A NEW FRAMEWORK FOR MONITORING THE GREAT LAKES WATER BALANCE ERROR

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Abstract: Agencies across multiple U.S. states and Canadian provinces seek to better understand the hydrologic cycle of the Great Lakes basin. Each estimated hydrologic component, whether based on models or observations, contributes an error to the Great Lakes water balance. A common goal among all agencies is to reduce the water balance error through improved modeling and measurement techniques such that the combined effect of the estimated components matches the water level behavior. Traditionally, different quantities for residual and component net basin supplies have been used to evaluate the Great Lakes water balance. However, these quantities add an unnecessary level of complexity and confusion when cooperating to target primary sources of error in the water balance. A relatively simple framework, based on conservation of mass, is presented in this study that calculates the water balance error for each lake. The primary outcome is a framework where different model estimates can be compared and large contributions to the water balance error can be cooperatively prioritized and targeted. General plots of each lake's error show a number of clear observations suggesting an oscillating seasonal error of precipitation, a potential bias in some connecting channel flow data, and what would happen to the water balance error with the hypothetical inclusion of thermal expansion and contraction. A cooperative reduction in the magnitude of the water balance error will improve Great Lakes water policy and management.

INTRODUCTION

The Great Lakes basin stretches internationally across eight states within the United States of America and two provinces within Canada, containing approximately 20% of the world's volume of fresh water. Water levels and the fluctuations of water levels have significant impact to a broad range of stakeholders, including economic and environmental impacts to both countries. The very important effort of monitoring the hydrologic system of the Great Lakes is cooperative between multiple agencies on each side of the border (Gronewold and Fortin 2012, Fry et al. 2014). There is a growing effort among the Great Lakes community to "close the water balance".

The U.S. Army Corps of Engineers (USACE), Detroit District has developed procedures for monitoring the Great Lakes' water balance and has implemented them as a Corps Division-level International Organization for Standardization (ISO) process. The process provides a standard for review and analysis of the Great Lakes hydrologic and hydraulic (H&H) data that the Division uses in operations and in support of the International Joint Commission (IJC) boards of control. There is a large amount of uncertainty in the current modeling and estimation techniques of each hydrologic component, and although a perfect estimate of each component is

impossible, there is room for improvement among the various techniques. Quantifying the uncertainty in each component as well as the uncertainty in the overall water balance will offer insight about which improvements would be most valuable.

The primary components of the water balance for each Great Lake can be represented by Equation 1. This equation, based on the law of conservation of mass, assumes that the density of water is constant, and is therefore presented as a conservation of volume relationship. In reality, the huge volumes of the lakes can allow for slight differences in density to have an impact, and the ΔS_T term accounts for this. Each term of the equation must have the same units; typically units of volumetric flow, such as m^3/s. The equation is typically used for a specific time period, such as one month or one year. Some terms may not apply to every lake (e.g. Lake Superior does not have a connecting channel inflow).

$$\Delta S = I + P + R - E - O + D + G - C + \Delta S_T \tag{1}$$

where:

ΔS	=	Change in volumetric storage of the lake
I	=	Connecting Channel Inflow
P	=	Precipitation falling directly on the lake surface
R	=	Runoff draining from the land surface to the lake
E	=	Evaporation of water from the lake surface
O	=	Connecting Channel Outflow
D	=	Diversion of water into (+) or out of (-) the lake
G	=	Groundwater flowing to the lake, arriving from below the land surface
C	=	Net effect of consumptive uses (withdrawn water minus returned water)
ΔS_T	=	Change in lake storage due to thermal expansion (+) or contraction (-)

A quantity known as the net basin supply (NBS) is useful for combining the effects of the hydrologic components into one value to represent the general basin conditions for each lake. There are two different ways to calculate the NBS, the residual method and the component method. The component method of calculating NBS is to add/subtract the estimates from each component, hence the name. In practice, the component method is equal to $P + R - E$. The other method is called the residual method, and in practice it is equal to $\Delta S + O - I +/- D$. The final three terms of Equation 1, G, C, and ΔS_T, are significantly smaller than the other terms and are often assumed to have a negligible influence. This assumption introduces some error, though it may be small, whenever it is implemented. Altogether, the residual and component methods of estimating NBS should be relatively similar.

Traditionally, the closure of the water balance has been measured by comparing residual net basin supplies with component net basin supplies (Lee 1992; Neff and Nicholas 2005; DeMarchi, et al. 2009; Deacu, et al. 2012). Although this comparison between component and residual net basin supplies can be informative, it also adds an extra level of explanation and potential confusion when evaluating uncertainty. The framework presented in this paper relates the individual terms directly to the overall water balance error. The analysis of just one overall equation for each lake will provide helpful information about the individual components and clear insight about how well they fit together. This proposed framework deviates from the

traditional analysis and eliminates the need for calculating or evaluating the net basin supplies when analyzing the uncertainty in each component.

Equation 1 can be rearranged such that everything is on the right side of the equation, and the water balance equation in theory should be equal to zero, as shown in Equation 2, for each lake. In reality the equation contains significant uncertainty, as shown by the rearranged Equation 3 representing the typical terms which are used in practice. There are numerous sources of the error in the water balance equation, and each term of Equation 3 contains uncertainty due to measurement errors, spatial and temporal variations, modeling errors, etc.

$$0 = -\Delta S + I + P + R - E - O + D + G - C + \Delta S_T \quad (2)$$

$$Error = -\Delta S_R + I_R + P_R + R_R - E_R - O_R + D_R \quad (3)$$

where:

$Error$	=	Overall error, or gap, in the lake's water balance equation
ΔS_R	=	Recorded/estimated change in volumetric storage of the lake
I_R	=	Recorded/estimated connecting channel inflow
O_R	=	Recorded/estimated connecting channel outflow
P_R	=	Recorded/estimated precipitation falling directly on the lake surface
R_R	=	Recorded/estimated runoff draining from the land surface to the lake
E_R	=	Recorded/estimated evaporation of water from the lake surface
D_R	=	Recorded/estimated diversion of water into (+) or out of (-) the lake

METHODOLOGY

An analysis of the *Error* for each lake was performed using Equation 3. Data sets were organized and converted into common units of m^3/s for each month, using the actual number of days in each month, so that the monthly *Error* could be calculated for each lake. Some of the terms in Equation 3 could be estimated using multiple methods which are available. This analysis chose one of the possible combinations based primarily on the historical availability of the data sets. The following list shows the data set which was used for each term in the water balance for this initial assessment:

Term	Data set used
ΔS_R	Calculated from coordinated beginning-of-month lake-wide average water levels
I_R	USACE records of connecting channel flows
O_R	USACE records of connecting channel flows
P_R	Coordinated over-basin precipitation (other data sets are also compared)
R_R	NOAA GLERL Area Ratio Method
E_R	NOAA GLERL Evaporation
D_R	USACE records of diversion flows

USACE and Environment Canada (EC) coordinate the official historical data set of Great Lakes beginning-of-month (BOM) lake-wide average water levels back to 1900. The network of water level gauges currently used for the lake-wide average levels is shown in Figure 1. Gauges in the United States are operated by the National Oceanic and Atmospheric Administration (NOAA) National Ocean Service (NOS) Center for Operational Oceanographic Products and Services

(CO-OPS). Gauges in Canada are operated by the Canadian Hydrographic Service (CHS). This network of gauges was chosen by the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrology Data (Coordinating Committee), a group composed of representatives from United States and Canadian federal agencies that keep official records of water levels, flows in the connecting channels, and other data related to the Great Lakes hydrologic system for the last fifty years. The difference in BOM water levels from one month to the next is multiplied by the officially coordinated lake surface area (Coordinating Committee, 1977) to determine the change in volume for each lake. This volume is divided by the time duration using the actual number of days for each month to obtain the change in volumetric storage with units of a flow rate, such as m^3/s.

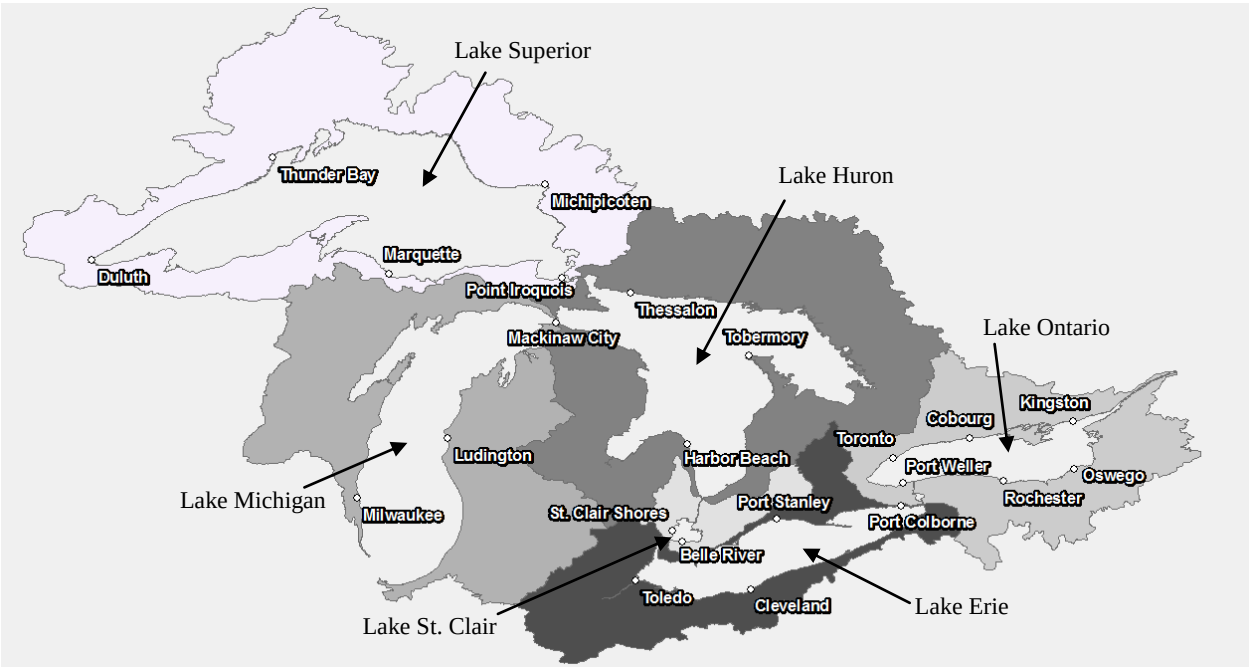

Figure 1 Location of water level gauges used in lake-wide average levels

USACE records of connecting channel flows consist of flows coordinated by the Coordinating Committee and preliminary flows. Preliminary flows are estimated by the Detroit District using a combination of the fall between the upstream and downstream lakes as well as information from NOAA and CHS water levels within the connecting channels. The officially coordinated records of connecting channel flows span 1900 to 2008, with the exception of St. Lawrence River which is coordinated through 2005. Similarly, flow through each of the five diversions (Long Lac, Ogoki, Chicago, the Welland Canal, and the New York State Canal System) is coordinated through the Coordinating Committee, with the official period of record varying for each diversion.

The coordinated over-basin precipitation data is first calculated by the NOAA Great Lakes Environmental Research Laboratory (GLERL) Thiessen Method for estimating precipitation. NOAA CO-OPS then reviews the data and compiles it to be passed on to USACE and EC for coordination. The Coordinating Committee has generally assumed that the over-lake precipitation is better estimated using the over-basin Thiessen method instead of the over-lake

Thiessen method. This assumption may have originated from Croley and Lee 1993, who explain that the Thiessen over-lake precipitation method relies on near-shore meteorology where the lake effects are significant. For this reason, Croley and Lee 1993 used all available meteorological stations throughout the basin to estimate over-lake precipitation, rather than using only near-shore stations. This assumption is investigated near the end of this report, where other data sets produced by the GLERL Thiessen Method were also evaluated; namely Thiessen over-lake and Thiessen over-land. The historical records of all GLERL Thiessen precipitation estimates span 1900 through 2010.

The most complete historical set of runoff data for each of the Great Lakes is the NOAA GLERL Area Ratio Method (ARM). This method extrapolates runoff from gauged drainage areas to un-gauged drainage areas using an area-weighted approach. The window of availability of runoff data varies, with beginning years ranging from 1900 to 1932 depending on the lake.

Evaporation data used in this study are calculated by NOAA GLERL, using their Large Lake Evaporation and Thermodynamics Model. The evaporation data set has the least amount of available data with a historic range going back to 1950.

Using the above data sets, the monthly error (units of m^3/s) is calculated for each lake as well as the annual error (units of m^3/s) from 1950 through 2010. Annual errors are calculated using the time duration of the entire year for each term in Equation 3. In order to perform useful lake-to-lake comparisons of the relative errors, the historical average of all flow into or out of each lake is used for normalizing the errors. This flow is calculated from $I + P + R$ ($+D$, if diversion flows into lake) and should be the same as $O + E$ ($+D$, if diversion flows out of lake) on average. The normalizing flow varies for each lake.

RESULTS

Table 1 shows the calculated annual and monthly average water balance errors for each lake using Equation 3. For interpretation, positive errors are generally caused by the overestimation of any term providing water to the lake or the underestimation of any term removing water from the lake. The converse is true for interpreting negative errors. Each lake's error was normalized by the total average flow into or out of the lake. These normalizing flows were 3700, 8000, 5500, 7000, and 7800 m^3/s for lakes Superior, Michigan-Huron, St. Clair, Erie, and Ontario, respectively, based on each lake's hydrology. Figure 2 shows the chart of average errors in units of m^3/s while Figure 3 shows the normalized percentages.

For more detail on the range of each lake's water balance error for each calendar month, the median, 25% quartile, 75% quartile, maximum and minimum were calculated. These statistical properties are shown in Figure 4 through Figure 8.

Table 1 Average Great Lakes water balance errors

Units of m^3/s													
	Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Superior	**120**	-20	340	-20	-570	100	210	510	710	790	300	-480	-380
Michigan-Huron	**400**	-410	100	-270	-360	300	370	880	1480	1970	1530	20	-810
St. Clair	**-10**	-30	-10	50	50	0	-60	-80	-50	-30	0	40	0
Erie	**-80**	150	-40	-140	-30	-30	0	130	-20	-150	-340	-240	-280
Ontario	**190**	20	110	130	230	160	100	180	320	390	400	240	20
Normalized (%)													
	Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Superior	**3.4**	-0.5	9.1	-0.6	-15.4	2.7	5.8	13.9	19.1	21.4	8.1	-13.1	-10.4
Michigan-Huron	**5.0**	-5.1	1.3	-3.4	-4.4	3.8	4.7	11.0	18.5	24.7	19.1	0.2	-10.1
St. Clair	**-0.2**	-0.6	-0.2	0.9	0.8	0.0	-1.1	-1.4	-0.9	-0.5	0.0	0.7	-0.1
Erie	**-1.2**	2.2	-0.5	-2.0	-0.4	-0.4	0.0	1.8	-0.3	-2.1	-4.9	-3.4	-4.0
Ontario	**2.5**	0.2	1.5	1.7	3.0	2.0	1.3	2.3	4.1	5.0	5.1	3.0	0.2

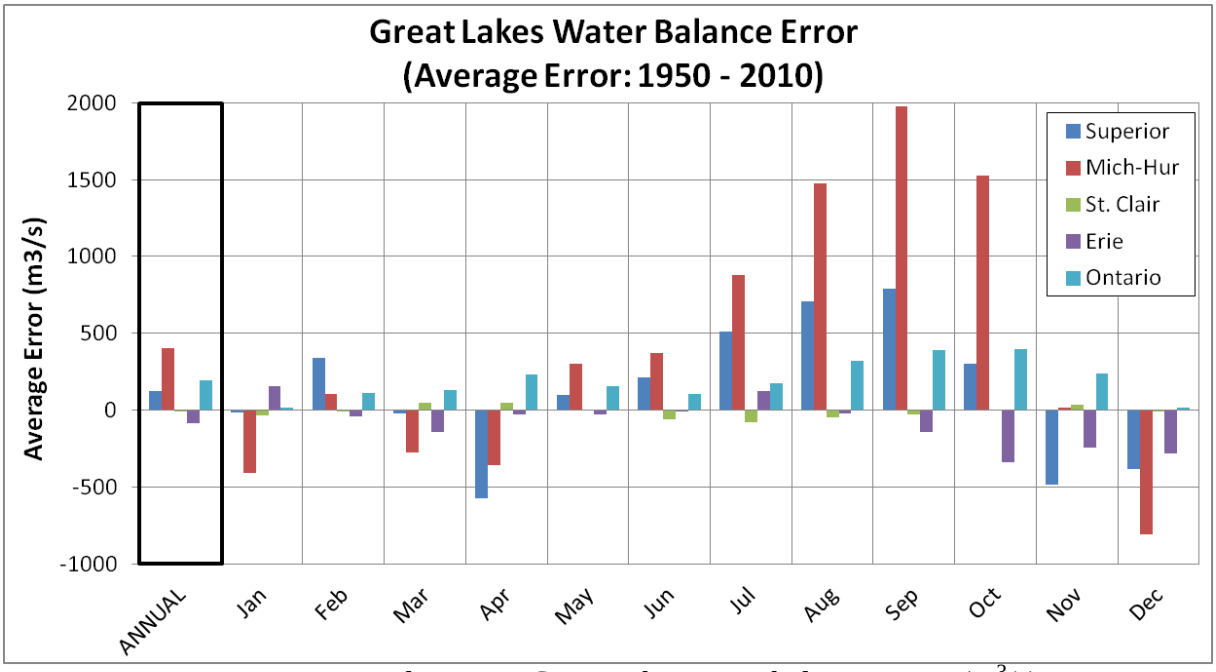

Figure 2 Historical average Great Lakes water balance errors (m^3/s)

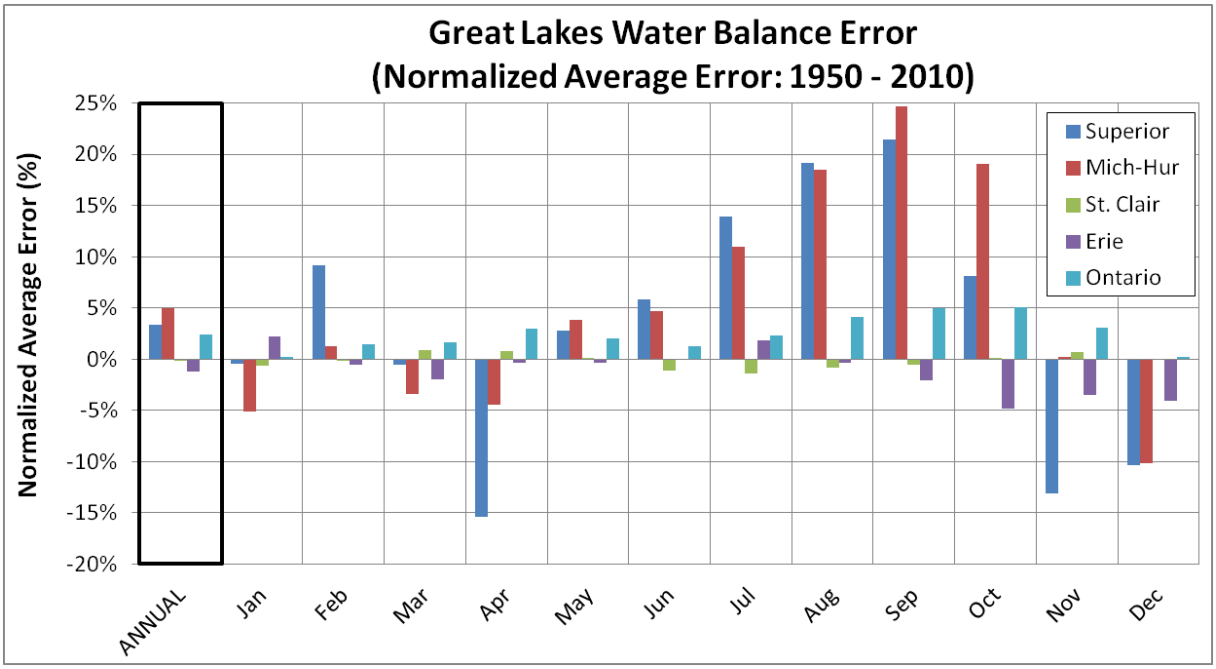

Figure 3 Historical average Great Lakes water balance errors (%)

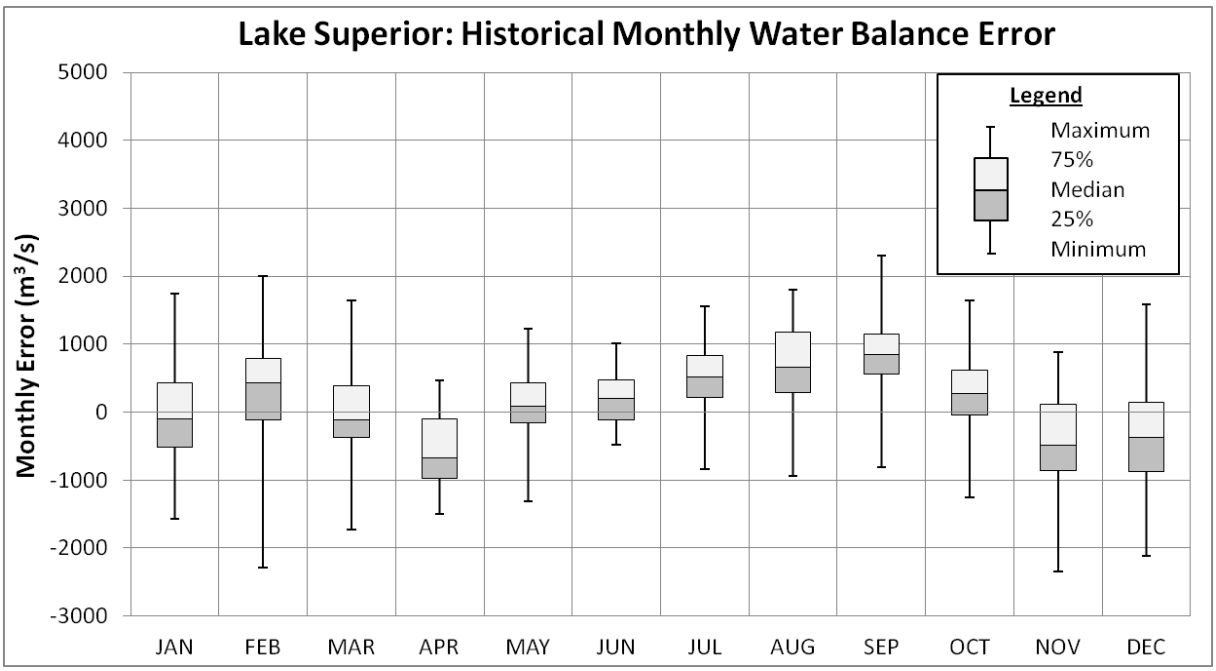

Figure 4 Lake Superior monthly water balance error statistics

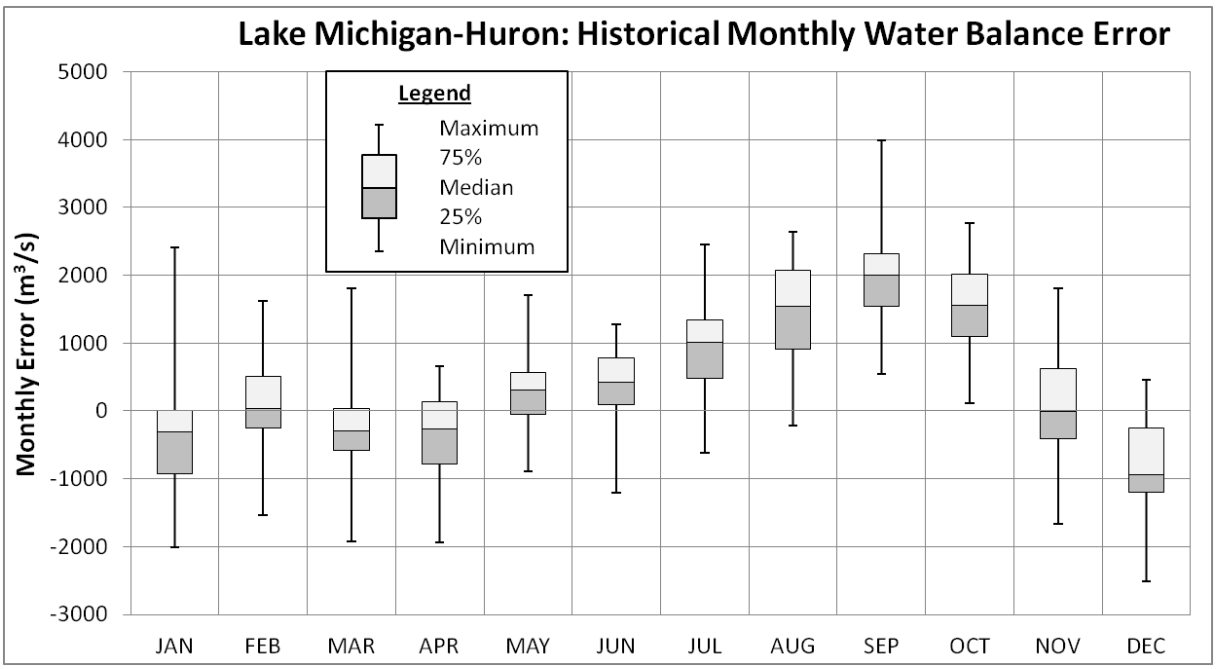

Figure 5 Lake Michigan-Huron monthly water balance error statistics

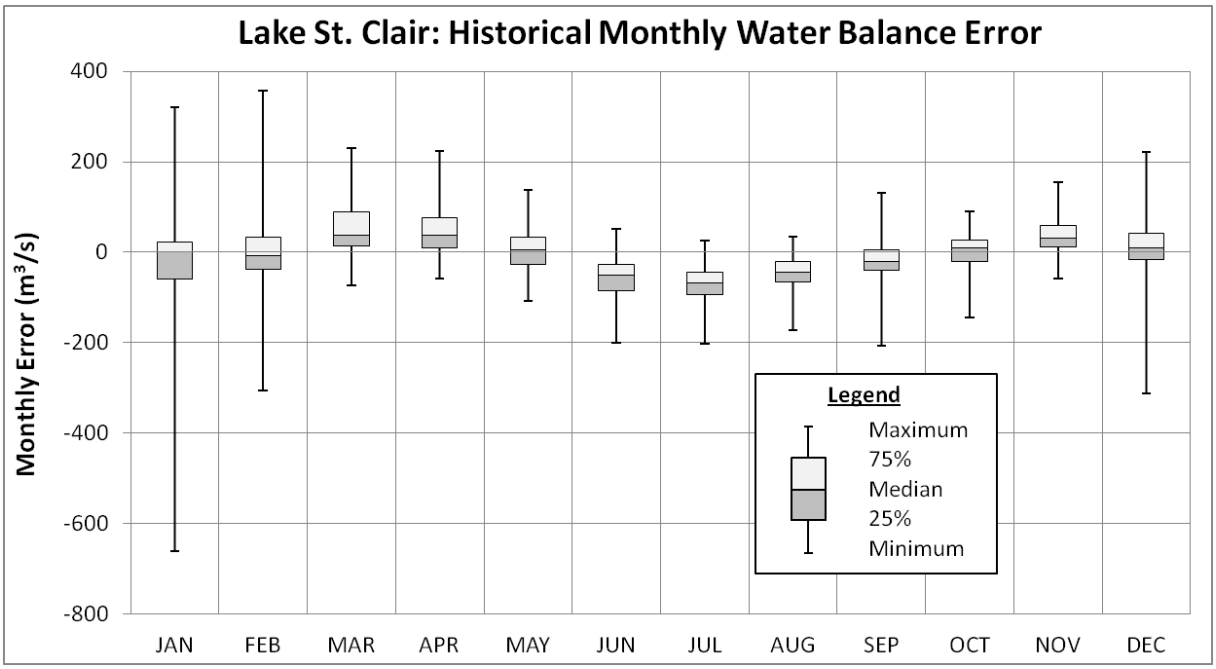

Figure 6 Lake St. Clair monthly water balance error statistics

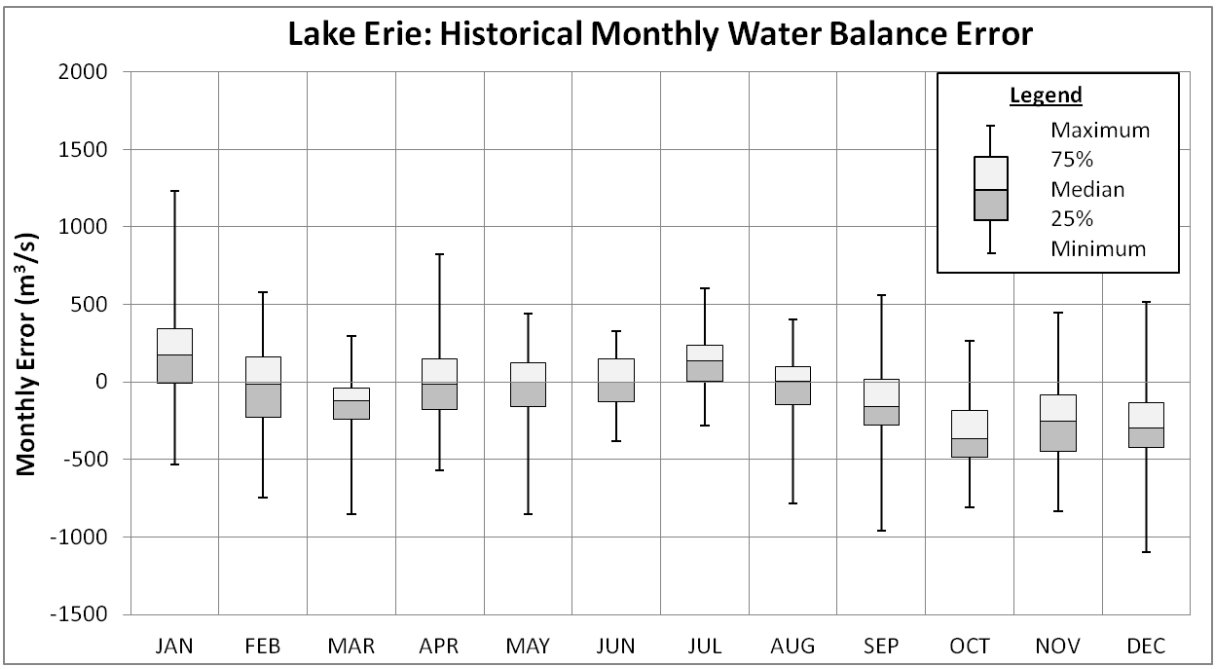

Figure 7 Lake Erie monthly water balance error statistics

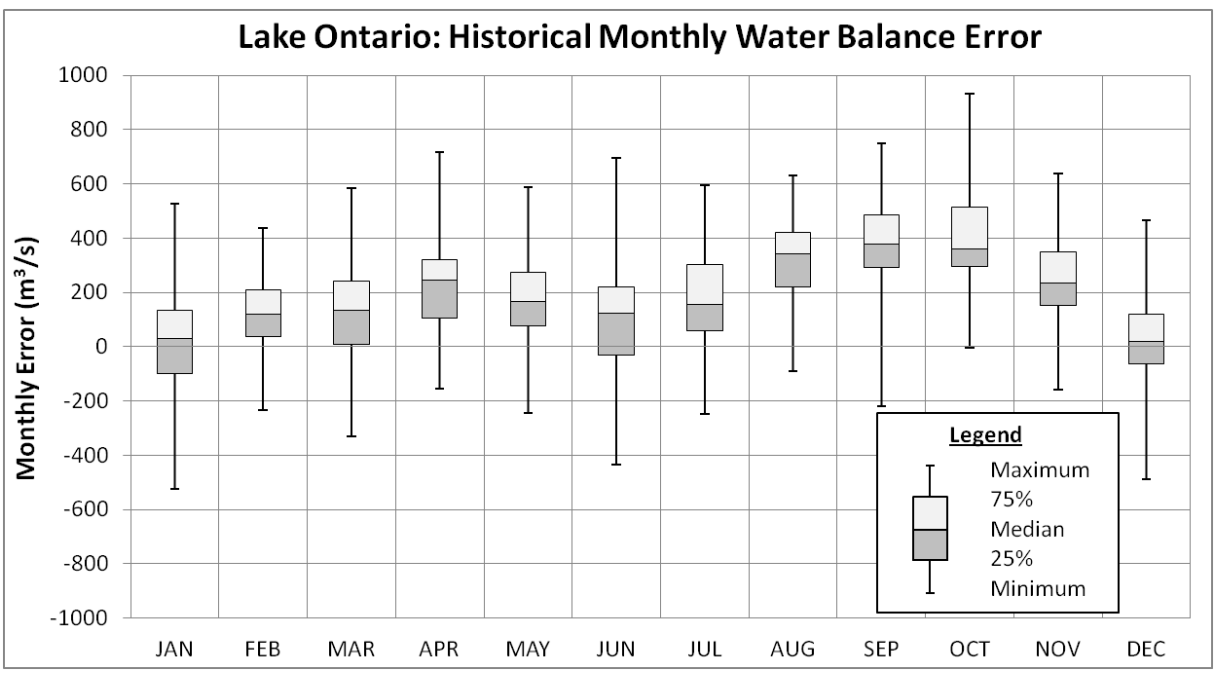

Figure 8 Lake Ontario monthly water balance error statistics

Drawing specific conclusions about errors in individual terms of the water balance requires caution, but these preliminary results reveal many interesting observations. Lakes Superior, Michigan-Huron, and Ontario each had a positive average annual error while lakes St. Clair and Erie had negative errors. In general, the Lake Michigan-Huron water balance errors are the largest while the Lake St. Clair errors are relatively small. This is apparently due to the lake surface area and drainage area of each lake. Since the area is small for Lake St. Clair, the components of *P*, *E*, and *R* are much smaller than the inflow through the St. Clair River and the

outflow through the Detroit River. For Lake Michigan-Huron, however, evaporation is approximately the same magnitude as the inflow from the St. Marys River and the combination of over-lake precipitation and runoff is larger than the outflow through the St. Clair River. A large error suggests that improving the estimates of over-lake precipitation, evaporation, and runoff, especially for Lake Michigan-Huron, should be a priority. A small water balance error for Lake St. Clair implies that the balance between connecting channel flows and water levels is relatively well estimated. However, it is possible that the St. Clair River and Detroit River could both have a bias error in the same direction which would not be detectable when looking at the Lake St. Clair error alone.

Interestingly, errors in the connecting channel flow estimates can influence both the lake upstream and downstream in an opposite manner. For example, decreasing the Niagara River flow estimates would cause both the Lake Erie and the Lake Ontario water balance errors to improve, i.e., move toward zero. Therefore, a re-evaluation of the Niagara River flow estimation method, and/or the investigation of any available hydraulic models, is suggested.

Another interesting observation can be made related to the thermal expansion and contraction of the lakes. In general, the summer water balance errors are positive for the Great Lakes, with the exceptions of lakes St. Clair and Erie. Lake St. Clair is generally below zero for June through August while Lake Erie is near zero for April through August. As the lake water warms in the summer time there is an increase in the lake's water volume due to thermal expansion, creating a positive contribution to the water balance error. Although this would be a more accurate representation of lake storage, it would generally move the Superior, Michigan-Huron, and Ontario errors further away from zero since the errors are already positive, and it would make Lake Erie's error worse as well since it is near zero during those months. This implies that the inclusion of thermal expansion and contraction alone would not perfectly solve the water balance. This is not to suggest that it should be purposefully ignored, but just that it may not be as high of a priority. A proper inclusion of thermal expansion and contraction should be included when available because the goal of monitoring is to have as good of an estimate for each term as possible.

Lakes Superior, Michigan-Huron, and Ontario exhibit some similar seasonal error patterns. The water balance error seems to increase through the summer and then drop significantly at the end of the fall season. This consistent error behavior across multiple lakes may indicate a bias in one or more of the methods used to estimate the components (P, E, or R). Relevant literature (Derecki 1976, Kresge et al. 1964, Holman et al. 2012, and Changnon 1961) acknowledges that the over-lake to over-land precipitation ratio is relatively low in the summer and relatively high in the winter. Since the Thiessen method precipitation estimates are based primarily on gauges over the land, it makes sense that the sign of the seasonal errors shown in the figures could be caused by the over-lake and over-land dynamics. A correction to account for the over-lake and over-land precipitation dynamics would seem to provide significant benefit to the water balance by decreasing the error in the summer months and increasing the error (from a negative value toward zero) in the winter months.

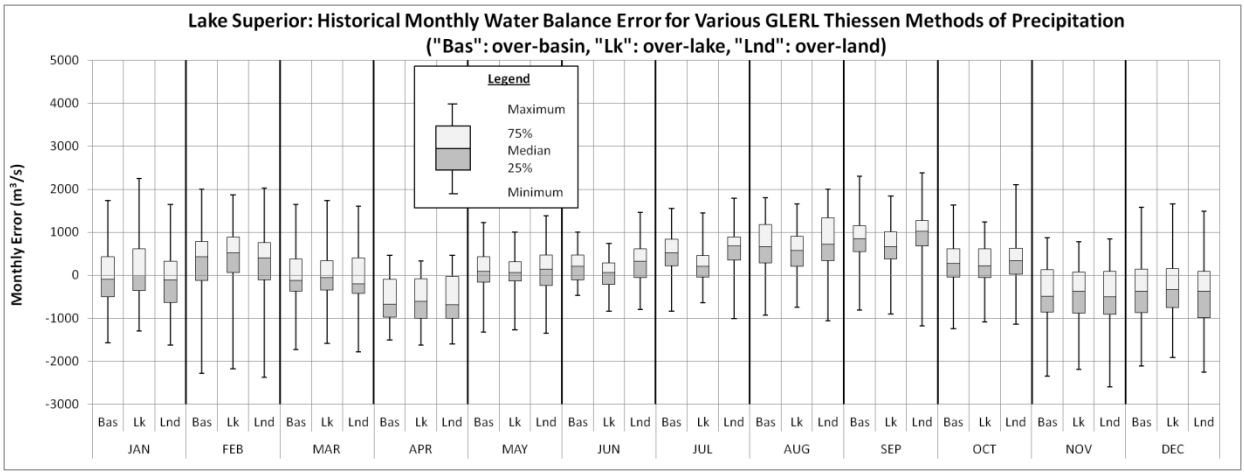

Figure 9 Comparison of GLERL Thiessen precipitation estimates within the framework of the Lake Superior water balance error

As mentioned above, the Thiessen over-basin method is typically used to estimate the over-lake precipitation component of the water balance. Figure 9 presents the side-by-side comparison of GLERL Thiessen Methods for over-basin, over-lake, and over-land precipitation in terms of their influence on the Lake Superior water balance error. In every month except for February, the median Lake Superior water balance error would be improved by using the Thiessen over-lake estimates instead of the over-basin estimates. The month of July is a clear example, where the Lake Superior median error would become 200 m^3/s instead of 500 m^3/s. This indicates that the assumption made by Croley and Lee 1993 appears to be incorrect. It is recommended that this type of comparison be made for each of the other lakes. The Coordinating Committee may wish to consider coordinating Thiessen over-lake precipitation estimates rather than Thiessen over-basin estimates. It is important to note that the Thiessen over-lake estimates are based on near-shore stations, and according to Holman et al. 2012, the seasonal differences between over-lake and over-land precipitation should be much greater than is calculated by the respective GLERL Thiessen methods.

DISCUSSION

The framework for computing the water balance error, presented in Equation 3, will be helpful for relating various sources of uncertainties to one another within the Great Lakes water balance. Comparisons using this basic conservation equation provide more readily apparent observations to a wide audience than the traditional comparisons between residual and component net basin supplies. From a preliminary analysis, which used only one method of estimation for each term of Equation 3, statistical properties were calculated for the monthly and annual water balance errors for each lake. One interesting observation is that the consistent error pattern across multiple lakes suggests that improving the historical precipitation estimates based on seasonal over-lake and over-land dynamics should be a high priority for moving toward “closing the water balance”. On the other hand, these preliminary results seem to indicate that although the inclusion of thermal expansion and contraction could provide a more accurate estimate of lake storage, it would not resolve some of the largest magnitudes of water balance error and could even push them further away from zero. Going forward, a comparison using multiple estimation

methods for each term within this framework could provide further insight about individual modeling and estimation techniques.

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