

NTS can be decomposed into an overlake precipitation component (P), an overlake evaporation component (E), and a runoff component (R_{total}). The runoff component includes contributions from tributaries upstream of, and discharging directly into, each lake. This decomposition leads to the following expression:

$$\Delta H = P - E + R_{total} - O + \Delta H_T$$

Other terms of the water balance, such as consumptive use and net groundwater flux into the lakes, are relatively small compared to the components identified above, and are therefore generally ignored (IUGLS, 2009).

NTS can be further decomposed into runoff from the lake's own watershed (R), inflow coming from the upstream lake (I), and any nonnatural diversion of water into or out of adjacent watersheds (D). Hence:

$$\Delta H = P - E + R - O + I + D + \Delta H_T$$

The first three terms in the equation above correspond to the water cycle within a lake's individual basin, including the lake itself but not including the watershed of any upstream lake or diversion, and are collectively referred to as the net basin supply (*NBS*):

$$NBS = P - E + R$$

NBS is the primary driver of lake levels on monthly and longer time scales, as inflows and outflows are essentially controlled by lake levels. Indeed, while Lake Superior and Lake Ontario outflows are regulated, which tends to reduce natural variability of lake levels, regulation has little impact on long-term trends: The climate, hence, essentially dictates what happens to lake levels, although other factors such as conveyance changes in the channels connecting the lakes and glacial isostatic adjustment do play a role (IUGLS, 2009). This relationship suggests that lake levels can be simulated and forecasted (Gronewold et al., 2011) on monthly time scales using monthly *NBS* sequences as input to a lake routing model in which regulation effects are predicted from lake levels, and diversions are prescribed.

The component and the residual methods

NBS can be computed by either estimating each of the three components P, E, and R (the component method), or as a residual of the water balance equation (the residual method), indicated in the following expression:

$$NBS = \Delta H + O - I - D - \Delta H_T$$

The thermal expansion term ΔH_T is generally ignored because it is close to zero on an annual time scale, but it can be significant on monthly time scales, given the strong annual cycle in water temperature. For example, according to Bruxer (*2010*), Lake Erie water levels increase on average by about 40 mm from May to July due to thermal expansion, and lose as much volume due to thermal contraction between September and November, which corresponds to approximately 15% of the May-to-July *NBS*, but close to 40% of the September-to-November *NBS*.

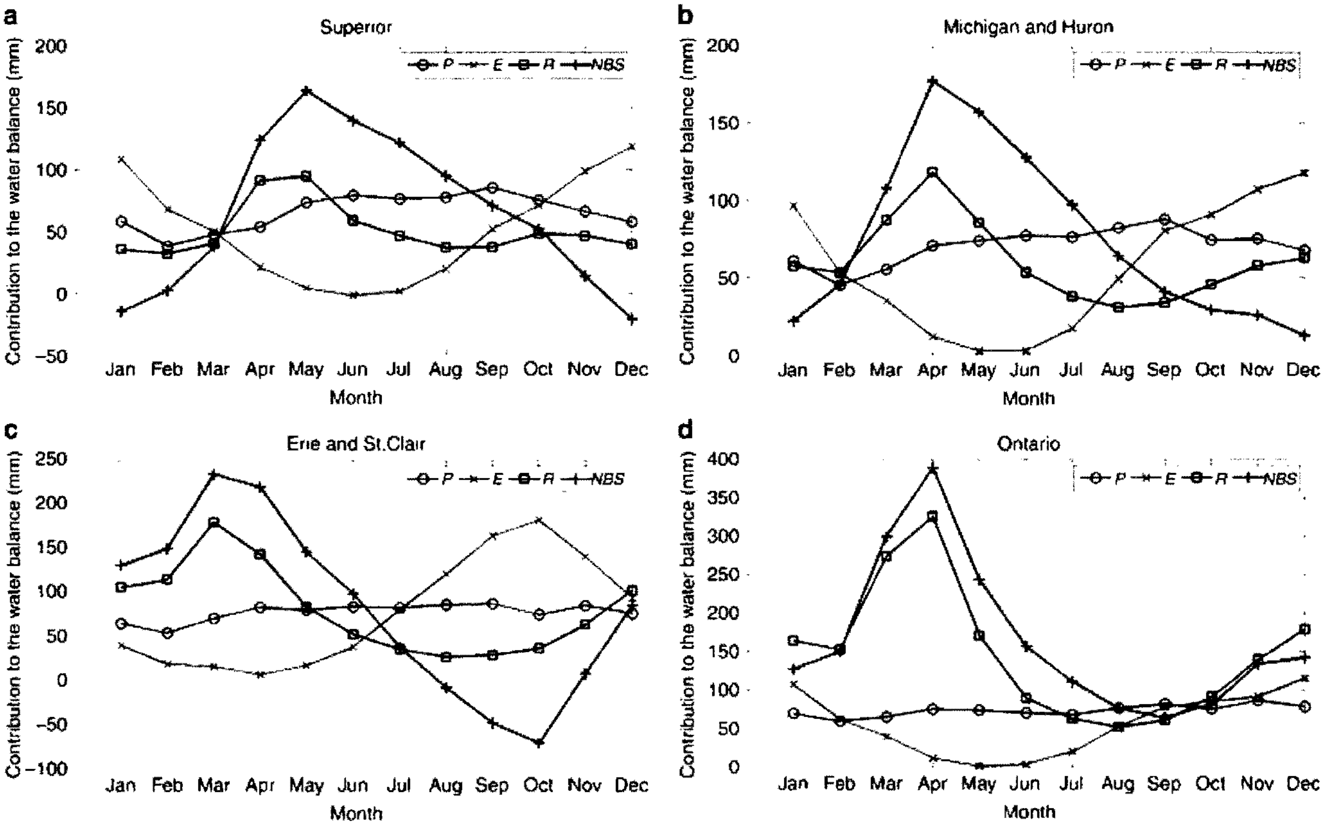
Note that the residual method cannot be used to estimate separately *NBS* for Lake Michigan and Lake Huron, which are connected at the Straits of Mackinac. Hence, when it comes to assessing the water balance of the Great Lakes, Lake Michigan-Huron is generally considered to be a single body of water, although the component method can be used to obtain separate estimates of *NBS* for both lakes. A separate water balance is, however, commonly estimated for Lake St. Clair, so that *NBS* is generally computed for five lake systems: Lake Superior, Lake Michigan-Huron, Lake St. Clair, Lake Erie, and Lake Ontario. However, because Lake St. Clair and its watershed are significantly smaller than the other Great Lakes, it is often incorporated into the Lake Erie system, particularly in time series plots and other graphical representations of *NBS* and water levels.

Components of net basin supply

Residual *NBS* can be computed from hydrological information alone (levels and flows); however, residual *NBS* estimates on time scales shorter than a month are often highly uncertain and variable. The component *NBS* method requires a mix of meteorological and hydrological observations, integrated in a hydrometeorological model (Hunter and Croley, *1993*; Pietroniro et al., *2007*), in order to accurately estimate each component, but provides an additional level of understanding as to why lake levels change over time, and makes it possible to forecast *NBS* and lake levels on monthly to seasonal time scales (Gronewold et al., *2011*). Long-term estimates of each *NBS* component, computed using techniques described by Hunter and Croley (*1993*), can be obtained from NOAA's Great Lakes Environmental Research Laboratory (GLERL):

http://www.glerl.noaa.gov/data/arc/hydro/mnth-hydro.html

Figure 2 includes GLERL's long-term (i.e., 1948–2008) average monthly NBS estimates and each of its components, and provides an indication of their seasonal dynamics. Results are shown for (a) Lake Superior, (b) Lake Michigan-Huron, (c) Lake Erie and St. Clair, and (d) Lake Ontario. It can be seen that the annual peak in *NBS* coincides with the annual peak in runoff for all lakes. For the Upper Great Lakes (all lakes but Lake Ontario), the annual minimum in *NBS* coincides with the annual peak in overlake evaporation.

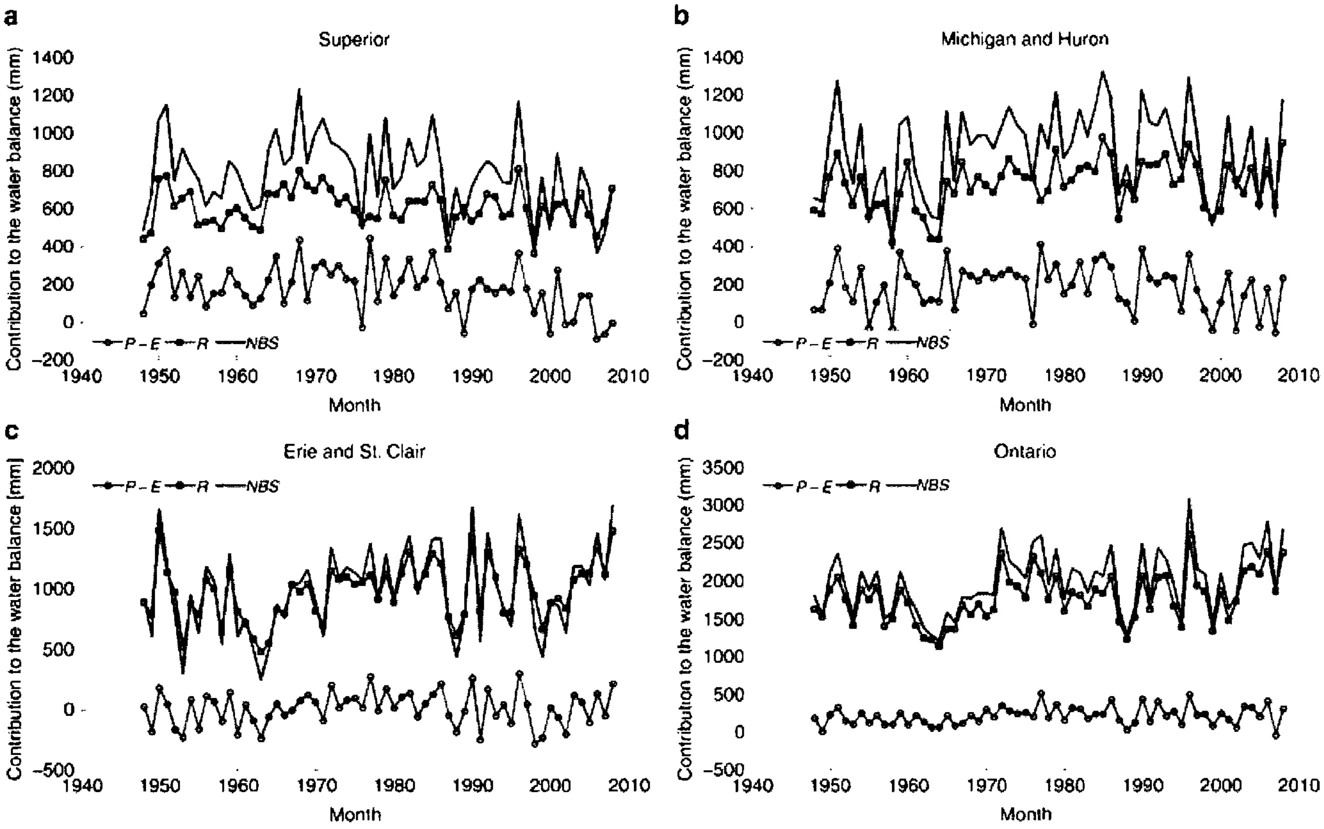


Water Balance of the Laurentian Great Lakes, Figure 2 Average monthly net basin supply (NBS) and NBS components for the North American Laurentian Great Lakes, averaged over the period 1948–2008.

For all lakes, mean annual overlake precipitation is larger than mean annual overlake evaporation but, more importantly, mean annual runoff is larger than the mean annual net overlake precipitation (*P* – *E*). On an annual basis, the ratio of net overlake precipitation to *NBS* is, on average, roughly 20% for Lake Superior and Michigan-Huron, roughly 1% for Lake Erie and St.Clair, and roughly 10% for Lake Ontario. In all cases, the contribution of net overlake precipitation is much smaller than the ratio of the lake area to the watershed area. Hence, for the purpose of understanding and predicting the water balance of the Great Lakes on an annual scale, it is critical to accurately assess the runoff component. However, all three components can have a significant influence on *NBS* for individual months. In fact, *NBS* is often negative in fall and winter months, with overlake evaporation being larger than *P* + *R*.

Natural variability, uncertainty, and climate change

Figure 3 includes annual mean net overlake precipitation (*P* – *E*), runoff, and *NBS* for each lake from 1948 to 2008, and indicates a general decrease in annual net overlake precipitation (*P* – *E*) for Lakes Michigan-Huron and Superior over the last several decades, with a noticeable increase in the frequency of negative net overlake precipitation for these two systems from roughly 2000 to 2008. On Lake Ontario, 2007 was the first year, for the period 1948–2008, with negative net overlake precipitation.



Water Balance of the Laurentian Great Lakes, Figure 3 Total annual net basin supply (NBS) and NBS components for the North American Laurentian Great Lakes for the period 1948–2008.

Important differences are in fact seen in *NBS* from one decade to the next for all lakes, and reflecting these dynamics in simulation and forecasting models is an important aspect of Great Lakes water resources management and planning. Shifting-level models, for example, have been used to describe, simulate, and predict *NBS* for water management purposes (Sveinsson et al., 2005; Fagherazzi et al., 2005), and represent a family of stochastic models that allows the mean of key process variables to change abruptly over time. Other modeling applications, including a time series segmentation algorithm based on the shifting-level model (Kehagias and Fortin, 2006), reveal that all lakes but the smaller Lake St. Clair have seen an upward shift in evaporation. This increase in evaporation is consistent with observed decreases in seasonal ice cover on all lakes (IUGLS, 2009), a phenomenon which can lead to increased heat input into the lake (Desai et al., 2009).

Figures 2 and 3 underscore the strong link between runoff and *NBS* for all lakes. Less obvious is the fact that net overlake precipitation adds variability to the signal. Indeed, the coefficient of variation of *NBS* (i.e., the standard deviation of *NBS* divided by its mean), is higher than the coefficient of variation of runoff for all lakes. Autocorrelation is therefore also lower for *NBS* than for runoff. The autocorrelation of annual runoff is in fact significantly different from zero at the 95% level for all lakes, but not the autocorrelation of annual *NBS*, suggesting that some of the persistence at the annual scale can be explained by the filtering effect of the watershed, although this signal could also be related to persistence in overland precipitation or evapotranspiration. This is consistent with the findings of Vogel et al. (1998), who found that annual streamflow records in the Great Lakes region showed higher persistence than in any other region of the conterminous United States.

All diagnostics based on the component *NBS* method are, however, limited by the accuracy with which each component is estimated. Indeed, the estimates we present here are simply one set of estimates, based on one set of model assumptions and one set of input data. Other model alternatives and data sources could be (and, increasingly, are being) used. Overlake precipitation, for example, can be estimated from near-shore precipitation gauges, radar and satellite imagery, and other sources, while runoff can be estimated from streamflow observations or conceptual rainfall-runoff models, although each method has unique intrinsic sources of uncertainty and variability (Neff and Nicholas, *2005*). There is however no operational observational network on which to base estimates of overlake evaporation, and therefore, these estimates are based on hydrometeorological models calibrated to other observed variables, such as water surface temperature. Recent observations using an eddy-correlation system installed on a light house on Lake Superior (Blanken et al., *2011*; Spence et al., *2011*) suggest, however, that current operational models being used to assess overlake evaporation tend to overestimate evaporation in winter, and in particular when the latent heat flux is strongest, but do capture the synoptic-scale fluctuations in overlake evaporation. Even after accounting for this potential bias, however, there is a strong evidence of a recent increase in annual overlake evaporation within the Great Lakes basin.

As indicated previously, relatively recent increases in overlake evaporation and other *NBS* component dynamics are likely related more to shifting climate dynamics over decadal time scales than to seasonal or annual variability. Recent efforts to predict future *NBS* dynamics under alternative climate scenarios, including the use of hydrometeorological models forced by general circulation models, suggest a broad range of potential future *NBS* sequences and water levels (Angel and Kunkel, *2010*). These models, however, may not appropriately represent basin evapotranspiration over decadal time scales (Lofgren et al., *2011*) and more precise climate-related *NBS* and Great Lakes water level projections might be expected from regional climate model simulations, many of which were recently conducted by both the United States and Canada as part of the International Upper Great Lakes Study (IUGLS, *2009*).

Cross-references

Great Lakes, North America

Laurentian Great Lakes, Interaction of Coastal and Offshore Waters

Water Balance of Lakes

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