Net Basin Supply Comparison Analysis

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Executive Summary

The net basin water supplies (NBS) are an important component of Great Lakes water resource studies. They are used to develop and operate regulation plans, to forecast water levels, to assess why lake levels are rising or falling, and to simulate water levels which might occur under climate warming and other climate scenarios. Prior to 1948 NBS were computed as a residual in the water balance equation for a lake. Monthly precipitation and runoff were available but not lake evaporation. Data have been available since 1948 to calculate lake evaporation from aerodynamic techniques. Therefore, we now have monthly component NBS available for water resource studies from 1948 to the present time. Residual NBS tend to work well in the development of regulation plans but are incapable of being used for the simulation of climate impacts on water levels and the explanation of why, for example, the Lake Michigan-Huron water levels are low. The purpose of this analysis is to compare the NBS calculated from both the residual and component methodology, to draw conclusions as to the use of the component NBS, and to make recommendations as to the use of the two techniques, the various uncertainties involved in the computations, and future changes to make the techniques more compatible.

Lake Superior

For Lake Superior there are significant differences between the residual and component NBS depending upon the month and the time periods involved. However, when the change-in-storage is corrected the average monthly differences between the two techniques are less than 200cms, about 60 mm on the lake. The time series was divided into 3 segments, 1948-1966, 1967-2000, and 2001-2006, based upon the differences between the two NBS sequences. The problems between the residual and component NBS in the period 2001-2006 appear to be due to the change-in-storage. Good agreement exists between the NBS estimates for the period 1967-2000. For this period, either methodology would give similar results for Lake Superior and can be used interchangeably. The difference would be in slightly modified flows in the St. Marys River. Therefore the component data for the period from 1967-2006 will give comparable results as the residual data.

The high correlations between the monthly changes-in-storage and the differences between the residual and component NBS indicate that additional attention should be focused on the beginning-of-month water levels. At present, only five of the nine water level gauges are used to compute the beginning-of-month levels and no weighting is utilized. The impact of using additional gauges and weighting factors should be evaluated as well as the averaging time period to determine a beginning-of-month water level. The methodology proposed in Appendix 2 to correct the changes-in-storage should be reviewed and applied to the residual technique. It appears to result in greatly improved NBS estimates for Lake Superior.

While thermal expansion does have an impact on the residual water levels which may explain some of the monthly differences between the component and residual NBS, we do not have sufficient accurate data to proceed with any corrections to the residual NBS.

Finally, the uncertainty analysis indicates that the component NBS fall within the uncertainty of the residual NBS for the vast majority of months. The converse was not true. Better results would be expected if the residual NBS was corrected for changes-in-storage as recommended.

The period 1967-2006 should serve as the base period for climate and other studies. We should never expect to have perfect agreement between the residual and component methodologies. The type of agreement in the period 1967-2000, with extension to 2006, is about as good as one could expect and allows the component methodology to be used in water resource studies on Lake Superior with confidence.

Lake Michigan-Huron

Similar results were obtained for Lake Michigan-Huron as was obtained from Lake Superior where significant differences between the residual and component NBS were found depending upon the month and the time periods involved. The time series was broken up into four components, 1948-1976, 1977-1986, 1987-2000, and 2001-2005. The component and residual NBS are equivalent for all time series on an annual basis. The largest differences in the monthly means between the two procedures are in the months of July – November and January with the largest differences between the residual and component NBS occurring in August, September, and October. The differences between the four time series may be due to flow coordination for the St. Clair River, differing precipitation and runoff gauges, and changes in evaporation computations, among other items. Some of the ongoing studies may help to resolve some of these issues.

One of the major problems in the residual NBS computations is the computation of the beginning-of-month water levels and the resulting changes in storage. This component accounts for the vast majority of variation in the residual computations. The high correlation between the average monthly residual and component NBS and the beginning-of-month water levels indicate unknown factors influencing the computations. This could be due to unaccounted thermal expansion, water level gauge networks not adequately accounting for the true change in water levels, the averaging periods for the beginning-of-month level computations, etc. This is particularly important as a one cm change is storage is equivalent to 445 cms, about nine percent of the St. Clair River monthly flow. Further analysis of this issue is a major requirement for increased understanding and improved accuracy of the residual computations.

As with Lake Superior, we do not have sufficient accurate data on thermal expansion to proceed with any corrections to the residual NBS.

The uncertainty analysis indicates that the component NBS fall within the uncertainty of the residual NBS for the vast majority of months. This, however, does not explain the bias during the summer and fall. We may find some clues in the current ongoing studies.

Finally, I believe that we can use the component NBS in the climate and other ongoing studies. This will result in slightly higher Lake Michigan-Huron water levels and a modified seasonal cycle than would be expected using the coordinated beginning-of-month water levels. However with the component supplies we can examine the impact of changes in the climatic variables on the water levels of the Great Lakes.

Lake Erie

The component NBS can be used interchangeably with the residual NBS for Lake Erie. Their use will only require minor changes in the coordinated Detroit or Niagara River flows, well within their uncertainty values. These flow values are currently being addressed in other studies and the resulting values may decrease the differences between the component and residual NBS time series. The relatively high differences in September through November appear to be the result of thermal contraction in the fall.

Two areas highlighted by this study that need further investigation are the Niagara River flows and the lake evaporation for the period 1995-2005. The NBS analysis for both Lakes Michigan-Huron and Superior also recommended that further effort be expended to examine the evaporation during this time. The very high correlation between the differences of the component and residual NBS with the Niagara River flows for this period, and not the other periods, indicate further analysis is required.

Finally, I believe that the Lake Erie component NBS are well suited for use in the climate and other ongoing studies on Lake Erie. They can also be used to assist in balancing the water balance of Lake St. Clair and resolving the dichotomy between the St. Clair and Detroit River Flows.

Recommendations

1) A comprehensive analysis of the most appropriate beginning-of-month water levels and their uncertainty should be undertaken for each of the Great Lakes. The methodology recommended for correcting changes-in-storage in this report should be reviewed and applied to the residual NBS computations.

2) The component NBS data for the all selected time periods on each Lake should be run through the routing models to verify the differences between the residual and component water levels and flows in the connecting channels.

3) The component and residual net basin supplies should be updated to reflect the ongoing studies on precipitation, runoff, and evaporation.

4) An assessment of an apparent problem between precipitation and runoff for the period 1948-1966 for Lake Superior needs to be undertaken.

5) The St. Clair and Detroit River flows have to be developed which will satisfy continuity at Lake St. Clair and fed back into the analysis.

6) The evaporation rates for Lake Erie NBS need to be carefully re-evaluated for the period 1995-2005.

7) The Niagara River flows for the period 1995-2005 need to be re-assessed in light of the variability in the residual NBS.

Lake Superior Net Basin Supply Comparison Analysis

Introduction

The purpose of this analysis is to compare the Lake Superior NBS calculated from both the residual and component methodology, to draw conclusions as to the use of the component NBS, and to make recommendations as to the use of the two techniques, the various uncertainties involved in the computations, and future changes to make the techniques more compatible. The NBS for both the residual and component values includes the OGOKI diversion because the release of the diversion into Lake Superior is included in the published basin runoff.

Net Basin Supply Computation

The water balance for Lake Superior is expressed as

$$P+R+D_O+D_L = E+Q_{SM} \pm\Delta S \qquad (1)$$

Where: P is the over-lake precipitation in cms
R is the runoff from the Superior land basin into the lake in cms
E is the evaporation from the lake surface in cms.
Q_{SM} is the St. Marys River outflow in cms
D_O is the Ogoki Diversion into the lake in cms
D_L is the Long Lac Diversion into the lake in cms
ΔS is the mass change in storage in cms, it does not include thermal Expansion

The net basin water supplies for Lake Superior can be computed directly by its components, Equation (2) or indirectly from the Lake Superior water balance, Equations (3).

NBS_C=P+R-E (2)

Where: NBS_C is the component net basin supply in cms

$NBS_R=Q_{SM}-D_O-D_L\pm\Delta S$ (3)

Where: NBS_R is the residual net basin supply in cms

All analysis is based on a monthly time scale. It should be noted that the change-in-storage from the coordinated data is based upon a standard month of 30.4369 days and not the actual number of days in a month. This results in a disconnect with the other data, all of which are computed on a true monthly basis. The impact is a 1.5 percent error in change-in-storage for months with 30 or 31 days and an 8.7 percent error in February with 28 days. The precipitation, runoff, and evaporation data are from Croley and Hunter (2008). The St. Marys flow data, the diversion data, and the beginning-of-month levels and resulting change-in-storage data are the coordinated data from the Sharepoint files. The percent of the basin that is gauged for runoff computations varied from a low of 27 percent in 1948 to a high of 64 percent in 1980. The present value is 42 percent. It must be noted that the runoff from Croley and Hunter contains the Ogoki Diversion which enters the lake through the Nipigon River. Therefore the component NBS is compared with the residual NBS including the Ogoki diversion to provide a valid comparison. Figures (1) and (2) show the monthly and annual averages for the component data for 1948-2006 (runoff through 2005), the period for which all data are available.

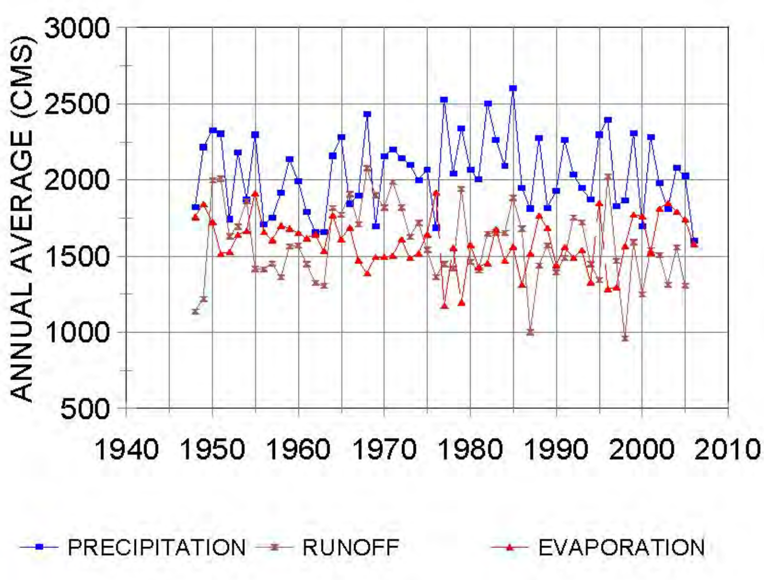

Figure 1. Average annual component data.

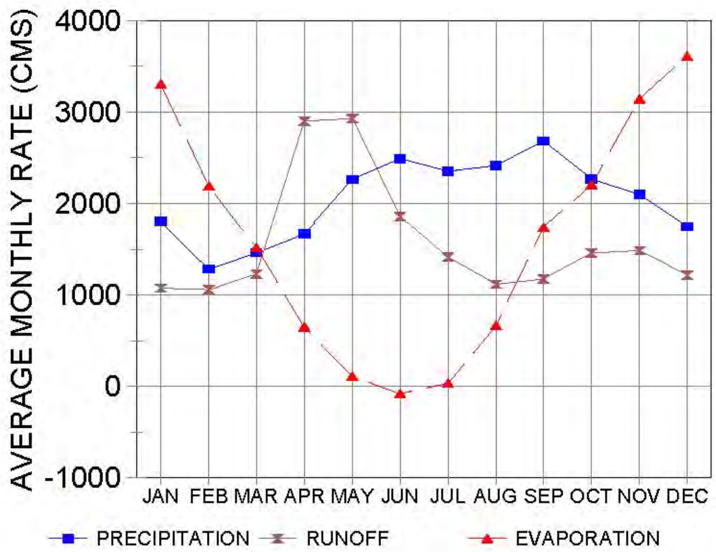

Figure 2. Average monthly component data.

Figures 3 and 4 show similar averages for the residual data. Table 1 gives the monthly averages and standard deviations for all the major components. Figure 5 shows the standard deviations for all the components.

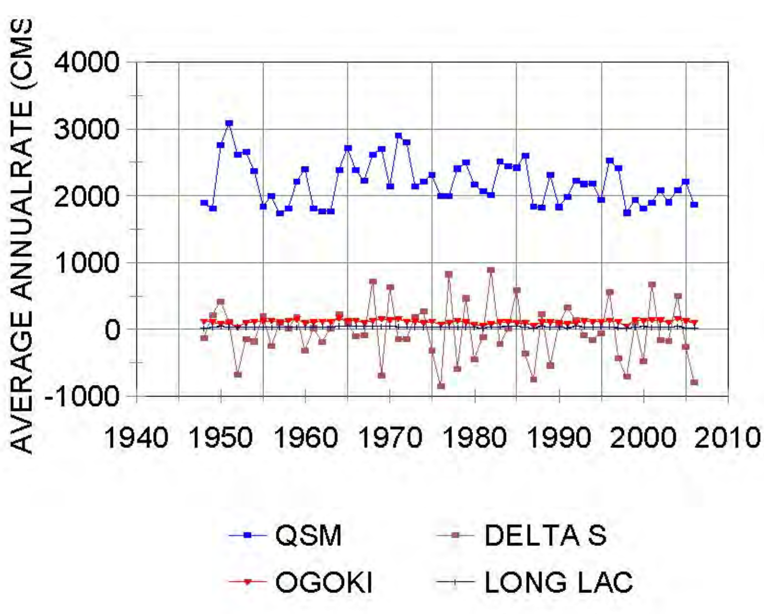

Figure 3. Average annual residual data.

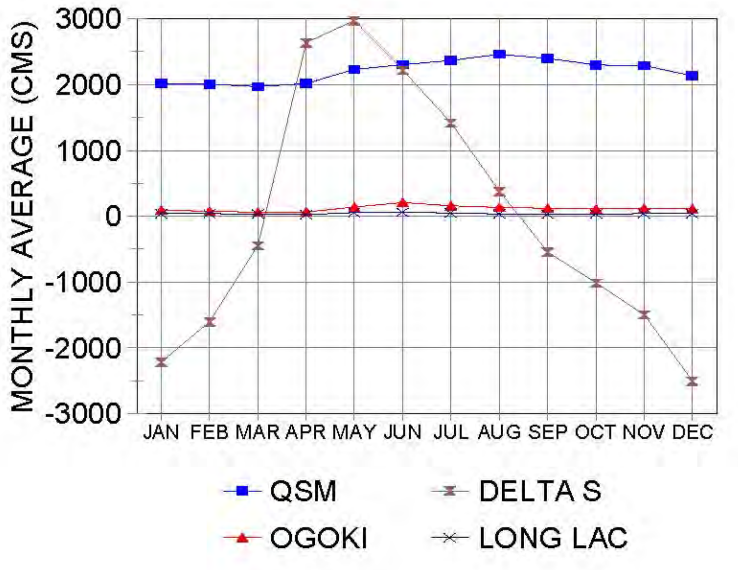

Figure 4. Average monthly residual data.

Table 1. Average values and standard deviations in cms for all major components.

	P		R		E		Q_{SM}		ΔS	
	AVE	STD	AVE	STD	AVE	STD	AVE	STD	AVE	STD
JAN	1801	633	1073	257	3308	647	2018	259	-2218	704
FEB	1283	492	1059	249	2192	582	2002	255	-1607	829
MAR	1458	666	1229	280	1518	529	1969	269	-447	1097
APR	1666	716	2903	830	649	242	2013	313	2633	1532
MAY	2260	793	2930	1105	110	119	2227	454	2968	1730
JUN	2486	778	1855	564	-81	93	2301	492	2213	1324
JUL	2350	841	1414	428	36	164	2365	569	1414	1373
AUG	2411	900	1117	332	668	302	2457	577	373	1361
SEP	2677	910	1175	408	1737	435	2394	605	-548	1495
OCT	2262	887	1460	494	2207	470	2297	608	-1016	1507
NOV	2092	755	1485	431	3140	502	2285	605	-1499	1326
DEC	1745	531	1217	298	3613	585	2132	409	-2504	733

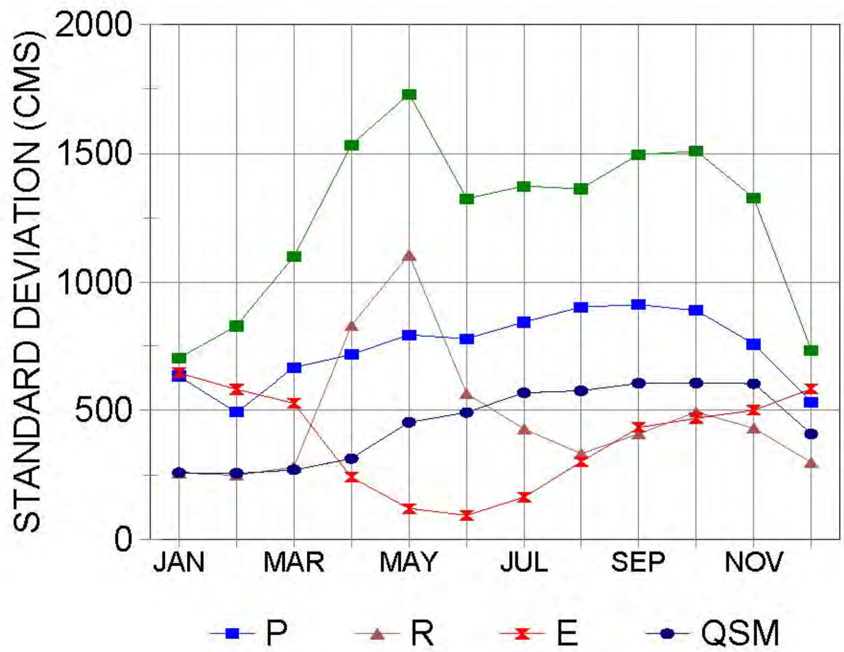

Figure 5. Standard deviation of monthly components. The top green line is the change-in-storage.

The most important comparisons are those of the monthly average components which show the range of values. The most surprising observation is that the change-in-storage has by far the largest seasonal variability of any of the other components in Figures 2 and 4. The second largest range is the monthly evaporation. Relatively little variability is seen in the St. Marys River flows. The seasonal changes in the diversions are negligible and will not be considered further in this analysis.

Comparison between residual and component NBS

The next step will be to compare the component and residual net basin supplies and their differences on an annual and monthly basis. A valid comparison of the two estimates requires that we add the Ogoki diversion to the residual NBS to compare with the component NBS. This is because the Ogoki Diversion is considered part of the runoff term in the component NBS computations. This also has the advantage in that the published monthly Ogoki Diversions are not the amount of water that enters Lake Superior, but rather the amount of water diverted into Lake Nipigon. The outflow from Lake Nipigon is determined from a regulation plan which does not immediately transfer the water diverted into the lake into Lake Superior. Figure 6 shows the difference between the two methods for the period of study. The figure shows a large amount of noise in the differences. The figure also shows a positive bias between 1948 and the late 1960s followed by relatively little bias until the year 2000. From 2000 through 2005 the positive bias reappears followed by extreme negative values in 2006. Appendix 2 indicates that these negative values may be due to problems with the monthly change-in-storage. A 12 month running mean is shown in Figure 7.

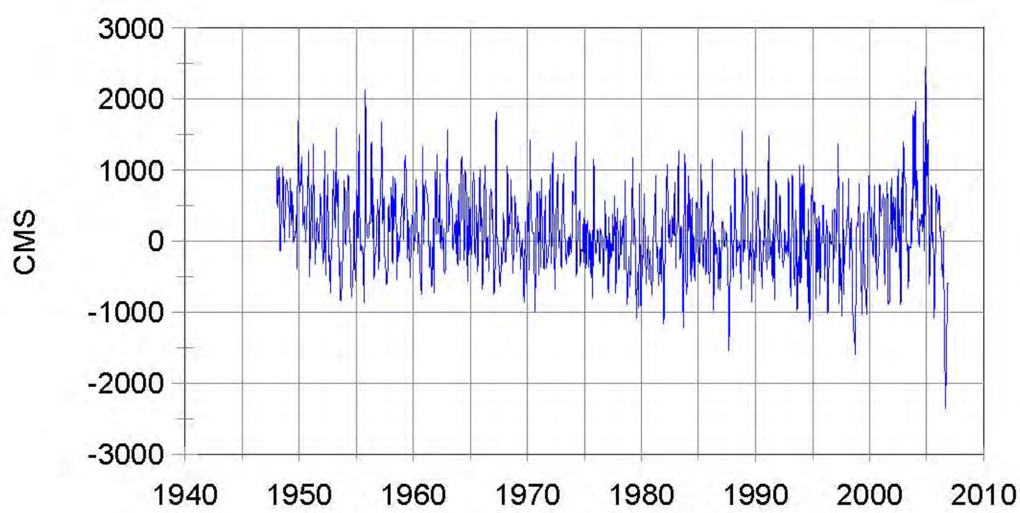

Figure 6. Monthly residual minus component differences

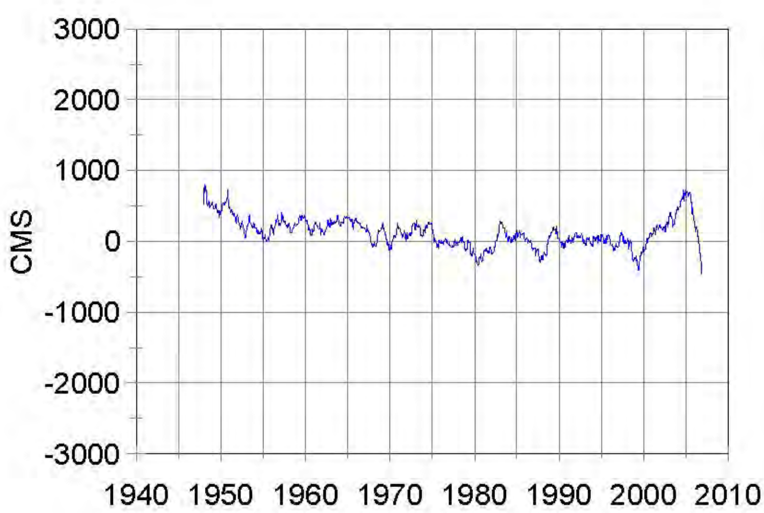

Figure 7. Monthly residual minus component differences (12 month running mean)

It should be noted that between 1955 and 2000, the difference in the two methods translates to about 1 cm on Lake Superior on an annual basis. Figure 8 shows a comparison of the two methods using annual average data. The final comparisons using annual data are given as Figures 8 and 9 using 5-year running averages to dampen out more of the noise. This figure also includes the 5-year averages of the over-lake precipitation, runoff and evaporation.

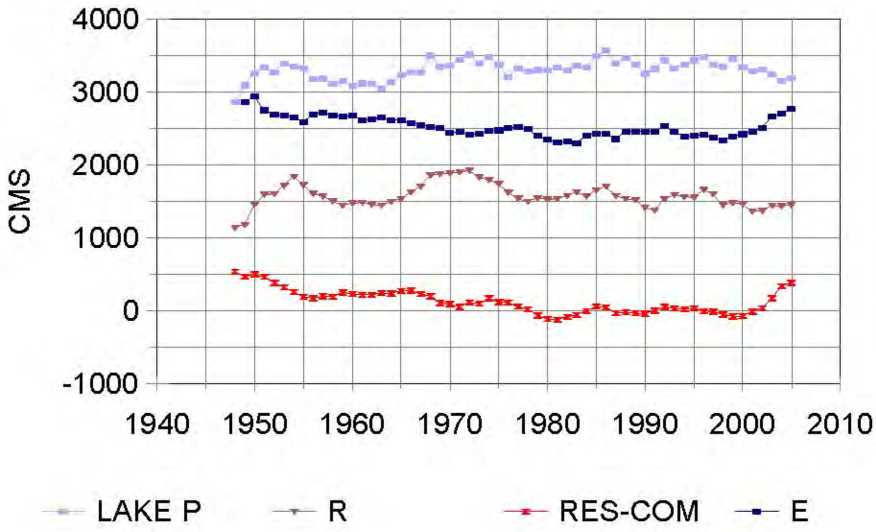

Figure 8. Comparison of 5-year running mean differences of the residual minus the component NBS with 5-year averages of over-lake precipitation, runoff, and evaporation.

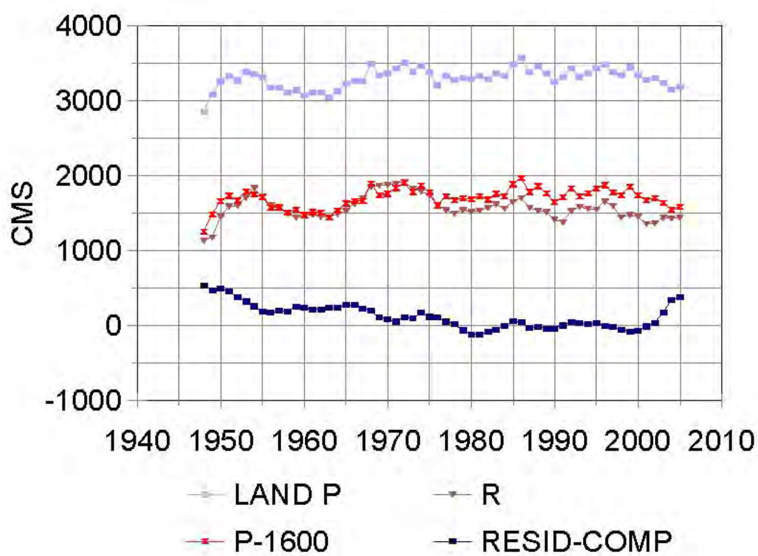

Figure 9. Comparison of 5-year running mean differences of the residual minus the component NBS with 5-year averages of over-land precipitation, runoff, and land precipitation – 1600 cms.

It was noted that if 1600 cms were subtracted from the over-land precipitation that it would match the first 25 years of the runoff time series. However, around 1975 the figure shows a sudden decrease of about 250 cms which continues through the end of the data set.   This could be an artifact of something that has changed in computing the runoff, a change in the Ogoki Diversion, or due to some natural cause.

The final comparison, Figure 10, examines the residual components. No general correlation exists between the time series with the exception of the changes-in-storage and the differences subsequent to 2000.

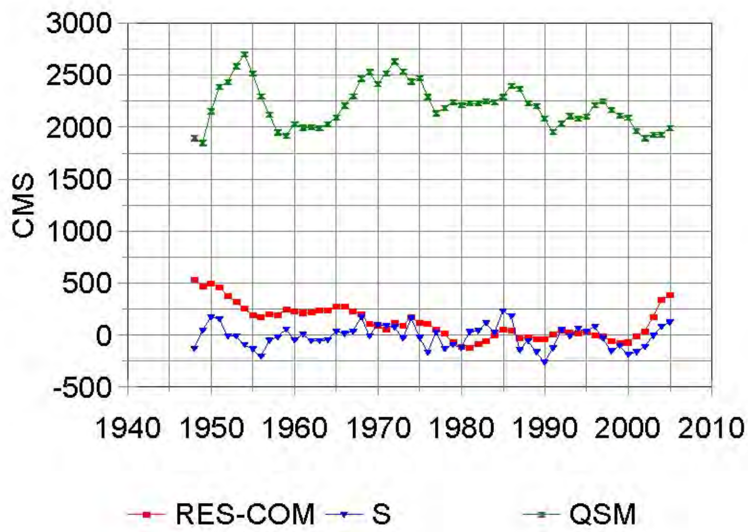

Figure 10. Comparison of 5-year running mean differences of the residual minus the component NBS with 5-year averages of the St. Marys River flows and the changes-in-storage.

A comparison of the correlation coefficients between the NBS differences and the individual components are given in Table 2 for monthly, annual, and 5-year moving averages. Based upon the preceding analysis, it was decided to break the time series into 3 segments, 1948-1966, 1967-2000, and 2001-2006, for further analysis

Table 2. Correlation between monthly, annual, 5-year running mean components and the differences between the residual and component NBS.

Component	r (monthly)	r (annual)	r (5-year mean)
precipitation	-0.05	0.06	-0.50
runoff	-0.15	0.05	0.12
evaporation	-0.09	0.48	0.79
St. Marys flows	-0.10	0.02	0.00
Change-in-storage	0.28	0.38	0.26

Monthly Analysis

Figures 11-13 show comparisons between the residual and component NBS for the three time series

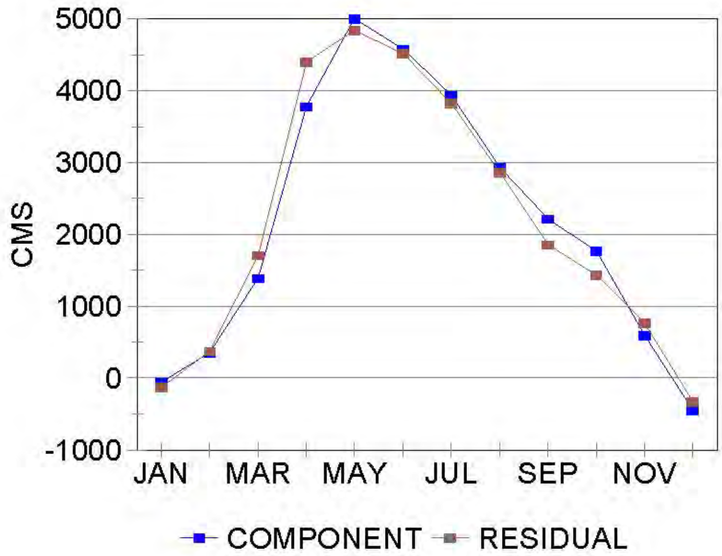

Figure 11. Monthly comparison of residual and component NBS for the period 1967-2000.

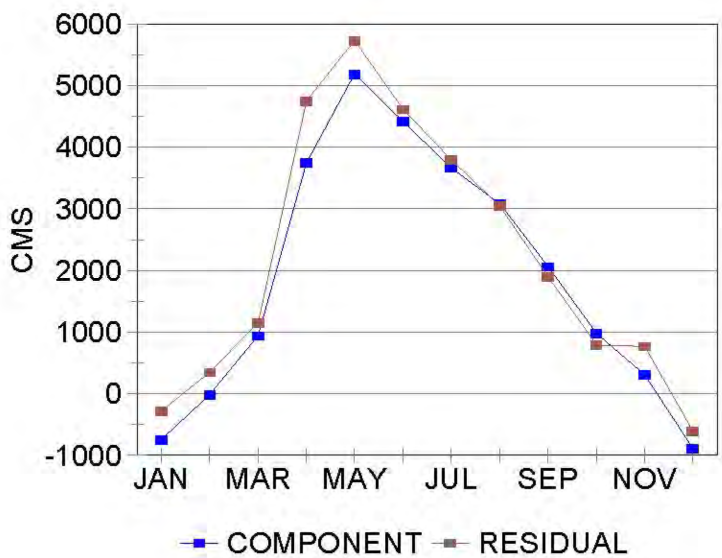

Figure 12. Monthly comparison of the residual and component NBS for the period 1948-1966.

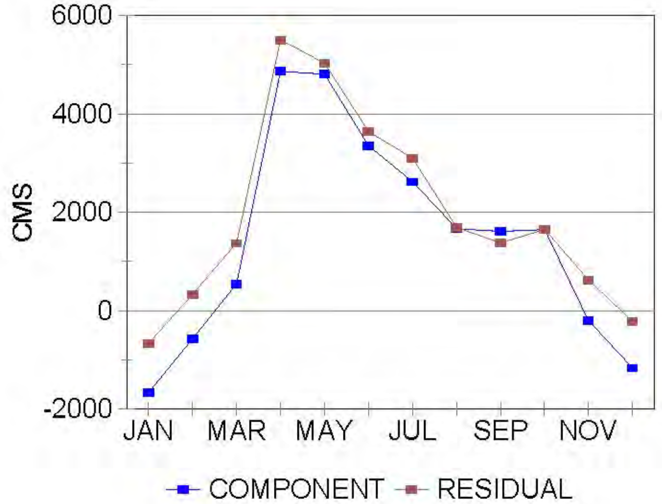

Figure 13. Monthly comparison of the residual and component NBS for the period 2001-2006.

The three figures show very different results for the three time periods. Very good agreement is observed for the 1967-2000 time period while there is a large difference in the November through March months for the 2001-2006 period. This appears to be due to excessive evaporation during this period. Tables 3-5 show the statistical comparison between the residual and component NBS for the three periods.

Table 3. Statistics of the 1948-1966 NBS Differences (Residual-Component)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
ave	469	366	210	1002	547	198	134	-42	-164	-182	463	286	274
std	452	511	287	383	470	398	362	487	415	482	666	530	132
f test	0.33	0.92	0.98	0.64	0.66	0.51	0.48	0.53	0.81	0.44	0.09	0.57	0.71
t test	0.00	0.01	0.01	0.00	0.00	0.05	0.13	0.72	0.11	0.13	0.01	0.03	0.00
ΔS	0.01	0.01	0.01	0.03	0.02	0.01	0.00	0.00	-0.01	-0.01	0.01	0.01	0.01

Table 4. Statistics of the 1967-2000 NBS Differences (Residual-Component)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
ave	-76	17	321	621	-161	-62	-116	-70	-361	-333	172	122	6
std	488	452	444	601	395	354	296	508	563	522	544	540	132
f test	0.62	0.46	0.63	0.13	0.89	0.76	0.51	0.28	0.37	0.35	0.16	0.10	0.60
t test	0.38	0.83	0.00	0.00	0.03	0.32	0.03	0.43	0.00	0.00	0.08	0.20	0.79
ΔS	-0.00	0.00	0.01	0.02	-0.01	-0.00	-0.00	-0.00	-0.01	-0.01	0.01	0.00	0.00

Table 5. Statistics of the 2001-2006 NBS Differences (Residual-Component)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
ave	827	763	637	153	-198	8	359	-137	-519	-264	572	705	242
std	694	329	355	428	229	486	418	643	1032	961	767	922	357
f test	0.52	0.59	0.82	0.79	0.72	0.31	0.98	0.23	0.11	0.32	0.76	0.81	0.33
t test	0.04	0.00	0.01	0.46	0.11	0.97	0.11	0.65	0.31	0.57	0.16	0.15	0.19
ΔS	0.03	0.02	0.02	0.00	-0.01	0.00	0.01	-0.00	-0.02	-0.01	0.02	0.02	0.01

Five statistical parameters are given for each of the time periods on both a monthly and annual basis. These are the average of the NBS differences, the standard deviation of the differences, the f test to compare the variances of the residual with the component NBS, the t test to compare the two means, and the change-in-storage represented by the average differences. The f tests for the period 1948-1966 show similar variances at the 5 percent significance level but only the means for July-October being within the 5 percent significance level. The variances of the annual data were statistically the same at the 5 percent level while the means were significantly different. However the annual difference resulted in only a 1 cm difference on the lake. In particular the months of April and May showed a very high bias, probably due to an underestimate of runoff. However, an assessment should be made of possible differences in the change-in-storage due to seasonal wind shifts over the lake.

The statistical tests indicate much better agreement between the component and residual NBS for the period 1967-2002. Table 4 shows that the variances for the two methods can be considered equal for all months at the 5 percent level while only March-May, July, September, and October have means that are significantly different. However the means of March, May, July, September, and October show change-in-storage differences of 1 cm or less which is not significant for water resource studies. In addition, the annual values showed no significant differences in either the means or the variances and show a zero impact on the annual average lake levels.

The final 2001-2006 period shows no significant differences in the variances and only the months of January-March show significant differences in the means. However, the change-in-storage for the months of November-March show consistently high values of change-in-storage for the high evaporation period which needs to be investigated. There are no significant differences on an annual basis in the variances or the means and a 1 cm impact of the change-in-storage.

Tables 6 and 7 show the correlation analysis between the differences of the NBS methods and the various components for the three time periods. Table 6 shows much higher correlations between the residual NBS and the differences for the 1st two periods while the component NBS shows a much larger difference for the last period. The latter is likely due to excessive evaporation as pointed out earlier.

Table 6. Correlation analysis between the differences of the residual and component NBS with the residual and component NBS.

	Time Period		
	1948-1966	1967-2000	2001-2006
Residual	0.33	0.29	0.02
Component	0.10	0.04	-.31

Table 7. Correlation analysis between the differences of the residual and component NBS with the various components.

	Time Period		
	1948-1966	1967-2000	2001-2006
Precipitation	0.08	-0.09	-0.15
Runoff	0.27	0.19	-0.06
Evaporation	0.04	-0.01	0.37
St. Marys flow	-0.16	-0.06	-0.03
Change-in-storage	0.36	0.31	0.03

Table 7 shows that the runoff and the changes in storage are the most important causes of differences in the 1948-1966 period, while the change-in-storage is by far the most important variable in the 2nd period. The evaporation is the most important variable in the 2001-2006 period, confirming the preceding analysis.

This analysis confirms the earlier conclusion that the change-in-storage is the leading contributor to differences between the component and residual NBS, prior to 2001, and thus requires a critical analysis of its uncertainty.

Impact of using a standard month

The impact of using a standard month of 30.4369 days vs. the actual number of days in a month is relatively small and is illustrated by Figure 14 which compares the difference between the residual and component NBS with the correction to be applied to the change-in-storage to correct for using the standard month. It is observed that only in the month of February is there a significant impact.

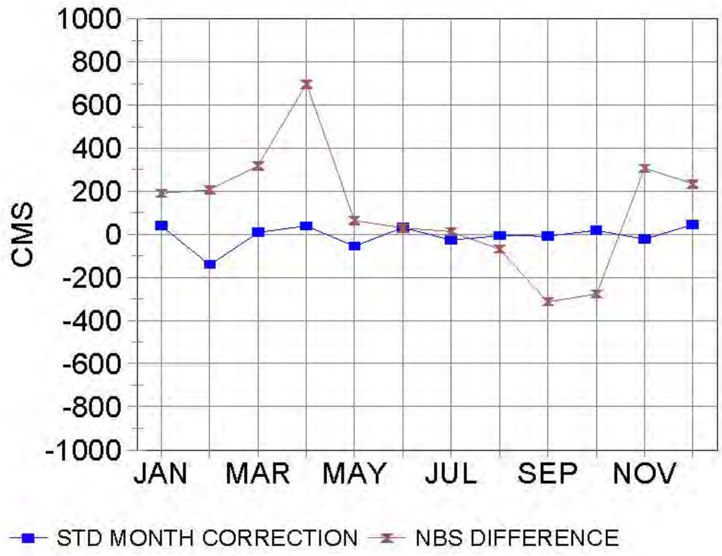

Figure 14. Comparison of NBS differences with corrections to adjust from a standard month to an actual month.

The difference in change-in-storage computations does not have a meaningful effect in explaining the differences between the residual and component NBS. However, it does not make any sense to use a standard month when the calculations are easy to use the actual number of days in a given month. The following computations will use the actual change-in-storage rather than the standard month procedure.

Correlation of NBS differences with beginning-of-month lake levels

Figure 15 shows a comparison between the monthly average NBS differences and the Lake Superior beginning-of-month water levels. An extremely high correlation (r = -0.75) is observed. This infers that the differences in the supplies may be due to selection of beginning-of-month water levels and the resulting changes in storage during the year. This will be investigated in the uncertainty analysis.

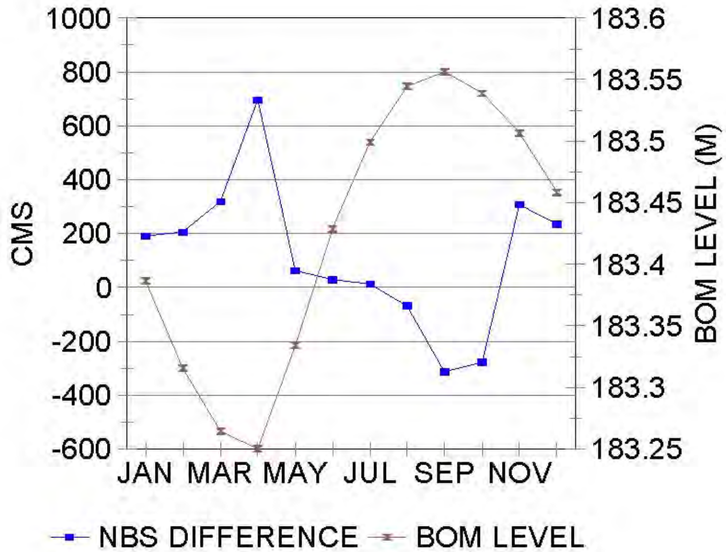

Figure 15. Comparison of the monthly average NBS differences with Lake Superior beginning-of-month levels.

Thermal Expansion

The thermal expansion of the Lake Superior water mass can have a major impact on the computation of the residual NBS. The change-in-storage of equation (1), when computed from beginning-of-month levels, can be expressed as:

$$\Delta S = \Delta S_m + \Delta S_t \qquad (4)$$

Where: ΔS_m is the change-in-storage due to a change in mass.
ΔS_t is the change-in-storage to thermal expansion.

The impact of thermal expansion on the Great Lakes water balance has been addressed by Meredith (1975). The time period analyzed ran from 1952-1965. For Lake Superior he found that the monthly values that should be added to the change-in-storage to eliminate the effects of thermal expansion and contraction range from a positive 580 cms in August 1964 to a negative 690 cms in February 1957. Figure 16 shows the monthly averages and standard deviations for the entire 1952-1965 period. Figure 17 shows the impact of the thermal corrections on the residual NBS. It is seen that in several months the impact is around 1 cm on Lake Superior water levels (312.2 cms/0.01m).

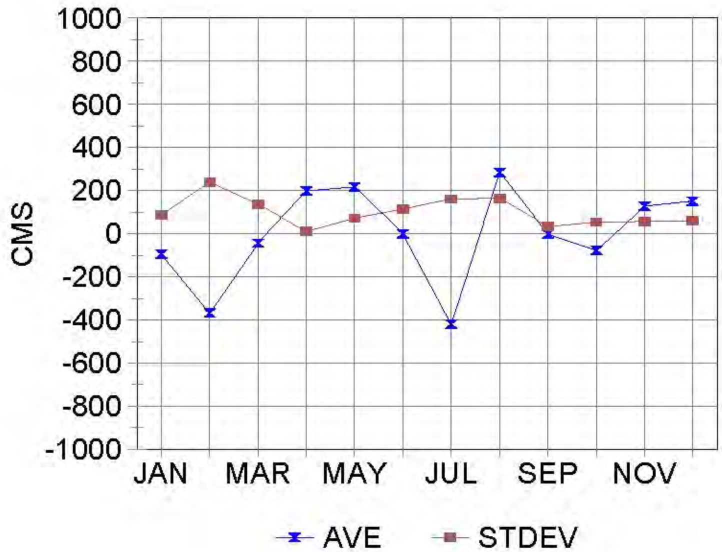

Figure 16. Monthly average corrections with standard deviations to be added to the residual NBS to correct for thermal expansion.

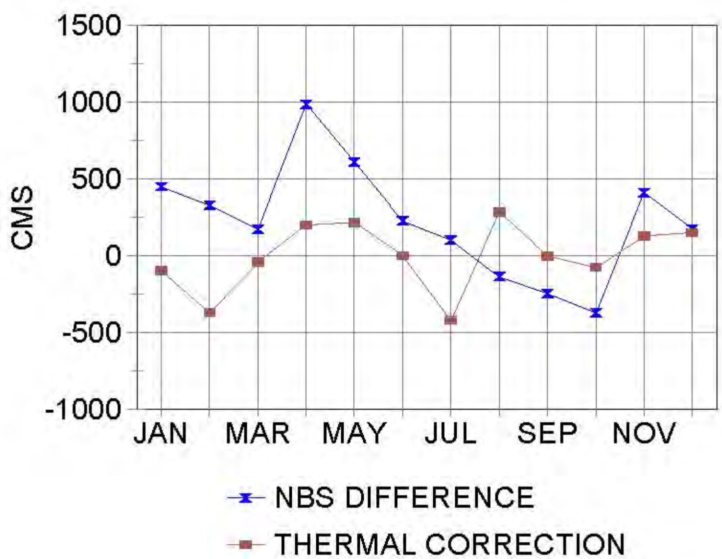

Figure 17. Comparison of NBS differences with the thermal expansion corrections.

Figure 17 compares the average monthly NBS differences with the average monthly thermal expansion terms for the period 1952-1965. It is observed that, in general, adding the thermal expansion terms to the residual NBS does not explain the differences between the component and residual NBS. It should be noted that Meridith suggests that the published values serve as guidelines as to impacts and are not exact. As the values for thermal expansion are not available subsequent to 1965, it is recommended that they not be considered for further analysis. However, their importance could increase as the waters of Lake Superior continue to warm as per the last several years.

Change-in-storage Analysis

The change-in-storage is the primary contributor to the seasonal and annual variability of the residual NBS as shown in Figure 4. It is computed from beginning-of-month water levels and the lake area as given in Equation (5).

$$\Delta S_t = (BOM_{T+1} - BOM_T)\ A_L/\Delta t \qquad (5)$$

Where: BOM_{T+1} is the end-of-month level at the end of month T
BOM_T is the beginning-of-month level at the beginning of month
A_L is the Lake Superior surface area in m2
Δt is the number of seconds in the month
ΔS_t is the total change in storage during the month in cms including thermal expansion.

All levels are in meters.

Lake-wide beginning of the month water levels are computed using a number of water level gauges located around the perimeter of the lake. The computational procedure is to use either straight averaging or apply weighting factors to each gauge used in the computations. The resulting values are a function of the number of gauges in the network and the averaging or weighting factors used in the computation (Quinn and Todd, 1974). There are currently five U.S. gauges and four Canadian gauges. The procedure used in deriving the coordinated beginning-of-month levels is to compute a straight average of BOM water levels recorded at the Duluth, Marquette, Thunder Bay, Michipicoten, and Point Iroquois gauges. The BOM water level, as currently estimated for coordinated values, is the mean of the two daily water levels for the first day of the month and the last day of the previous month.

A second method using the same gauges computes the beginning-of-month water levels as the mean of two consecutive monthly mean water levels using the five water level gauges. The GLERL beginning-of-month levels employes a Theissen Polygon network using all available gauges (Croley and Hunter, 1994). This analysis will only address the first two procedures. Additional information is provided in Appendix 2.

Table 8 shows a statistical comparison between the coordinated BOM levels and the BOM levels computed as the mean of two adjacent monthly mean levels.

Table 8. Comparison of coordinated BOM water levels with those computed from monthly mean levels for 1951-2006. All values are in meters.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Ave Difference	0.00	0.01	-0.02	-0.02	0.01	0.00	0.01	0.01	0.01	0.00	0.01	0.00
Standard Deviation	0.00	0.01	-0.02	-0.02	0.01	0.00	0.01	0.01	0.01	0.00	0.01	0.00

With an average difference of 2 cm or less and a standard deviation of 2 cm or less the two methods are equivalent and either could be used to determine the change-in-storage.

One method for examining the uncertainty with respect to the water level gauges used in the BOM computations is to compare the average of the BOM and EOM levels with the monthly mean. Because the storage computation yields an average rate of change over a month, the average of the BOM and EOM levels should be the same as the monthly mean water level. The monthly differences are in the range of ±3 cm with an annual average range of 0 to -1 cm.

The next step is to correct the coordinated change-in-storage by a factor of two times the difference listed in Table 8 times 31,380 cms/m/month. The factor of two results from the fact that a BOM or EOM level must be increased by 2 cm to change the mean monthly level by 1 cm. The monthly average change-in-storage correction values in m are given in Table 9 and are shown in cms on a seasonal basis with the differences between the residual and component NBS in Figure 18. The symmetry is readily apparent and the correlation coefficient between the two time series is -0.87. Figures 19 and 20 shows the impact of the storage corrections on an annual and monthly basis respectively. Note the change subsequent to the year 2000.

Table 9. Average corrections to be applied to the coordinated change-in-storage. All values are in cms.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Ave Difference	-40	-96	-217	-541	-6	-8	72	1	102	68	-89	-74

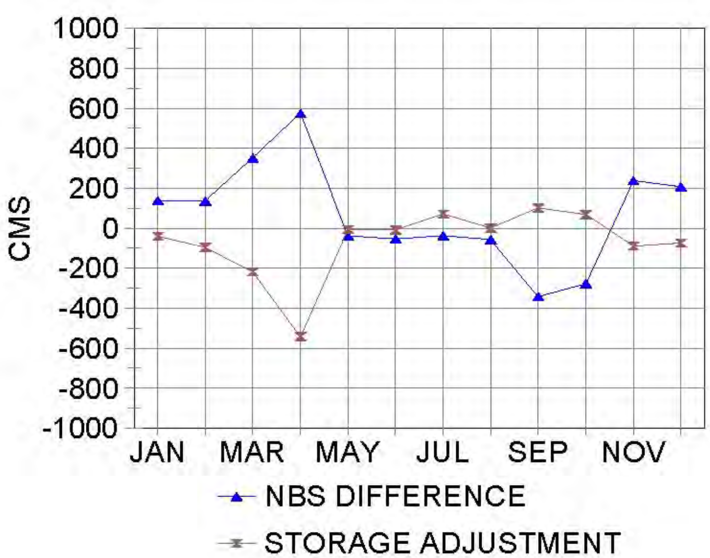

Figure 18. Computed average change-in-storage adjustment and difference between the residual and component NBS for 1951-2006.

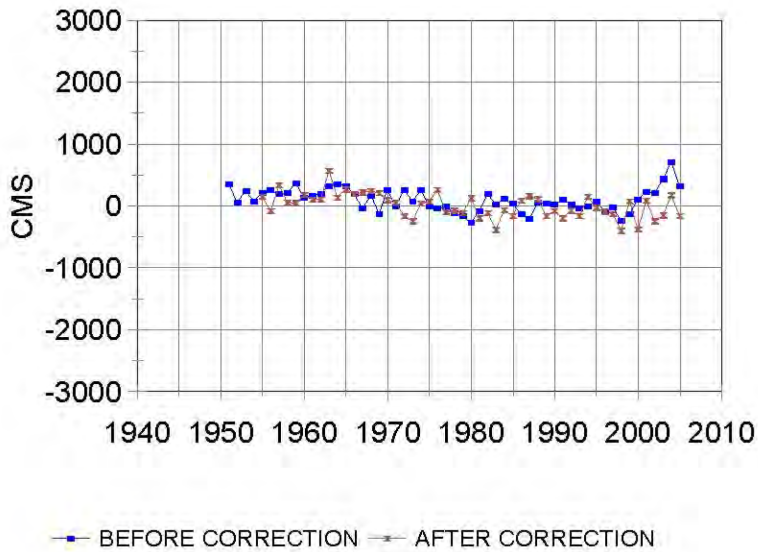

Figure 19. Annual NBS differences before and after corrections.

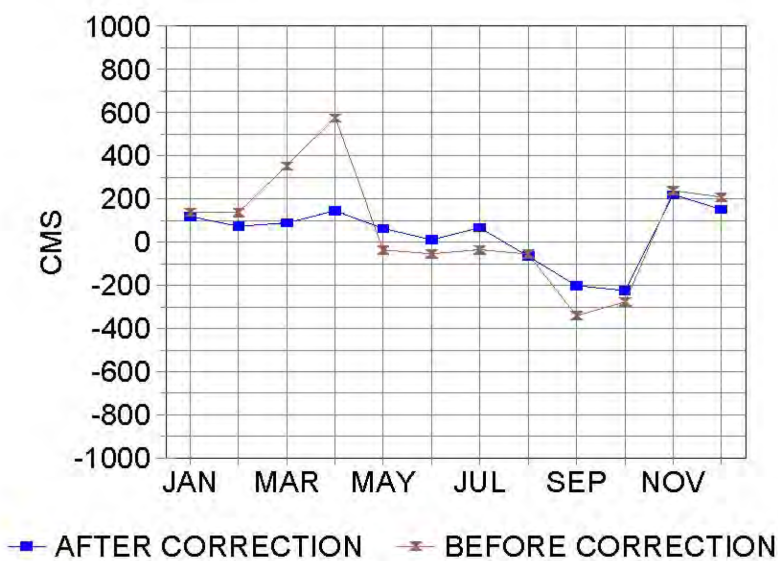

Figure 20. Difference between residual and component NBS after corrections to the coordinated change-in-storage.

Based on the above analysis and Appendix 1, an average uncertainty value of 3 cm for the change-in-storage is recommended and used in this analysis.

Uncertainty/error analysis

The final step is to conduct an uncertainty analysis with emphasis on the change-in-storage and runoff. The uncertainty is defined as plus or minus one standard deviation of the variable or the confidence interval of the variable (95 percentile) divided by 1.96 to convert to one standard deviation. Confidence estimates for the Lake Superior water balance are given in Neff and Nicholas, 2005. Mean values of the low and high estimates were used for the St. Marys outflows; the precipitation, the runoff, and the evaporation are based upon Table 1. An average standard deviation of 3 cm is used in this analysis for the change-in-storage. Note that this greatly increases the average uncertainty of the residual computations which assumed the uncertainty of the change in storage to be from 3 to 12 mm (Neff and Nicholas, 2005).

The NBS uncertainty limits are computed for each month in the analysis by taking the square root of the sum of the individual component standard deviations squared and adding and subtracting that value from the monthly NBS. Figures 21 and 22, for example, show the uncertainty of the April and September residual NBS compared with the component NBS. These are the months with the maximum positive and negative differences after correcting for changes-in-storage.

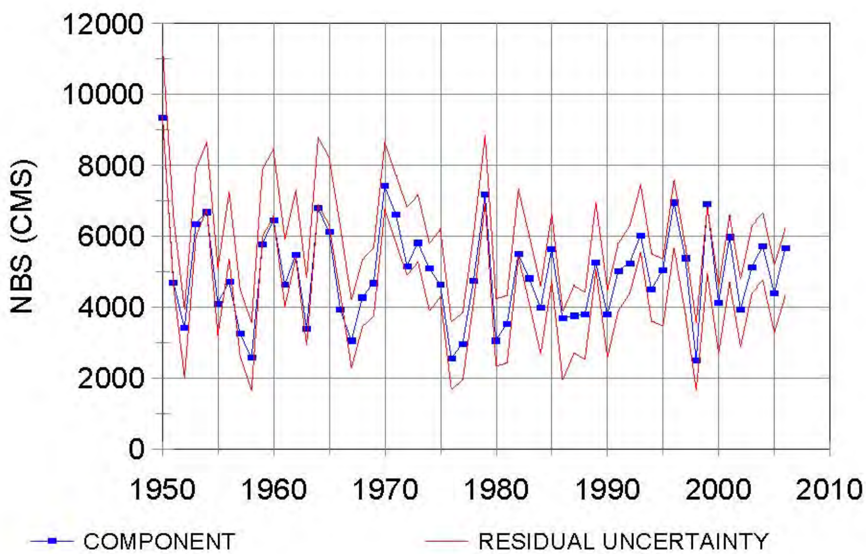

Figure 21. April component NBS compared with the residual NBS uncertainty.

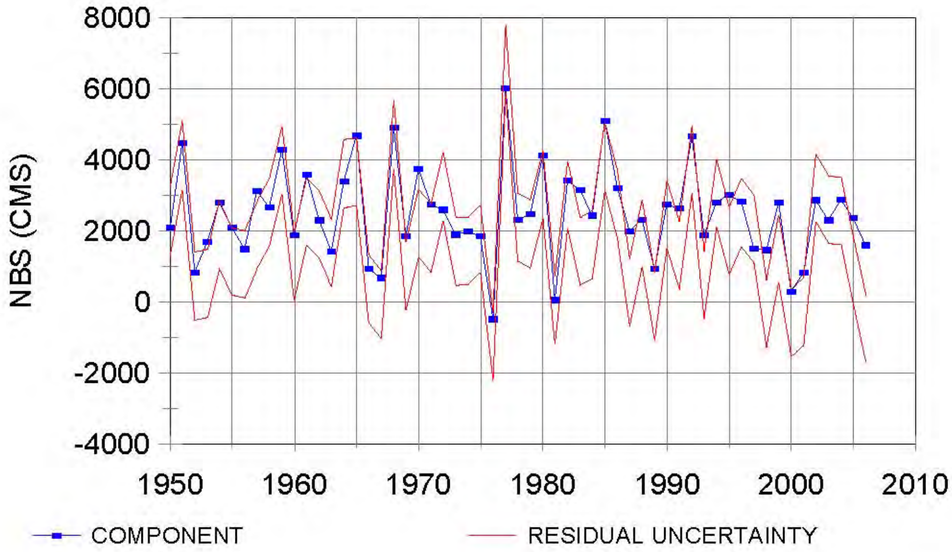

Figure 22. September component NBS compared with the residual NBS uncertainty.

Both Figures 21 and 22 show that the component NBS is within the uncertainty of the residual NBS. In general, all months are within the confidence limits of the residual NBS although some months are right on the border.

Figures 23 and 24 show similar plots with the residual NBS compared with the component uncertainty.

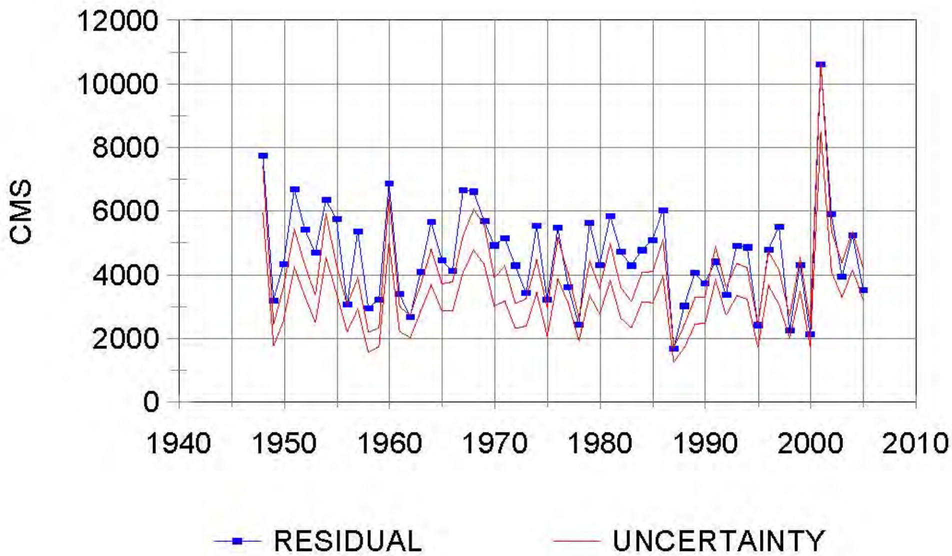

Figure 23. April residual NBS compared with the component NBS uncertainty.

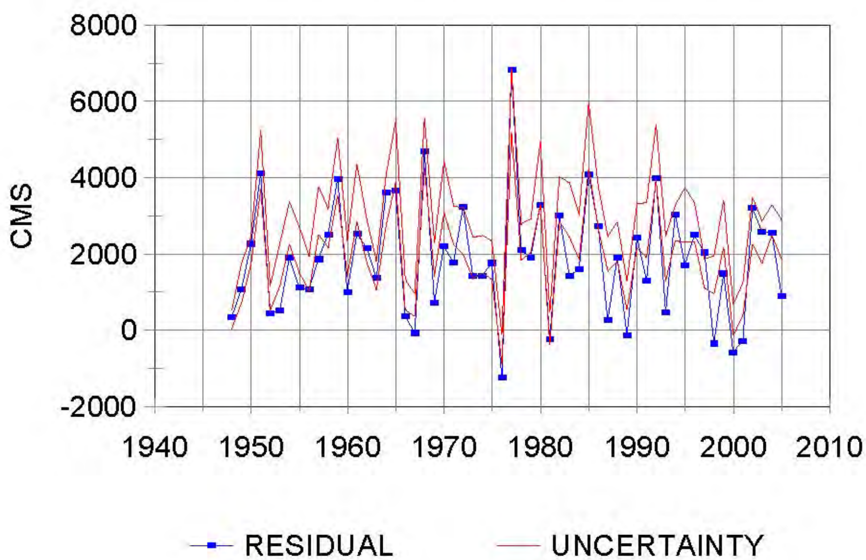

Figure 24. September residual NBS compared with the component NBS uncertainty.

While the component NBS in general fell within the uncertainty band of the residual NBS, the converse is not true. The residual NBS falls outside of the uncertainty bands of the component NBS in the above two cases. This would probably not be the case if the change-in-storage were corrected as recommended.

Figures 25-28 provide a different way of looking at the uncertainty.

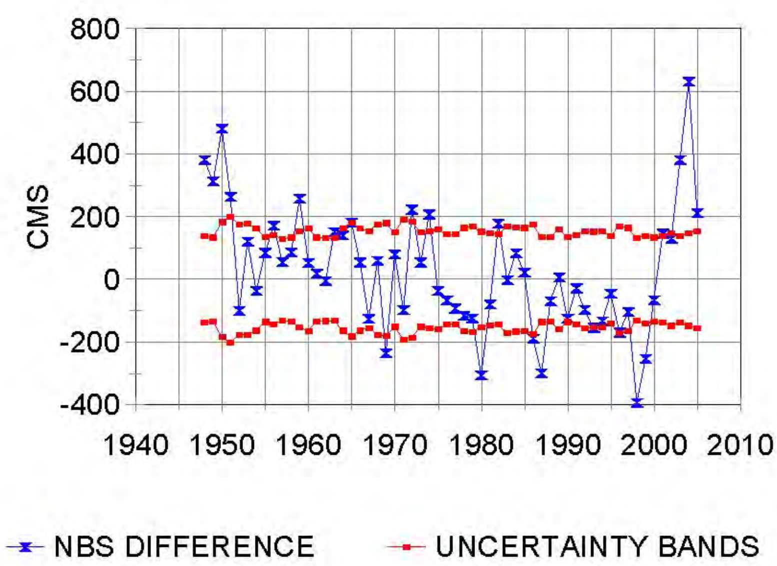

Figure 25. Annual average NBS difference compared with the residual NBS uncertainty.

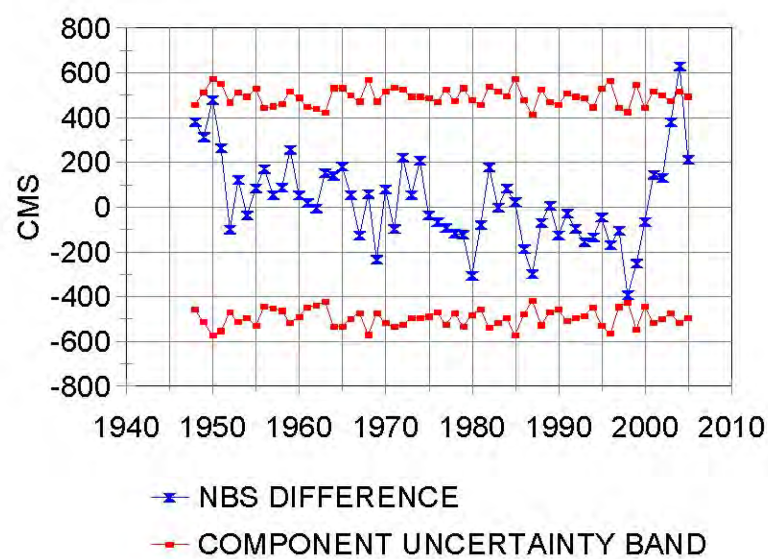

Figure 26. Annual average NBS difference compared with the component NBS uncertainty.

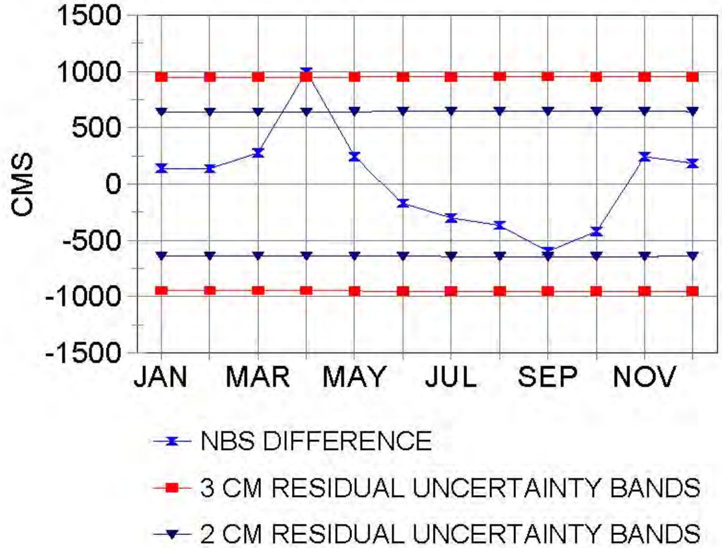

Figure 27. Monthly average NBS difference compared with the residual NBS uncertainty.

Figure 28 shows monthly uncertainty bands with both a 3 cm and 2 cm uncertainty for the monthly change-in-storage.

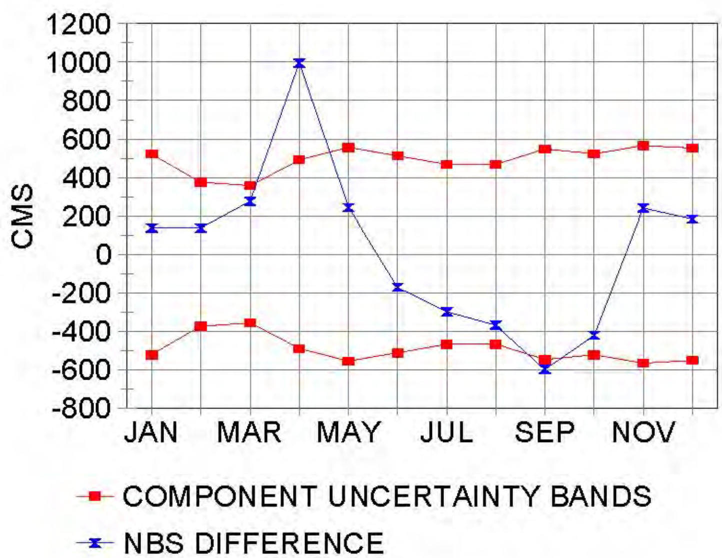

Figure 28. Monthly average NBS difference compared with the component NBS uncertainty.

Conclusions

There are significant differences between the residual and component NBS depending upon the month and the time periods involved. However, when the change-in-storage is corrected as per the above analysis, the average monthly differences between the two techniques are less than 200cms, about 60 mm on the lake. The problems between the residual and component NBS in the 2001-2006 time period appear to be primarily due to the change-in-storage. Good agreement exists between the NBS estimates for the period 1967-2000. For this period, either methodology would give similar results for Lake Superior and can be used interchangeably. The difference would be in slightly modified flows in the St. Marys River. Therefore the component data for the period from 1967-2006 will give comparable results as the residual data.

The use of a standard month for the changes-in-storage is not a major factor in the analysis. However, to assure valid comparisons with other components the changes-in-storage should be recomputed using the actual number of days in a month. I know of no valid reason why the use of a standard month should be continued.

The high correlations between the monthly changes-in-storage and the differences between the residual and component NBS indicate that additional attention should be focused on the beginning-of-month water levels. At present, only five of the nine water level gauges are used to compute the beginning-of-month levels and no weighting is utilized. The impact of using additional gauges and weighting factors should be evaluated as well as the averaging time period to determine a beginning-of-month water level. The methodology proposed to correct the changes-in-storage should be reviewed and applied to the residual technique. It appears to result in greatly improved NBS estimates for Lake Superior.

While thermal expansion does have an impact on the residual water levels which may explain some of the monthly differences between the component and residual NBS, we do not have sufficient accurate data to proceed with any corrections to the residual NBS.

Finally, the uncertainty analysis indicates that the component NBS fall within the uncertainty of the residual NBS for the vast majority of months. The converse was not true. Better results would be expected if the residual NBS was corrected for changes-in-storage as recommended.

The period 1967-2006 should serve as the base period for climate and other studies. We should never expect to have perfect agreement between the residual and component methodologies. The type of agreement in the period 1967-2000, with extension to 2006, is about as good as one could expect and allows the component methodology to be used in water resource studies on Lake Superior with confidence.

Recommendations

1) A comprehensive analysis of the most appropriate beginning-of-month water levels and their uncertainty should be undertaken including the impact of changing the BOM averaging period and the number of gauges used. The methodology recommended for correcting changes-in-storage in this report should be reviewed and applied to the residual NBS computations.

2) An assessment of an apparent problem between precipitation and runoff for the period 1948-1966 needs to be undertaken.

3) The component NBS data for the three periods, 1948-1966, 1967-2000, and 2001-2006, should be run through the routing models to verify the differences between the actual and component water level and flows in the connecting channels.

Lake Michigan-Huron Net Basin Supply Comparison Analysis

Introduction

The purpose of this analysis is to compare the Lake Michigan-Huron NBS calculated from both the residual and component methodology, to draw conclusions as to the use of the component NBS, and to make recommendations as to the use of the two techniques, the various uncertainties involved in the computations, and future changes to make the techniques more compatible.

Net Basin Supply Computation

The water balance for Lake Michigan-Huron is expressed as

$$P+R+Q_{SM} = E+Q_{SC}+D_C \pm\Delta S \qquad (1)$$

Where: P is the over-lake precipitation in cms
R is the runoff from the Michigan-Huron land basin into the lake in cms
E is the evaporation from the lake surface in cms.
Q_{SM} is the St. Marys River inflow in cms
Q_{SC} is the St. Clair River outflow in cms
D_C is the Lake Michigan Diversion at Chicago into the lake in cms
ΔS is the change in storage in cms, It includes thermal expansion

The net basin water supplies for Lake Michigan-Huron can be computed directly by its components, Equation (2) or indirectly from the Lake Michigan-Huron water balance, Equation (3).

$$NBS_C=P+R-E \qquad (2)$$

Where: NBS_C is the component net basin supply in cms

$$NBS_R= Q_{SC} - Q_{SM} +D_C \pm\Delta S \qquad (3)$$

Where: NBS_R is the residual net basin supply in cms

All analysis is based on a monthly time scale. It should be noted that the change-in-storage from the coordinated data is based upon a standard month of 30.4369 days and not the actual number of days in a month. The precipitation, runoff, and evaporation data are from Croley and Hunter (2008). The St. Marys flow data, the St. Clair River flow data, the diversion data, and the beginning-of-month levels and resulting change-in-storage data are the coordinated data from the Sharepoint files. Figures (1) and (2) show the monthly and annual averages for the component data for 1948-2006 (runoff through 2005), the period for which all data are available. Figures 3 and 4 show similar averages for the residual data. Table 1 gives the monthly averages and standard deviations for all the major components. Figure 5 shows the standard deviations for all the components.

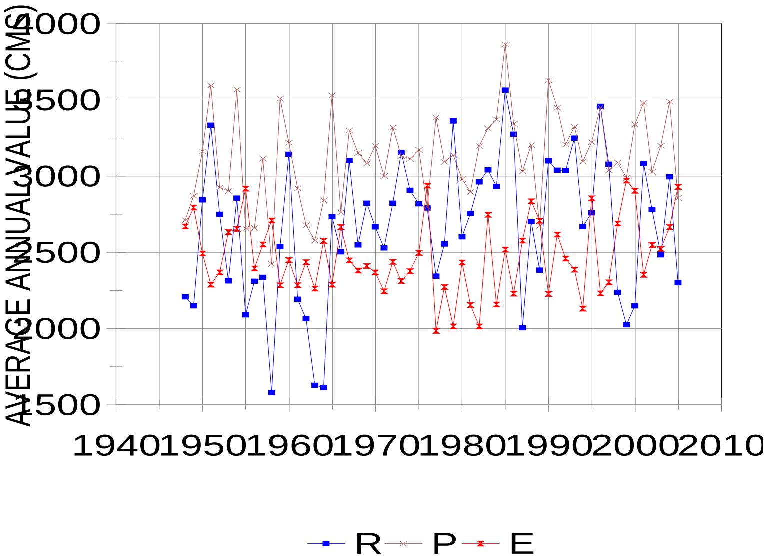

Figure 1. Average annual component data.

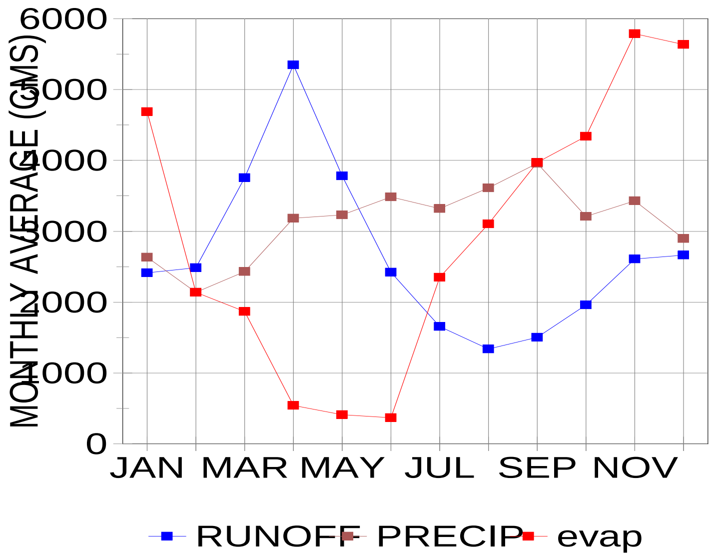

Figure 2. Average monthly component data.

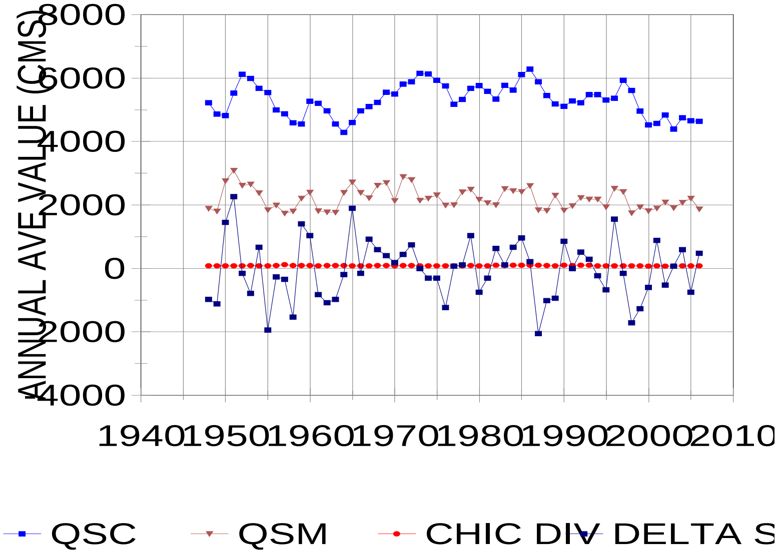

Figure 3. Average annual residual data.

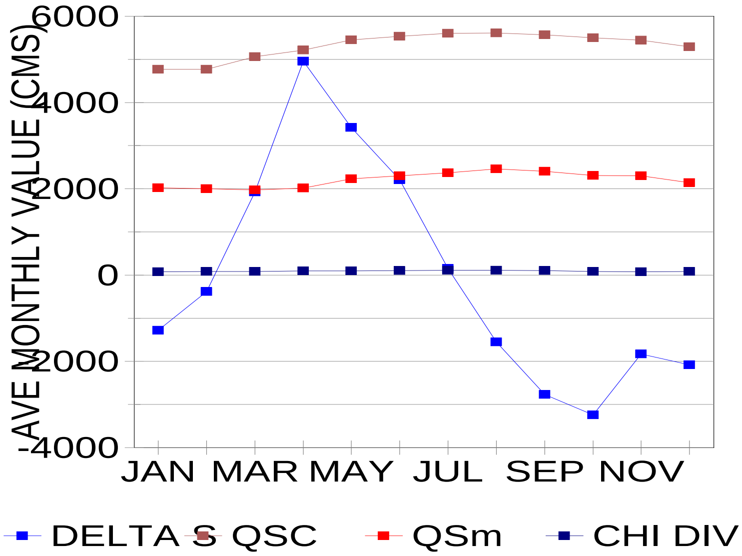

Figure 4. Average monthly residual data.

Table 1. Average values and standard deviations in cms for all major components.

	P		R		E		Q_{SM}		ΔS		Q_{SC}	
	AVE	STD	AVE	STD	AVE	741	AVE	STD	AVE	STD	AVE	STD
JAN	2636	807	2414	745	4230	618	2019	261	-1278	1545	4771	639
FEB	2137	763	2486	725	2477	520	2003	257	-385	1490	4768	597
MAR	2430	1000	3757	1032	1552	238	1971	271	1925	2182	5061	500
APR	3185	828	5349	1401	545	271	2015	316	4960	2173	5214	561
MAY	3232	1200	3781	1228	121	387	2232	456	3420	2294	5450	521
JUN	3483	1171	2424	839	180	602	2303	496	2210	1953	5537	525

JUL	3319	874	1654	491	877	654	2369	573	154	1665	5607	528
AUG	3613	1038	1338	273	2295	774	2461	581	-1555	1678	5614	532
SEP	3961	1624	1503	574	3694	728	2405	605	-2772	2559	5566	532
OCT	3210	1353	1961	901	3914	768	2309	605	-3165	2287	5503	533
NOV	3430	1139	2607	1008	4788	822	2297	602	-1832	2257	5447	516
DEC	2898	795	2665	831	5056	741	2142	405	-2079	1973	5287	516

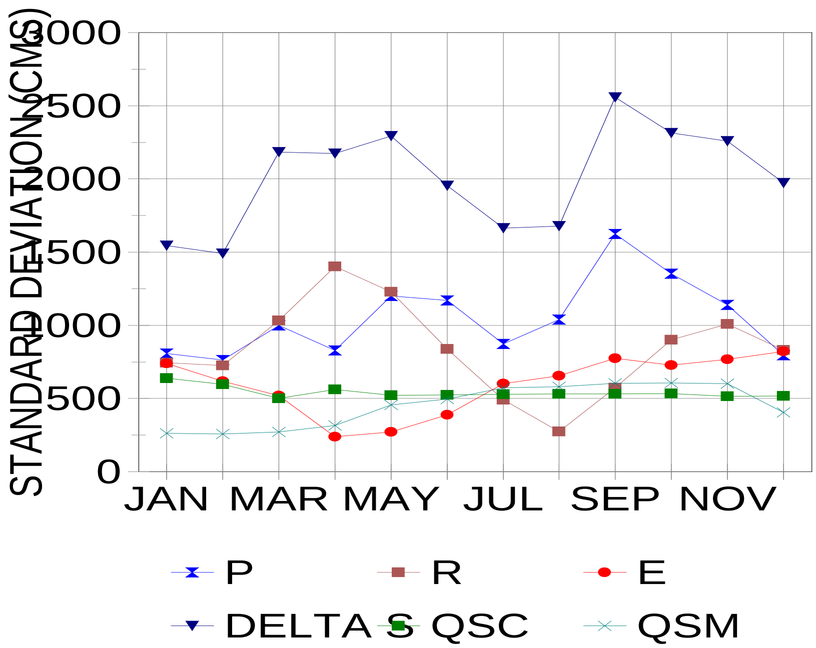

Figure 5. Standard deviation of monthly components

The most important comparisons are those of the monthly average components which show the range of values. The most surprising observation is that the change-in-storage has by far the largest seasonal variability of any of the other components in Figures 2 and 4. The second largest range is the monthly evaporation. Relatively little variability is seen in the St. Marys River flows. The seasonal changes in the diversions are negligible and will not be considered further in this analysis.

Comparison between residual and component NBS

The next step will be to compare the component and residual net basin supplies and their differences on annual and monthly basis. Figure 6 shows the difference between the two methods for the period of study. The figure shows a large amount of noise in the differences. The figure also shows a consistent regime between 1948 and the mid 1980s followed by a negative bias through the end of the time series, with the component NBS being larger than the residual NBS. The extreme low point is for October 2002 where the change-in-storage is about 8 times its standard deviation. There appears to be unusual fluctuations in the hourly water levels in the northern parts of Michigan-Huron during this time period. The value was set to the change-in-storage given by the Lakeport, Harbor Beach and Chicago gauges.   A 12 month running mean using the corrected data is shown in Figure 7.

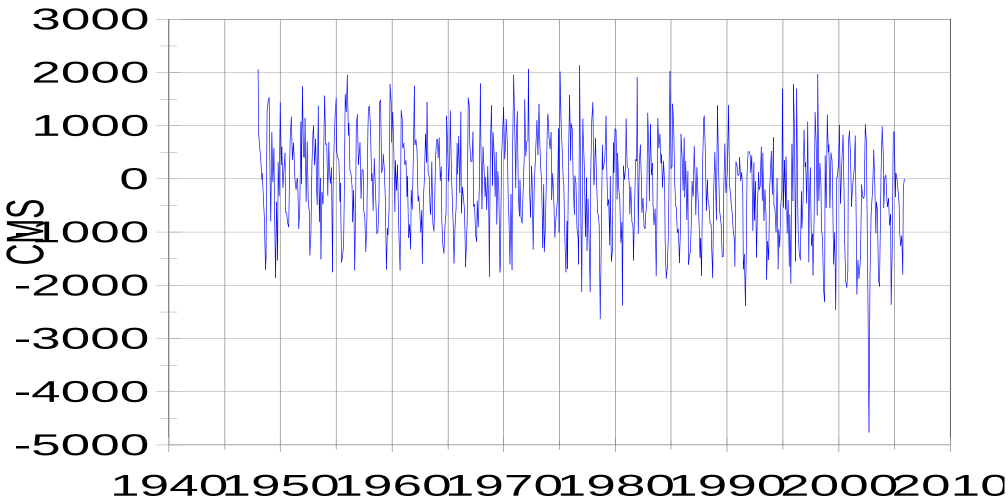

Figure 6. Monthly residual minus component differences

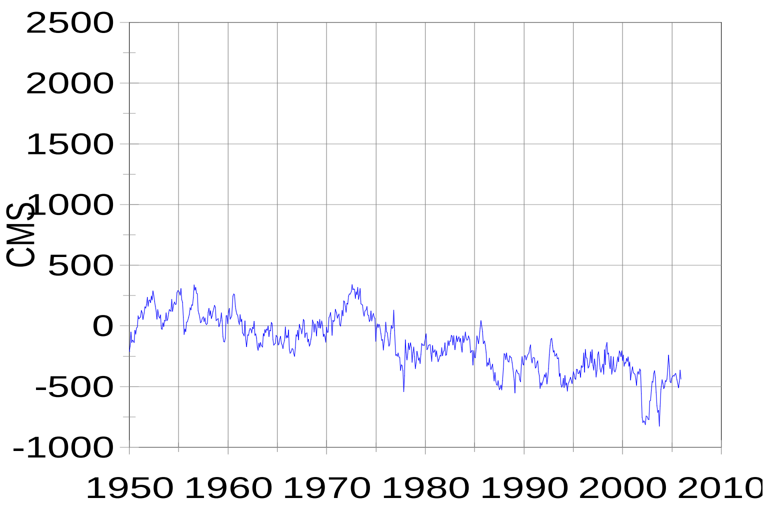

Figure 7. Monthly residual minus component differences (12 month running mean)

Figure 7 shows a shift of about 250 cm occurring around 1970. This difference in the two methods translates to about 60 mm on Lake Michigan on an annual basis. A second shift appears to occur shortly after 1985. This translates to about an additional 30 mm on the lake. These shifts are well within the accuracy of the beginning-of-month water level measurements. A major anomaly occurs about 2000 which needs further investigation. Figure 8 shows a comparison of the two methods using annual average data. The final comparisons using annual data are given as Figure 10 using 5-year running averages to dampen out more of the noise. This figure also includes the 5-year averages of the various components. The only relationship appears to be a negative correlation between precipitation and the NBS differences.

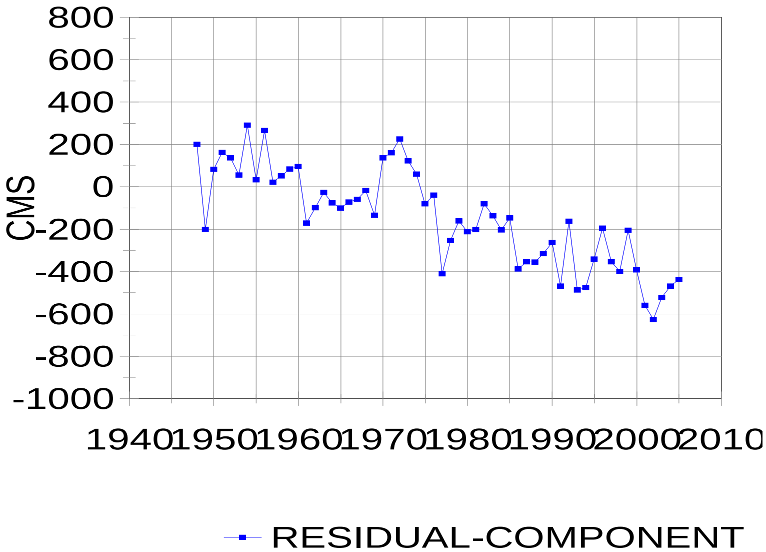

Figure 8. Annual mean differences of the residual minus the component NBS.

The aforementioned shifts show up very clearly in the annual average data. The shift about 1962 could be due to the addition of the Tobermory water level gauge which came on line in 1962. The second shift could be due to an anomaly or apparent shift in the Thesselon gauge occurring around the early 1970s (Quinn and Southam, 2008). These shifts could easily account for the 100-200 cms shifts in the differences between the computed and residual NBS prior to 1986. Figure 8 shows the annual mean differences using the corrected data.

The final comparisons using annual data are given as Figures 9 and 10 using 3-year running averages to dampen out more of the noise. This figure also includes the 3-year averages of the various components. Looking in particular at the period 1975-2006 we find that the highest correlations between the NBS differences and the various components are for the St. Clair and St. Marys Rivers flows. This is shown in Table 2.

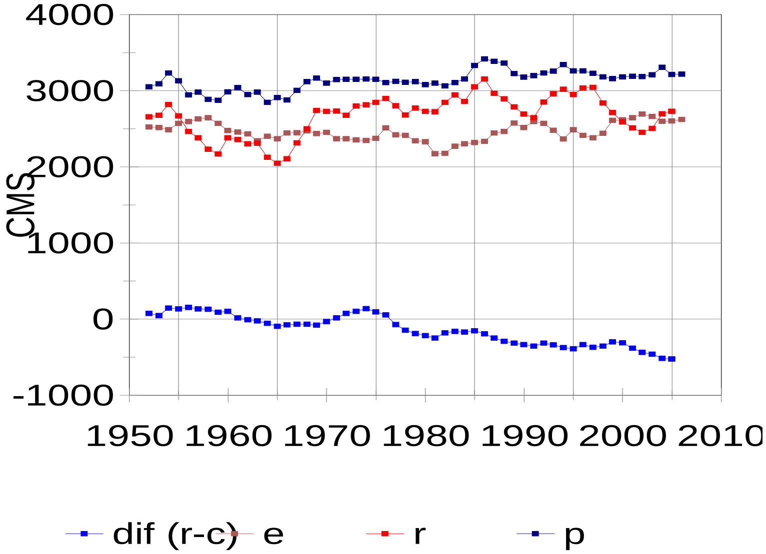

Figure 9. Comparison of 3-year running mean differences of the residual minus the component NBS with 5-year averages of the component values.

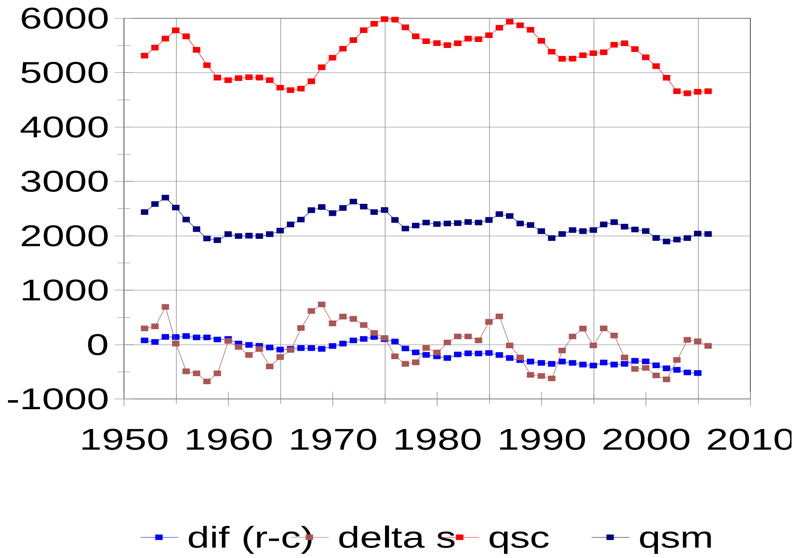

Figure 10. Comparison of 5-year running mean differences of the residual minus the component NBS with 5-year averages of the residual NBS components

A comparison of the correlation coefficients between the NBS differences and the individual components are given in Table 2 for monthly, annual, and 5-year moving averages. Based upon the preceding analysis, it was decided to break the time series into 3 segments, 1948-1976, 1977-1986, and 1987-2000, and 2001-2005 for further analysis on an annual basis. It should be noted that the 2001-2006 time period was also significant in the Lake Superior NBS comparison. Table 3 gives the t test and f test statistic for comparing the annual values of the component vs. the residual NBS.

Table 2. Correlation between monthly, annual, and 3-year running mean components and the differences between the residual and component NBS for the period 1975-2000.

Component	r (annual)	r (3-year mean)
precipitation	-0.08	-0.18
runoff	0.21	-0.19
evaporation	-0.08	-0.36
St. Marys flows	0.34	0.45
Change-in-storage	0.12	-0.05
St. Clair flows	0.52	0.75
Harbor Beach	0.53	0.24

Table 3. T test and f test statistics for selected periods

Period	t test	f test	Mean Diff (cms)	Diff (cm on lake)
1948-1976	0.17	0.82	35	0.9
1977-1986	0.00	0.92	-250	-6.7
1987-2000	0.00	0.98	-360	-9.9
2001-2005	0.00	0.96	-527	-14.2

Table 3 shows that while the variances of the component NBS and the residual NBS are statistically the same at the 0.05 significance level, in only the period 1948-1976 are their means statistically the same for the 0.05 significance level. However, with the exception of the period 2000-2005, the differences in the means are less than 1 cm. As this is within the assumed accuracy of the beginning-of-month levels, either the component NBS or the residual NBS will give equivalent Lake Michigan-Huron annual water levels. The period 2001- 2005 needs further analysis. Also, the steady downward trend of the differences indicates a probable continuing shift in one of the variables.

Monthly Analysis

Figures 11-14 show comparisons between the residual and component NBS for four time series given in Table 3.

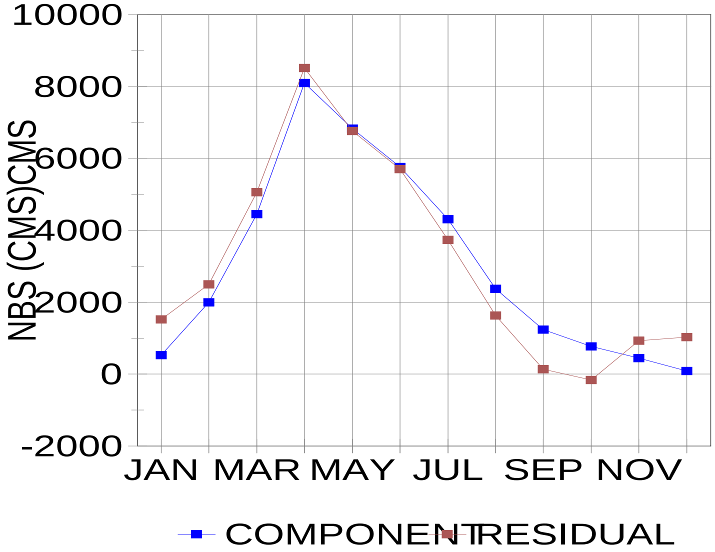

Figure 11. Monthly comparison of the residual and component NBS for the period 1948-1976.

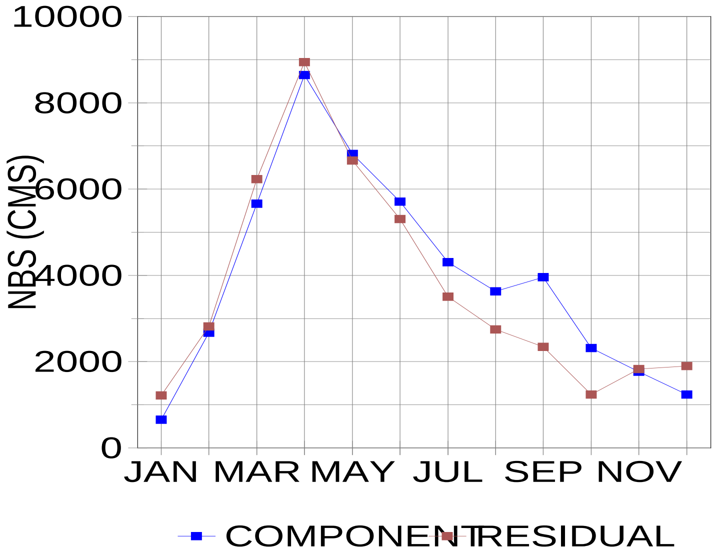

Figure 12. Monthly comparison of the residual and component NBS for the period 1977-1986.

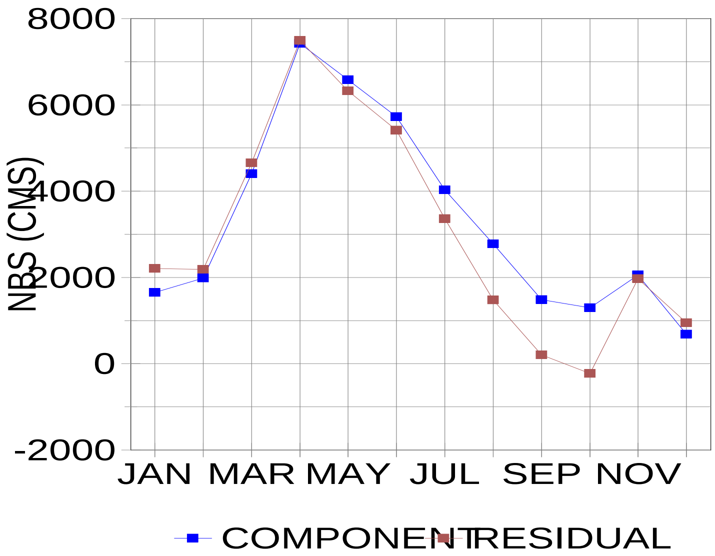

Figure 13. Monthly comparison of the residual and component NBS for the period 1987-2000.

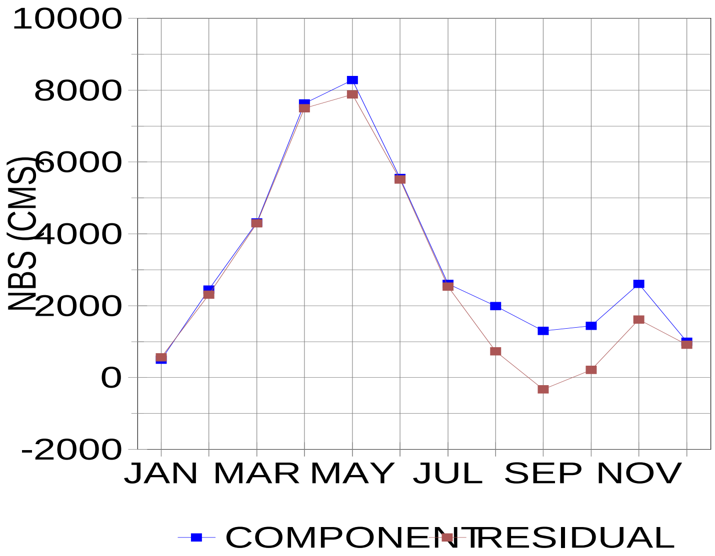

Figure 14. Monthly comparison of the residual and component NBS for the period 2001-2005.

The four figures show very different results for the four time periods. Major differences occur for the period July-November for all time periods. The most likely explanations would appear to be low evaporation, high changes-in-storage, thermal expansion, or beginning-of-month water levels. The NBS differences are shown in Figure 15 for the period 1987-2000. Note that in October the difference is extremely high, 1500 cms.

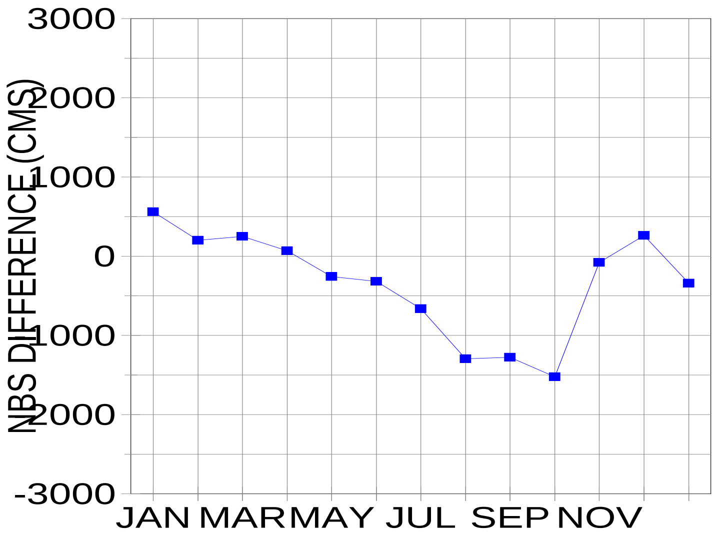

Figure 15. Monthly NBS differences (residual-component) for the period 1987-2000.

Tables 4-7 show the statistical comparison between the residual and component NBS for the four periods.

Table 4. Statistics of the 1948-1976 NBS Differences (Residual-Component)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
ave	957	457	571	478	-58	-42	-576	-736	-1101	-939	481	924	35
std	646	506	419	611	360	473	501	627	400	542	778	614	132
f test	0.97	0.83	0.58	0.79	0.71	0.98	0.44	0.54	0.78	0.65	0.47	0.74	0.82
t test	0.00	0.00	0.00	0.00	0.40	0.65	0.00	0.00	0.00	0.00	0.00	0.00	0.17
ΔS	0.02	0.01	0.01	0.01	-0.00	-0.00	-0.01	-0.02	-0.02	-0.02	0.01	0.02	0.00

Table 5. Statistics of the 1977-1986 NBS Differences (Residual-Component)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
ave	509	100	500	242	-166	-406	-797	-879	-1652	-1114	45	616	-250
std	1028	601	520	416	423	253	443	523	519	605	620	613	99
f test	0.18	0.80	0.61	0.69	0.73	0.96	0.50	0.45	0.98	0.75	0.81	0.49	0.92
t test	0.17	0.63	0.02	0.11	0.27	0.00	0.00	0.00	0.00	0.00	0.83	0.01	0.00
ΔS	0.01	0.00	0.01	0.01	-0.00	-0.01	-0.02	-0.02	-0.04	-0.02	0.00	0.01	-0.00

Table 6. Statistics of the 1987-2000 NBS Differences (Residual-Component)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
ave	518	148	189	28	-261	-311	-667	-1296	-1292	-1556	-114	217	-366
std	636	542	898	641	585	524	493	440	542	644	602	565	99
f test	0.76	0.73	0.33	0.57	0.92	0.87	0.76	0.97	0.62	0.63	0.86	0.50	0.98
t test	0.01	0.34	0.46	0.88	0.13	0.05	0.00	0.00	0.00	0.00	0.51	0.19	0.00
∆S	0.01	0.00	0.01	0.00	-0.01	-0.01	-0.01	-0.03	-0.03	-0.03	-0.00	0.01	-0.01

Table 7. Statistics of the 2001-2006 NBS Differences (Residual-Component)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
ave	34	-188	-108	-149	-387	-40	-61	-1241	-1630	-1460	-985	-110	-527
std	884	327	389	160	360	586	723	345	642	674	818	983	50
f test	0.57	0.81	0.96	0.80	0.98	0.68	0.72	0.66	0.78	0.93	0.69	0.98	0.96
t test	0.94	0.31	0.61	0.14	0.10	0.90	0.87	0.00	0.01	0.01	0.07	0.83	0.00
∆S	0.00	-0.00	-0.00	-0.00	-0.01	-0.00	-0.00	-0.03	-0.04	-0.03	-0.02	-0.00	-0.01

Five statistical parameters are given for each of the time periods on both a monthly and annual basis. These are the average of the NBS differences, the standard deviation of the differences, the f test to compare the variances of the residual with the component NBS, the t test to compare the two means, and the change-in-storage represented by the average differences. The monthly and annual f tests for all periods show equivalent variances at the 5 percent significance level. The monthly t tests show that a large percentage of the monthly mean differences are significantly different at the 5 percent confidence level with the exception of the 2001-2006 period. However, the average annual values of both the residual and component NBS are equivalent at the 5 percent confidence level and will provide the same (within 1 cm) annual water levels when run through the routing models.

Tables 8 and 9 below show the correlation analysis between the differences of the NBS methods and the various components. Table 8 shows the correlations between the residual NBS and the differences to be essentially the same for the first three periods while the residual NBS shows a much larger difference for the last period. Table 9 shows that the precipitation, St Marys and St. Clair flows are highly correlated with the differences between the two net basin supply estimates. The most surprising finding is that the highest correlations are with the beginning-of-month levels. This indicates that additional attention should be focused on factors affecting these levels such as thermal expansion, network size and weighting, the networks not representing the true lake level, and the averaging periods.

Table 8. Correlation analysis between the differences of the residual and component NBS with the residual and component NBS for the monthly average data.

	Time Period			
	1948-1976	1977-1986	1987-2000	2001-2006
Component	0.00	-0.05	0.19	0.32
Residual	-0.08	-0.04	0.17	0.56

Table 9. Correlation analysis between the differences of the residual and component NBS with the various components.

	Time period			
	1948-1976	1977-1986	1987-2000	2000-2005
Precipitation	-0.59	-0.76	-0.69	-0.57
Runoff	0.50	0.54	0.70	0.54
Evaporation	0.18	0.10	-0.08	-0.38
St. Marys flow	-0.80	-0.81	-0.52	-0.41
ΔS	0.29	0.28	0.49	0.54
St. Clair Flows	-0.72	-0.71	-0.73	-0.48
BOM Level	-0.64	-0.81	-0.75	-0.54

Table 10 analyses in detail the average amount of change required in each individual parameter to balance the average October and January differences. October and January have the largest negative and positive differences between the residual and component NBS.

Table 10. Percent change required in each individual parameter to balance the average October and January differences. All component values are in cms unless otherwise noted.

Component	Oct (-1160 cms)	% Difference	Jan (694 cms)	% Difference
P	3210	-36	2635	26
R	1980	-59	2452	28
E	-3914	30	-4230	-16
ΔS	-3241	36 (3cm on lake)	-3241	-21 (2cm on lake)
QSC	5502	21	4771	-15
QSM	2309	-50	2019	+34

The percentage differences in Table 10 are pretty much outside the confidence levels of the parameters with the possible exception of the change-in-storage, which is related to the beginning-of-month levels.

The largest month to month difference between the residual and component NBS occurs between the months of October and November. Table 11 gives a comparison of the individual parameters for the two months. One would expect the measurement errors to be comparable for the two months for the precipitation, runoff, evaporation, and the flows in the St. Clair and St. Marys Rivers. The major parameter therefore affecting the change in NBS between the two months is the change-in-storage. This again illustrates the need for a comprehensive study on the beginning-of-month levels. It does not appear reasonable to me that the NBS for the average November should be 39 times the average NBS for the average October as shown by the residual NBS.

Table 11. Individual monthly average components for November and December

Component	Oct (-1160 cms)	Nov (136 cms)	Difference
P	3210	3430	230
R	1980	2696	647
E	-3914	-4788	-874
ΔS	-3241	-1832	1419
QSC	5502	5447	-55
QSM	2309	2297	-12
DivC	84	77	-7
NBSC	1275	1258	-17
NBSR	112**	1394	1382

**35cms before adjusting October 2002

Thermal Expansion

The thermal expansion of the Lake Michigan-Huron water mass can have a major impact on the computation of the residual NBS. The change-in-storage of equation (1) can be expressed as:

$$\Delta S = \Delta S_m + \Delta S_t \qquad (4)$$

Where: ΔS_m is the change-in-storage due to a change in mass
ΔS_t is the change-in-storage to thermal expansion.

The impact of thermal expansion on the Great Lakes water balance has been addressed by Meredith (1975). The time period analyzed ran from 1952-1965. For Lake Michigan-Huron he found that the monthly values that should be added to the change-in-storage to eliminate the effects of thermal expansion and contraction range from a positive 867 cms in November 1963 to a negative 807 cms in July 1955. Figure 19 shows the monthly averages change-in-storage compared with the effects of thermal expansion. It shows the impact to be less than 1 cm (446 cms) or less in all months. Based on the correlation between the differences in the two supplies and the beginning-of-month levels, the impact of the thermal expansion may be underestimated.

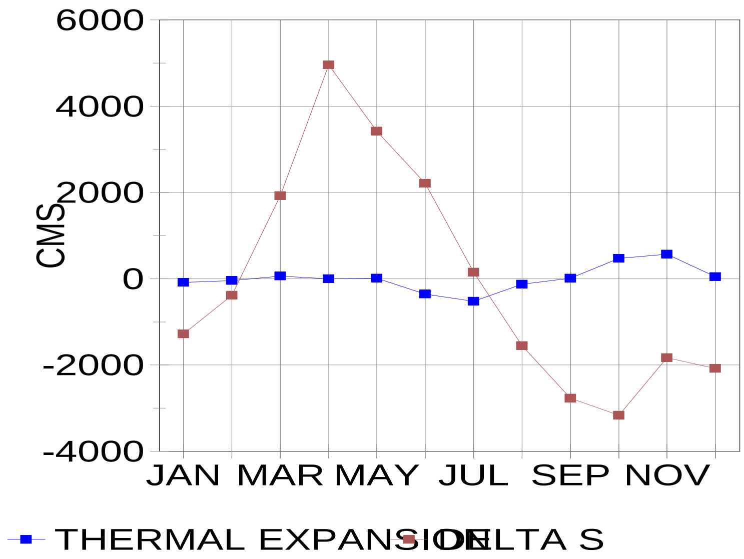

Figure 19. Monthly average computed change-in-storage compared with the thermal expansion.

Uncertainty/error analysis

Uncertainty analysis is very complex for Lake Michigan-Huron because of the large surface area and the fact that the St. Clair River outflows are a function of the water level of Lake Huron. For example, Equation (1) can be expressed as

$$NBS + Q_{SM} = D_C + a(MH\text{-}ym)^2(MH\text{-St. Clair})^{.5} \pm (MH_{t+1}\text{-}MH_t)\, A_{MH}/\Delta t \quad (5)$$

Where: MH is the elevation of Lake Michigan-Huron
St. Clair is the elevation of Lake St. Clair
t is the time
A_{MH} is the area of Lake Michigan-Huron
A, and ym are constants.

Thus it can be seen that any uncertainty in the NBS will affect the level of Lake Michigan-Huron and the flow in the St. Clair River. The residual uncertainty, regardless of how it is obtained, must therefore be limited to the uncertainty in the St. Clair River flows. The St. Clair River flows and discharge equations will have to be adjusted to match the recorded water levels within their range of uncertainty. Otherwise, Lake Michigan-Huron would either be raised or lowered to an unacceptable level. Neff and Nicholas give an average monthly uncertainty of 10 percent for the St. Clair River flows. This would yield a standard deviation of the uncertainty of 5.1 percent or about 270 cms for the St. Clair River flow. In like manner, the standard deviation of the uncertainty of the St. Marys River flows will also be 5.1 percent or about 112 cms. The uncertainty in the residual NBS, neglecting the change-in-storage, will therefore be about 300 cms.

Figure 20 indicates that only the months of February though June come close to meeting the uncertainty criteria of NBS differences being within ± 300 cms on a monthly average basis. Figure 21 shows that only during the period 1948-1985 do the annual NBS differences fall within the uncertainty band.

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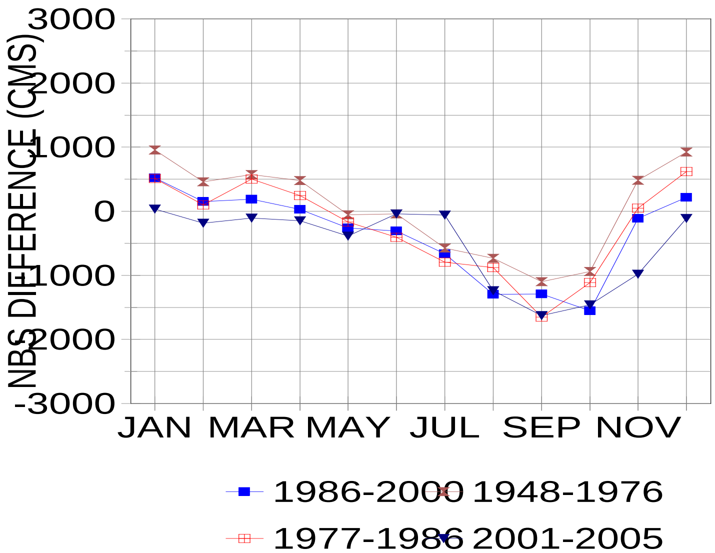

Figure 20. Average monthly differences between the component and residual NBS.

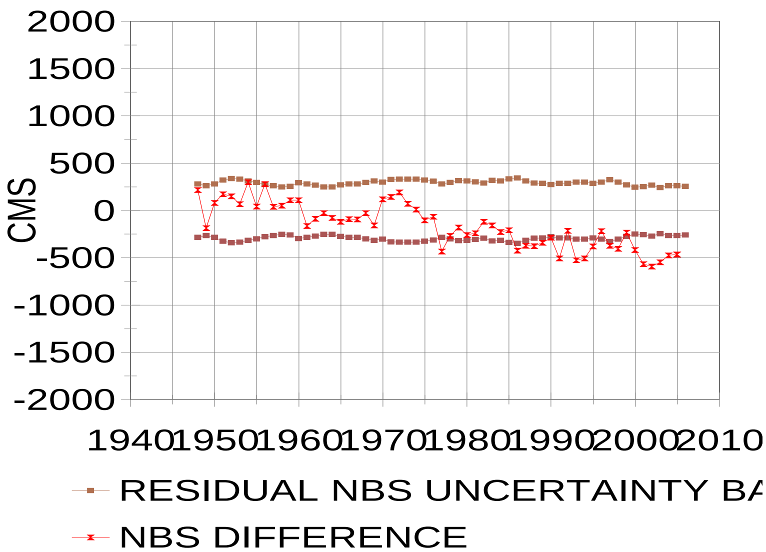

Figure 21. Annual residual uncertainty analysis.

The final step is to conduct a full uncertainty analysis including uncertainty in the change-in-storage. The uncertainty is defined as plus or minus one standard deviation of the variable or the confidence interval of the variable (95 percentile) divided by 1.96 to convert to one standard deviation. Confidence estimates for the Lake Michigan-Huron water balance are given in Neff and Nicholas, 2005. Mean values of the low and high estimates were used for the St. Marys and St. Clair River flows, the precipitation, the runoff, and the evaporation. Based upon the analysis of the uncertainty in Appendix 1, average standard deviations of 1 to 3 cm are used in this analysis for monthly values and 50 mm for annual values. Note that this would change the average uncertainty of the residual computations from Neff and Nicholas (2005). This again confirms the necessity of carefully examining the beginning-of-month levels and change-in-storage.

The NBS uncertainty limits are computed by taking the square root of the sum of the individual components standard deviations squared. Figures 22 through 25 show the uncertainty of the NBS differences compared with the residual and component NBS uncertainty bounds on a monthly and annual basis. Figures 22 and 24 show that the NBS differences for the period from 1986 to present fall outside the uncertainty bands for both residual and component NBS. Figure 23 shows the monthly NBS differences for August through October fall outside the residual NBS monthly uncertainty bands. Figure 25 shows only August through October falling outside the component uncertainty bands.

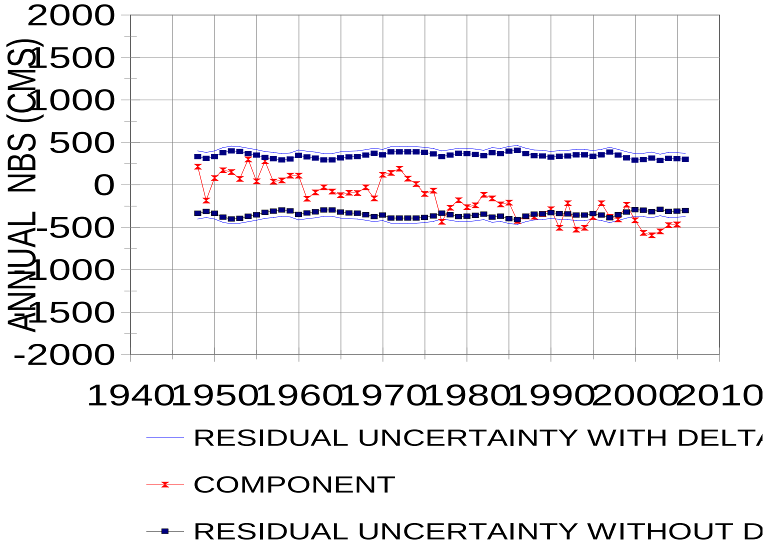

Figure 22. Annual average NBS difference compared with the residual NBS uncertainty.

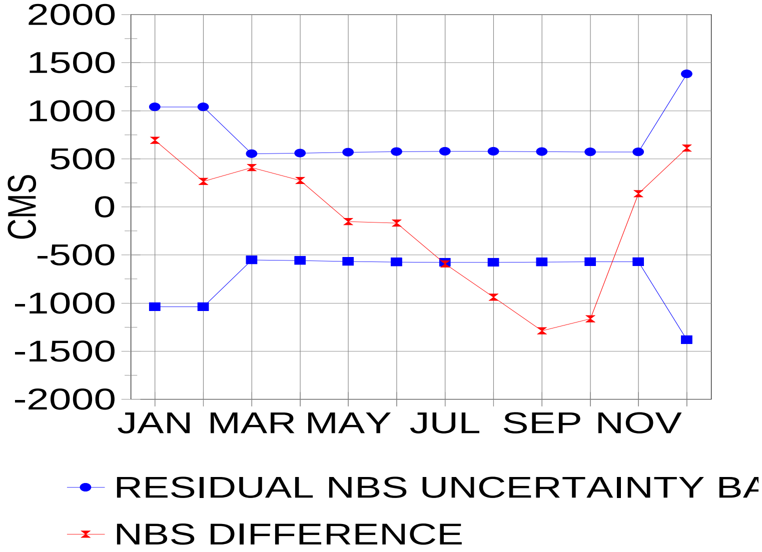

Figure 23. Monthly average NBS difference compared with the residual NBS uncertainty.

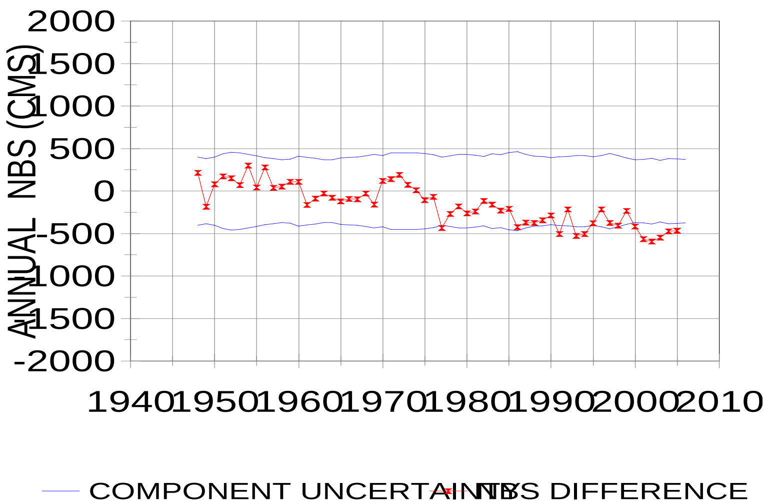

Figure 24. Annual average NBS difference compared with the component NBS uncertainty.

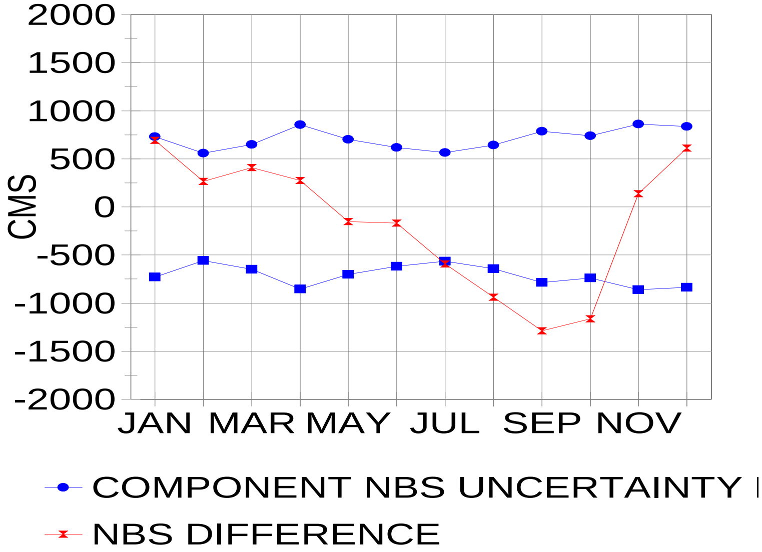

Figure 25. Monthly average NBS difference compared with the residual NBS uncertainty.

Conclusions

There are significant differences between the residual and component NBS depending upon the month and the time periods involved. The time series can be broken up into four components, 1948-1976, 1977-1986, 1987-2000, and 2001-2005. The component and residual NBS are equivalent for all time series on an annual basis. The largest differences in the monthly means between the two procedures are in the months of July – November and January with the largest differences between the residual and component NBS occurring in August, September, and October. The differences between the four time series may be due to flow coordination for the St. Clair River, differing precipitation and runoff gauges, and changes in evaporation computations, among other items. Some of the ongoing studies may help to resolve some of these issues.

One of the major problems in the residual NBS computations is the computation of the beginning-of-month water levels and the resulting changes in storage. This component accounts for the vast majority of variation in the residual computations. The high correlation between the average monthly residual and component NBS and the beginning-of-month water levels indicate unknown factors influencing the computations. This could be due to unaccounted thermal expansion, water level gauge networks not adequately accounting for the true change in water levels, the averaging periods for the beginning-of-month level computations, etc. This is particularly important as a one cm change is storage is equivalent to 445 cms, about nine percent of the St. Clair River monthly flow. Further analysis of this issue is a major requirement for increased understanding and improved accuracy of the residual computations.

While thermal expansion does have a small impact on the residual water levels, which may explain part of the monthly differences between the component and residual NBS, we do not have sufficient accurate data to proceed with any corrections to the residual NBS.

Finally, the uncertainty analysis indicates that the component NBS fall within the uncertainty of the residual NBS for the vast majority of months. This, however, does not explain the bias during the summer and fall. We may find some clues in the current ongoing studies.

Finally, I believe that we can use the component NBS in the climate and other ongoing studies. This will result in slightly higher Lake Michigan-Huron water levels and a modified seasonal cycle than would be expected using the coordinated beginning-of-month water levels. However with the component supplies we can examine the impact of changes in the climatic variables on the water levels of the Great Lakes.

Recommendations

1. A comprehensive analysis of the beginning-of-month water levels and their uncertainty should be undertaken for each of the Great Lakes.

2. An analysis of the reasons for the large differences between the component and residual NBS for the summer and early fall months needs to be undertaken. Thus analysis should be expanded to include the annual differences subsequent to 1986.

3. Final St. Clair and Detroit River flows have to be developed which will satisfy continuity at Lake St. Clair and fed back into the analysis.

4. The component and residual net basin supplies should be updated to reflect the ongoing studies on precipitation, runoff, and evaporation.

Lake Erie Net Basin Supply Comparison Analysis

Introduction

The purpose of this analysis is to compare the Lake Erie NBS calculated from both the residual and component methodology, to draw conclusions as to the use of the component NBS, and to make recommendations as to the use of the two techniques, the various uncertainties involved in the computations, and future changes to make the techniques more compatible.

Net Basin Supply Computation:

The water balance for Lake Erie is expressed as

$$P+R+Q_D = E+Q_N+D_W \pm \Delta S \qquad (1)$$

Where: P is the over-lake precipitation in cms
R is the runoff from the Michigan-Huron land basin into the lake in cms
E is the evaporation from the lake surface in cms.
Q_D is the Detroit River inflow in cms
Q_N is the Niagara River outflow in cms
D_W is the Welland Diversion out of the lake in cms
ΔS is the change in storage in cms, it includes thermal expansion

The net basin water supplies for Lake Erie can be computed directly by its components, Equation (2) or indirectly from the Lake Erie water balance, Equation (3).

$$NBS_C=P+R-E \qquad (2)$$

Where: NBS_C is the component net basin supply in cms

$$NBS_R= Q_N - Q_D +D_W \pm \Delta S \qquad (3)$$

Where: NBS_R is the residual net basin supply in cms

All analysis is based on a monthly time scale. It should be noted that the change-in-storage from the coordinated data is based upon a standard month of 30.4369 days and not the actual number of days in a month. The precipitation, runoff, and evaporation data are from Croley and Hunter (2008). The Detroit flow data, the Niagara River flow data, the diversion data, and the beginning-of-month levels and resulting change-in-storage data are the coordinated data from the Sharepoint files. Figures (1) and (2) show the monthly and annual averages for the component data for 1948-2006 (runoff through 2005), the period for which all data are available. Figures 3 and 4 show similar averages for the residual data

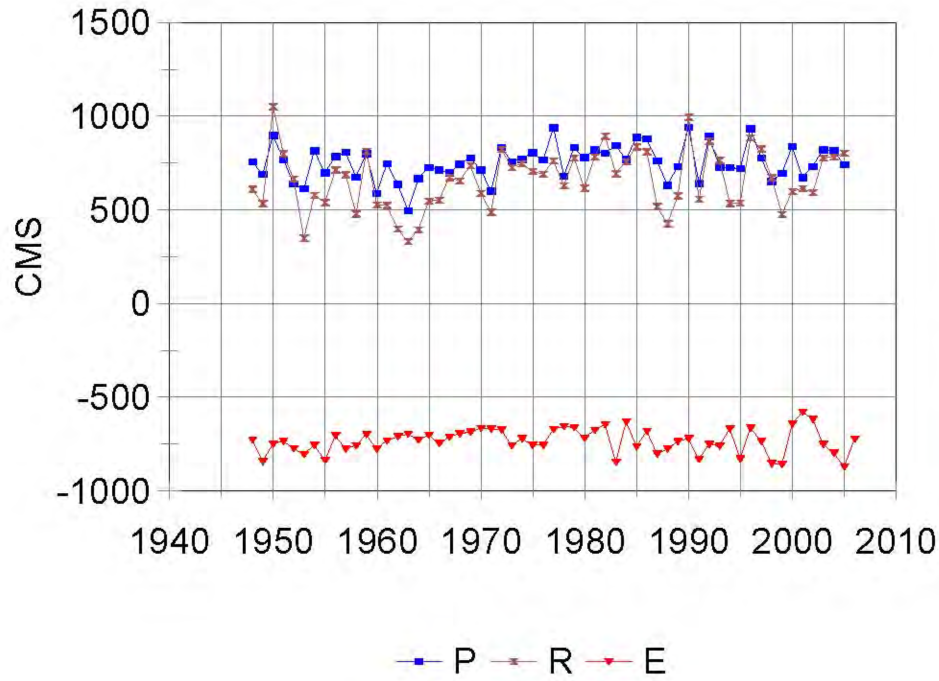

Figure 1. Average annual component data.

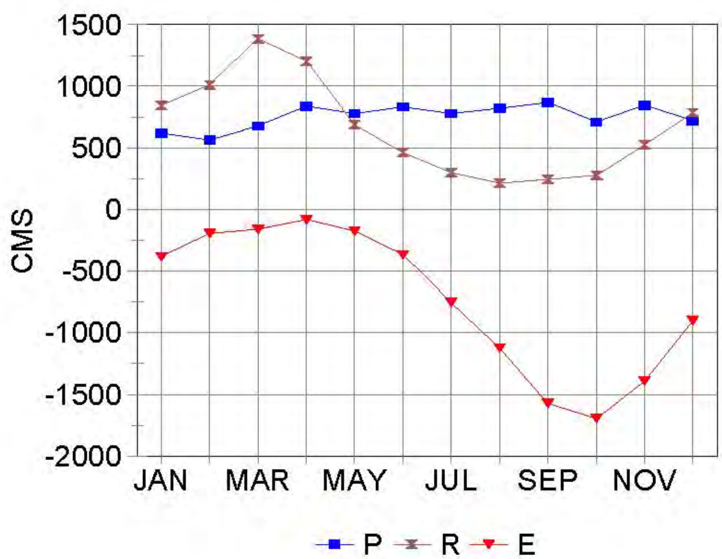

Figure 2. Average monthly component data.

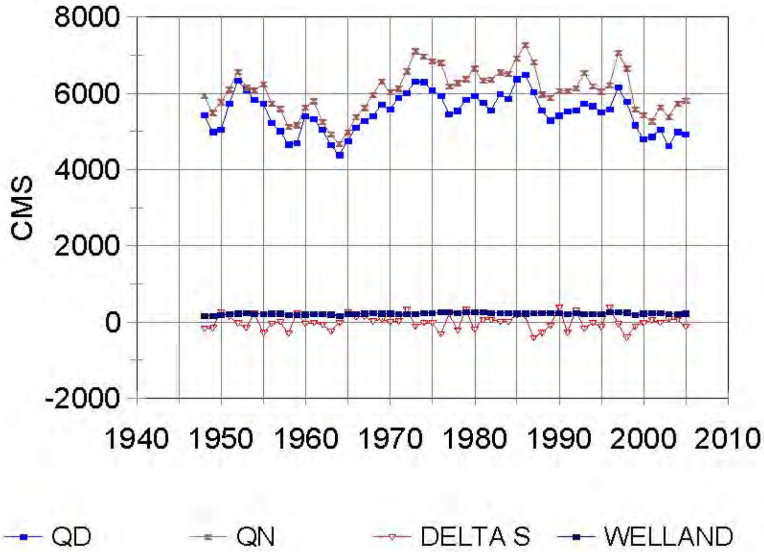

Figure 3. Average annual residual data.

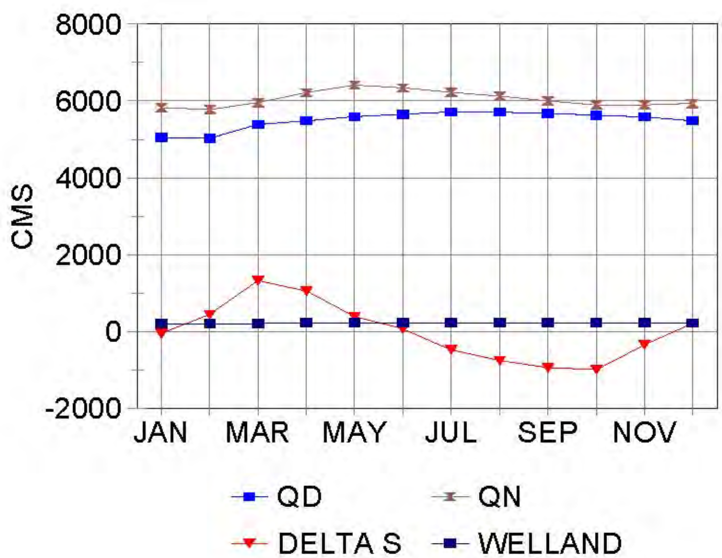

Figure 4. Average monthly residual data.

Figure 3 shows a marked divergence between the Niagara and Detroit River flows beginning around 1970. This dichotomy is shown in greater detail in Figure 5. The majority of this difference appears to be largely due to a long term increase in the annual component NBS of about 200 cms beginning about 1972. An additional factor is the differences in flow due to flow coordination.

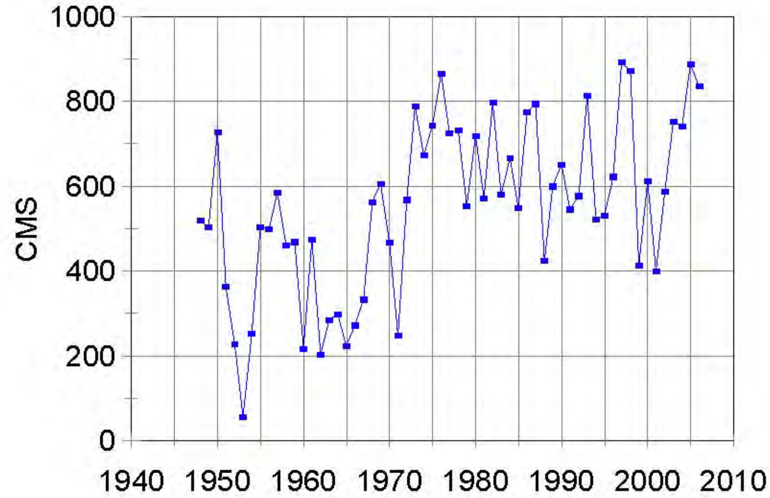

Figure 5. Annual differences between the Detroit and Niagara River flows.

Table 1 gives the monthly averages and standard deviations for all the major components. Figure 6 shows the standard deviations for all the components

Table 1. Average values and standard deviations in cms for all major components.

	P		R		E		QDET		QNIA	ΔS		
	AVE	STD	AVE	STD	AVE	STD	AVE	STD	AVE	STD	AVE	STD
JAN	619	260	843	606	382	138	5052	648	5823	663	-49	952
FEB	563	245	1010	551	193	101	5030	639	5777	630	441	806
MAR	678	251	1382	552	160	71	5386	570	5958	672	1326	751
APR	837	264	1200	397	83	75	5481	553	6211	691	1052	770
MAY	777	305	690	351	174	124	5591	507	6412	621	389	739
JUN	830	294	463	312	367	125	5652	512	6339	615	74	563
JUL	777	258	299	196	754	149	5716	515	6225	609	-472	456
AUG	822	324	214	141	1122	169	5704	522	6117	584	-754	437
SEP	868	363	243	211	1571	253	5675	526	5996	597	-938	542
OCT	709	334	278	231	1694	288	5626	528	5891	579	-986	578
NOV	846	314	526	384	1390	248	5584	521	5893	565	-337	754
DEC	720	223	786	483	899	172	5477	525	5931	624	221	759

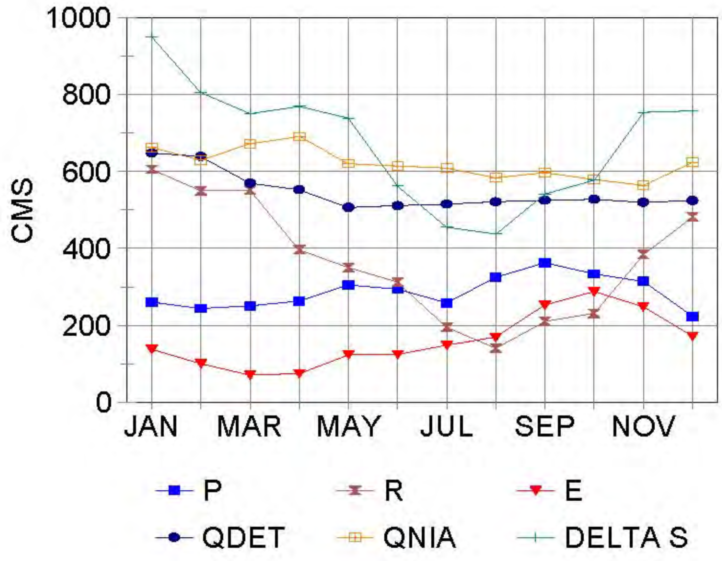

Figure 6. Standard deviation of monthly components

The most important comparisons are those of the monthly average components which show the range of values. Note that the change-in-storage has by far the largest seasonal variability of any of the other components in Figures 2 and 4. The second largest range is the monthly runoff.

Comparison between residual and component NBS

The next step will be to compare the component and residual net basin supplies and their differences on an annual and monthly basis. Figure 7 shows the difference between the two methods for the period of study. The figure shows a large amount of noise in the differences. The figure also shows a consistent regime between 1948 and 1959 followed by a stable regime with a positive bias, the residual NBS being larger than the component NBS, from 1960 through 2005. A 12 month running mean is shown in Figure 8 which also shows the change in regime about 1960. The figure also shows a major increase in variability over the last 10 years of the record. Figure 9 shows a comparison of the two methods using annual average data.

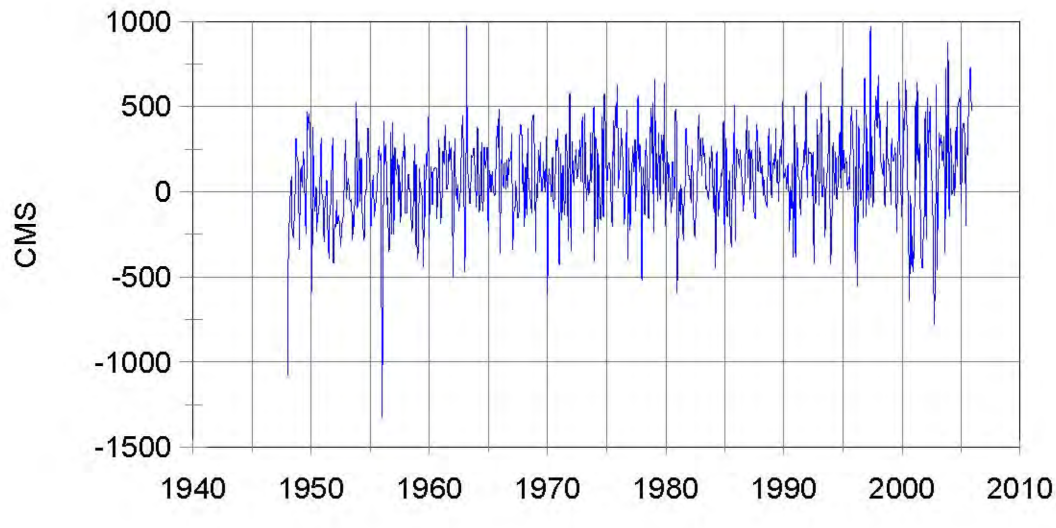

Figure 7. Monthly residual minus component differences

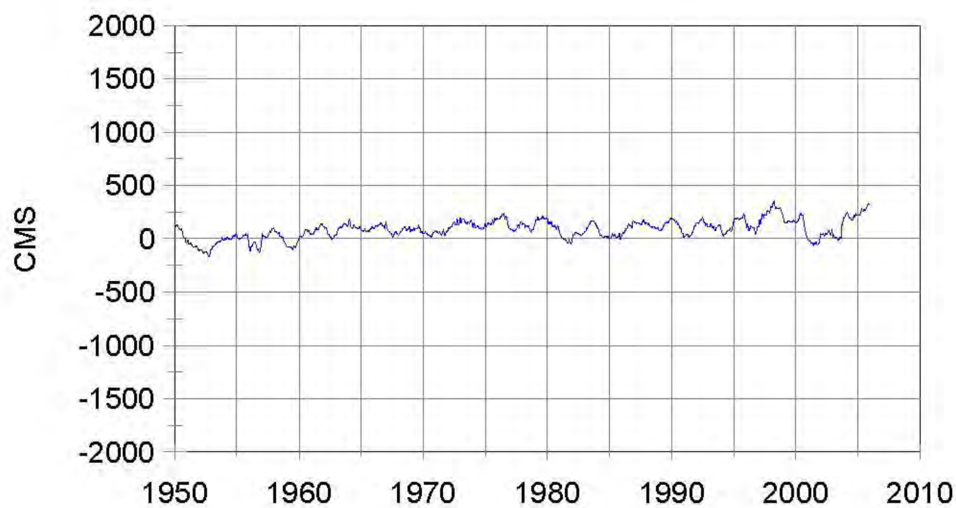

Figure 8. Monthly residual minus component differences (12 month running mean)

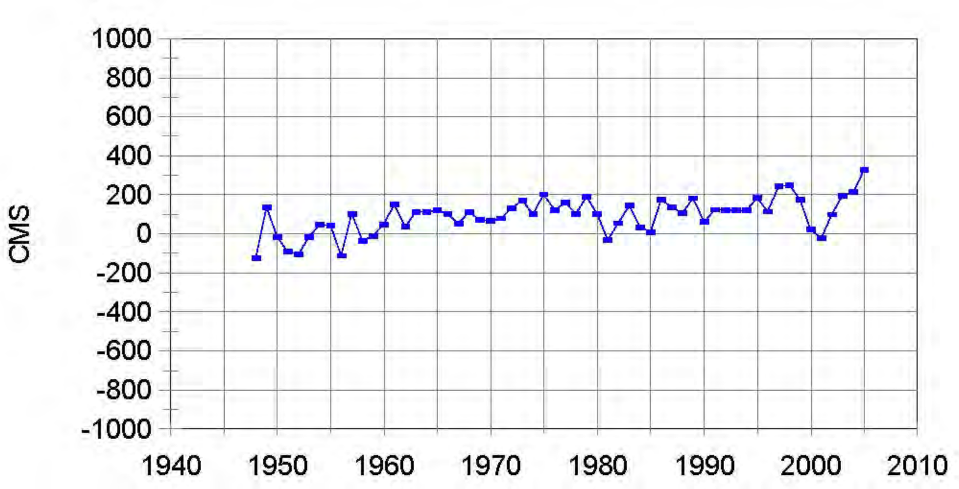

Figure 9. Annual mean differences of the residual minus the component NBS.

Based upon the preceding analysis, it was decided to break the time series into 2 segments, 1948-1959, and 1960-2005 for further analysis.

Table 2 gives the correlation coefficients between the NBS differences and the individual NBS components for various time periods. The high variability period of 1995-2005 is also broken out. Most notable is the correlations with the high variability period. Table 2 shows extremely high correlations between the annual differences, the Niagara River flows, and the evaporation. This indicates that the coordinated Niagara River flows may be responsible for much of the variability in the annual differences in the later period. It should also be noted that the evaporation is much more highly correlated with the differences than either the runoff or the runoff. The high correlation with the evaporation during the last period was also noted for the other lakes. This requires further investigation. The relatively high correlation with the Cleveland water level gauge is probably the result of the Niagara River flows being a direct function of the Lake Erie water level

Table 2. Correlation between the annual mean components and the differences between the residual and component NBS.

Component	r (1948-2005)	r (1948-1959)	r (1960-1994)	r (1995-2005)
precipitation	0.07	0.06	0.13	-0.11
runoff	0.04	-0.21	-0.12	0.31
evaporation	0.31	0.64	0.23	0.84
Detroit River flows	0.10	-0.29	0.12	0.34
Niagara River flows	0.50	0.17	0.30	0.75
Change-in-storage	-0.10	-0.03	-0.08	-0.40
Cleveland Gauge	0.18	-0.32	0.15	0.53

Welland Diversion	0.27	-0.12	0.07	0.06
Component NBS	0.03	-0.22	-0.02	-0.20
Residual NBS	0.32	0.32	0.19	0.20

Table 3 gives the t test and f test statistic for comparing the annual values of the component vs. the residual NBS.

Table 3. Paired T test and f test statistics for selected periods

Period	t test	f test	Mean Diff (cms)
1948-1959	0.56	0.95	-14
1959-2005	0.00	0.88	120

Table 3 shows that while the variance of the component NBS and the residual NBS are statistically the same at the 0.05 significance level, in only the period 1948-1959 are their means statistically the same at the 0.05 significance level. However, it should be noted that 120 cms is only about 2 percent of either the Detroit or Niagara River flows.

Monthly Analysis

Figures 10 and 11 show comparisons between the residual and component NBS for the two time series given in Table 3. The two figures show very complementary results for both time periods with the largest differences found in October through December. The most likely explanations would appear to be low evaporation or thermal expansion. Figure 12 shows the monthly NBS differences for the two time periods. The maximum differences are relatively small, only about 200 cms.

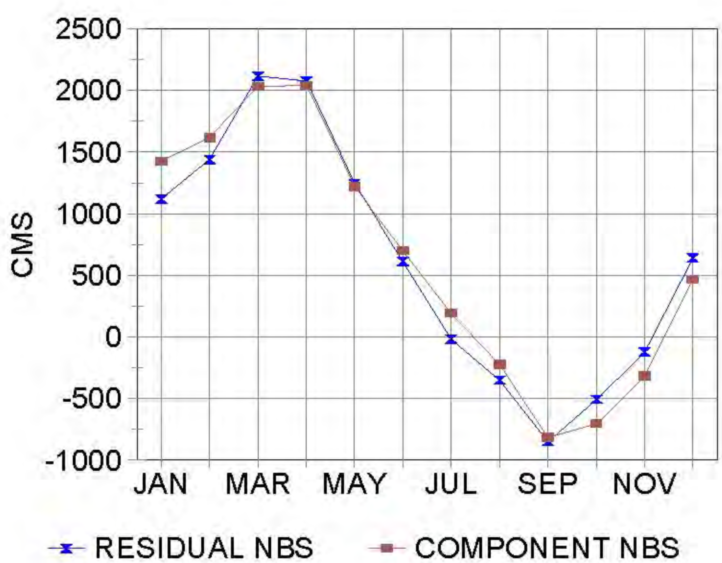

Figure 10. Monthly comparison of the residual and component NBS for the period 1948-1959.

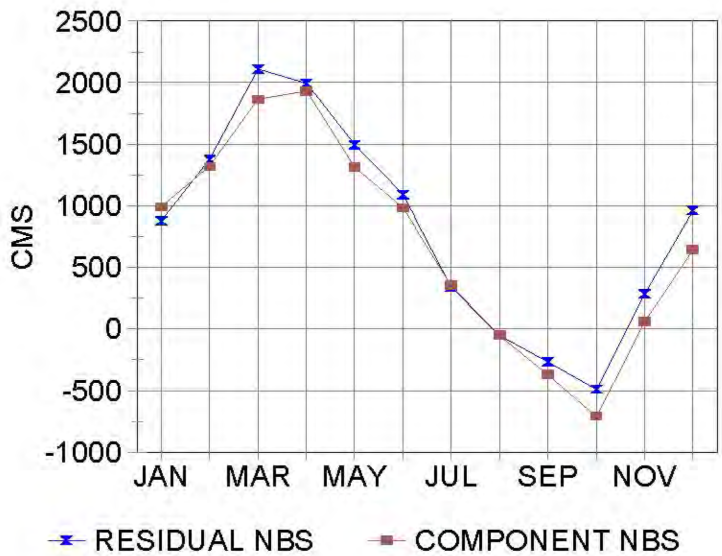

Figure 11. Monthly comparison of the residual and component NBS for the period 1960-2005.

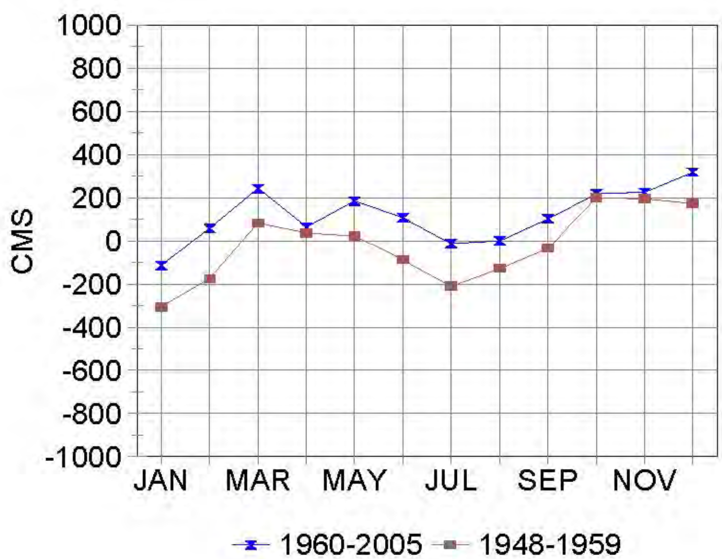

Figure 12. Monthly NBS differences (residual-component).

Tables 3 and 4 show the statistical comparison between the residual and component NBS for the four periods.

Table 3. Statistics of the 1948-1959 NBS Differences (Residual-Component). The average and standard deviation are given in cms.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual

ave	-306	-176	83	36	23	-88	-210	-129	-33	199	195	172	-15
std	427	291	170	100	149	112	160	130	198	137	239	236	82
f test	0.53	0.60	0.98	0.87	0.66	0.94	0.59	0.79	0.96	0.86	0.64	0.79	0.95
t test	0.04	0.07	0.13	0.25	0.62	0.03	0.00	0.01	0.59	0.00	0.02	0.03	0.56

Table 4. Statistics of the 1960-2005 NBS Differences (Residual-Component). The average and standard deviation are given in cms.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
ave	113	56	242	62	184	107	-13	0	103	219	225	319	52
std	301	219	200	194	203	160	153	174	220	281	278	247	73
f test	0.36	0.96	0.81	0.74	0.41	0.79	0.73	0.42	1.00	0.86	0.60	0.46	0.79
t test	0.01	0.09	0.00	0.04	0.00	0.00	0.58	0.99	0.00	0.00	0.00	0.00	0.04

Four statistical parameters are given for each of the time periods on a monthly basis. These are the average of the NBS differences, the standard deviation of the differences, the f test to compare the variances of the residual with the component NBS, and the paired t test to compare the two means. The monthly f tests for both periods show equivalent variances at the 5 percent significance level. The monthly t tests for the period 1948-1959 show 5 months with equivalent means at the 5 percent significance level compared with 3 months for the period 1959-2005. The average annual values of both the residual and component NBS are equivalent at the 5 percent confidence level for only the period 1948-1959. As will be illustrated later, the NBS are basically equivalent when examining their uncertainties.

Tables 5 and 6 show the correlations between the differences of the NBS methods and the various components. Table 5 shows low correlations between both the residual and component NBS and the differences for both periods.

Table 5. Correlation analysis of the differences of the residual and component NBS with the residual and component NBS for the monthly average data.

	Time period	
	1948-1959	1960-2005
Component	-0.25	-0.02
Residual	-0.06	0.18

Table 6. Correlation analysis between the differences of the residual and component NBS with the various components.

	Time period	
	1948-1959	1960-2005

Precipitation	-.02	-0.18
Runoff	0.10	-.48
Evaporation	0.20	0.08
Detroit Flows	-0.04	-.29
Niagara Flows	-0.19	-.46
ΔS	0.15	-0.15
BOM Level	-.21	-0.49
Welland	0.04	-.33

Table 6 shows low correlations for all components for the period 1948-1959. The period 1960-2005 shows relatively high correlations with the Niagara River flows, the runoff, and the beginning-of-month water levels, with slightly lower correlations with the Detroit River flows and the Welland Diversion. The beginning-of-month levels are also related to the Niagara River flows as the flows are a direct function of the lake level.

Thermal Expansion

The thermal expansion of the water mass can have a major impact on the computation of the residual NBS. The change-in-storage of Equation (1) can be expressed as:

$$\Delta S = \Delta S_m + \Delta S_t \qquad (4)$$

Where: ΔS_m is the change-in-storage due to a change in mass
ΔS_t is the change-in-storage to thermal expansion

The impact of thermal expansion on the Lake Erie water balance has been addressed by Meredith (1975) and Quinn and Guerra (1986). The results are summarized in Table 9. For Lake Erie the monthly values that should be subtracted from the change-in-storage to eliminate the effects of thermal expansion and contraction range from a positive 131 cms in June to a negative 93 cms in November. Figure 13 shows the monthly average change-in-storage compared with the effects of thermal expansion. It shows that much of the difference between the NBS time series for the months of September through November may be caused by thermal contraction.

Table 9 Monthly mean change-in-Storage due to thermal expansion and contraction (cms)

Month	Change-in-Storage Meredith (1975)	Change-in-Storage Quinn (1986)
January	11	17
February	1	-1
March	-10	-15
April	-1	4

May	33	92
June	102	131
July	106	73
Aug	16	-18
September	-92	-105
October	-91	-73
November	-72	-93
December	-5	-15

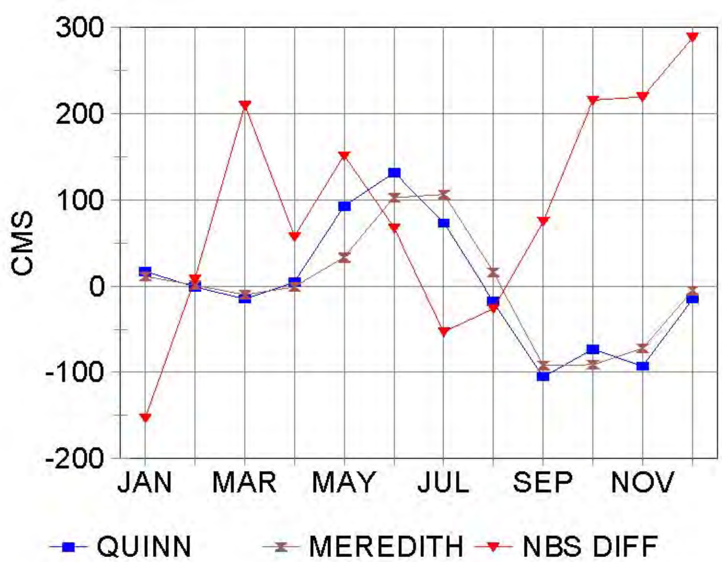

Figure 13. Monthly average thermal change-in-storage compared with the NBS difference

Uncertainty/error analysis

The final step in this study is to conduct a full uncertainty analysis including uncertainty in the change-in-storage. The uncertainty is defined as plus or minus one standard deviation of the variable or the confidence interval of the variable (95th percentile) divided by 1.96 to convert to one standard deviation. Confidence estimates for the Lake Erie water balance are given in Neff and Nicholas, 2005. Mean values of the low and high estimates were used for the Detroit and Niagara River flows, the precipitation, the runoff, and the evaporation. Based upon the analysis of the uncertainty in Appendix 3, average standard deviations of 2 cm are used in this analysis for monthly values and 3 cm for annual values. Note that this would change the average uncertainty of the residual computations from Neff and Nicholas (2005). This again confirms the necessity of carefully examining the beginning-of-month levels and change-in-storage.

The NBS uncertainty limits are computed by taking the square root of the sum of the individual components standard deviations squared. Figures 14 through 17 show the uncertainty of the NBS differences compared with the residual and component NBS uncertainty bounds on a monthly and annual basis. We would expect the uncertainty in the residual NBS for Lake Erie will be relatively large as the NBS is, in essence, a small difference between two large numbers, the Detroit and Niagara River flows. Figures 14 and 16 indicate the annual NBS differences for the entire time series falling inside the uncertainty bands for both residual and component NBS. Figures 15 and 17 indicate the monthly NBS differences to fall well within the residual uncertainty bands for all months while being at the margins for the component uncertainty bands.

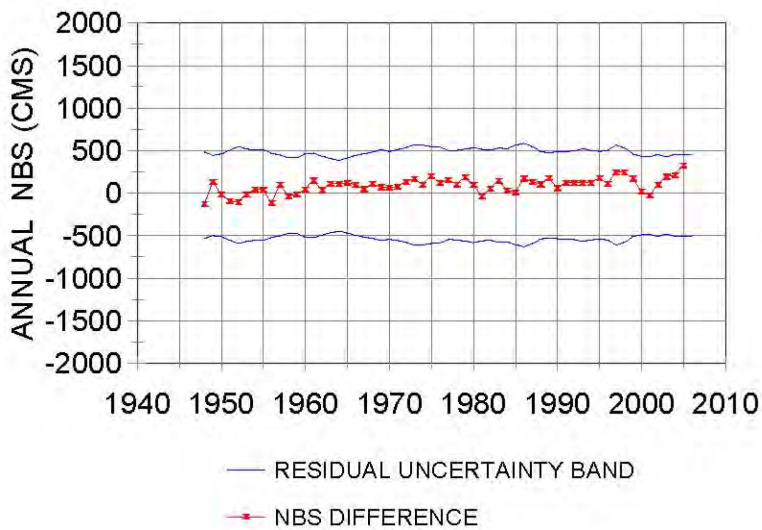

Figure 14. Annual average NBS difference compared with the residual NBS uncertainty.

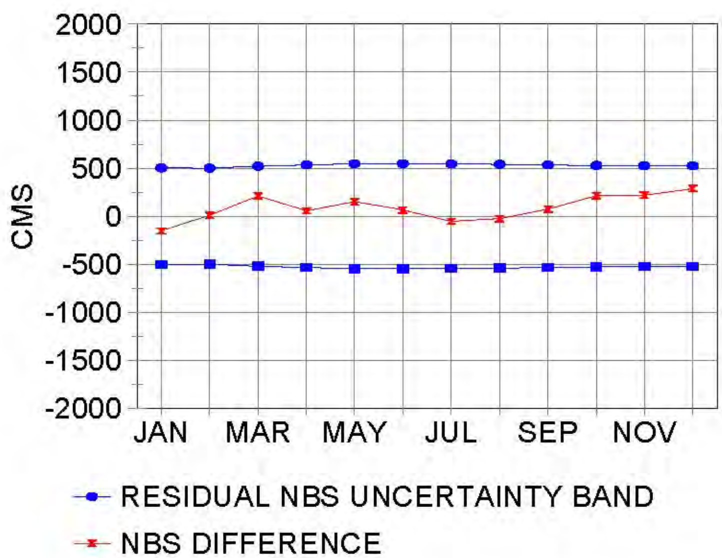

Figure 15. Monthly average NBS difference compared with the residual NBS uncertainty.

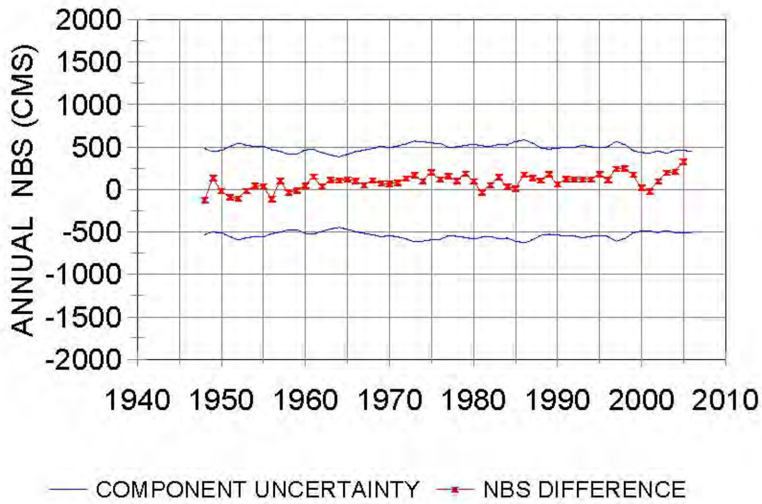

Figure 16. Annual average NBS difference compared with the component NBS uncertainty.

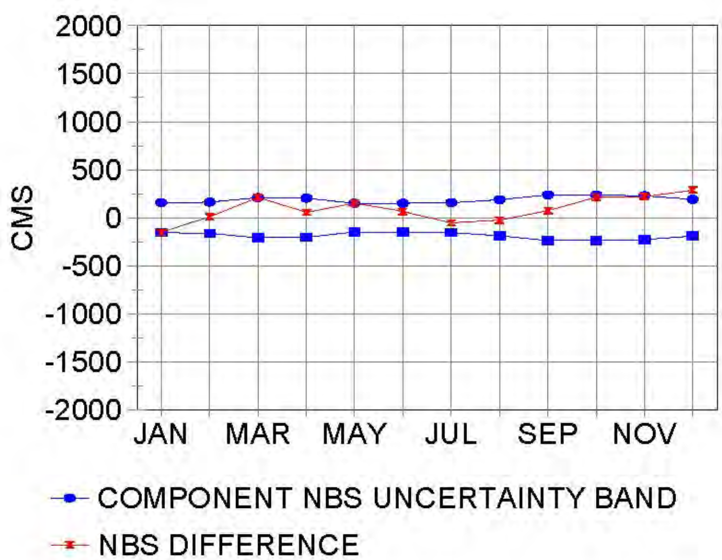

Figure 17. Monthly average NBS difference compared with the component NBS uncertainty.

Conclusions

The component NBS can be used interchangeably with the residual NBS for Lake Erie. Their use will only require minor changes in the coordinated Detroit or Niagara River flows, well within their uncertainty values. These flow values are currently being addressed in other studies and the resulting values may decrease the differences between the component and residual NBS time series. The relatively high differences in September through November appear to be the result of thermal contraction in the fall.

Two areas highlighted by this study that need further investigation are the Niagara River flows and the lake evaporation for the period 1995-2005. The NBS analysis for both Lakes Michigan-Huron and Superior also recommended that further effort be expended to examine the evaporation during this time. The very high correlation between the differences of the component and residual NBS with the Niagara River flows for this period, and not the other periods, indicate further analysis is required.

Finally, I believe that the Lake Erie component NBS are well suited for use in the climate and other ongoing studies on Lake Erie. They can also be used to assist in balancing the water balance of Lake St. Clair and resolving the dichotomy between the St. Clair and Detroit River Flows.

Recommendations

1) A comprehensive analysis of the beginning-of-month water levels and their uncertainty should be undertaken for each of the Great Lakes. As a start, all water level gauges should be used with appropriate weighting factors to compute beginning of month levels.

2) The evaporation rates need to be carefully re-evaluated for the period 1995-2005.

3) The Niagara River flows for the period 1995-2005 need to be re-assessed in light of the variability in the residual NBS.

4) Final St. Clair and Detroit River flows have to be developed which will satisfy continuity at Lake St. Clair and feed back into the analysis.

5) The component and residual net basin supplies should be updated to reflect the ongoing studies on precipitation, runoff, and evaporation.

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Appendix 1

Lake Superior Beginning-Of-Month Levels analysis

Frank H. Quinn

Introduction

Beginning-of-month water levels are important components of the Lake Superior water balance, being used to determine the amount of water stored in the lake during any given month. Equation (1) shows the change-in-storage relationship. The beginning-of-month level for any gauge is defined as the level at 12:00:00 a.m. (midnight) on the first day of that month. Practically, however, representative instantaneous water levels are difficult, if not impossible, to measure because of short term fluctuations in wind speed and direction and changes in barometric pressure over small time periods. These fluctuations could cause considerable error in computing a true instantaneous level for the lake. It is the current standard practice to compute the value by averaging the daily mean level for the last day of the previous month with the daily mean level for the first day of the current month. However, the value could be also being based upon either the 6 hour or 12 hour average water levels before or after 12:00 am of the first day of the month. The two day average was established years ago before the advent of digital analysis. The resulting differences between the techniques have not been investigated, to my knowledge. It would be interesting to analyze the impact of changing the averaging period on the change-in-storage computations.

$$\Delta S = (BOM_{T+1} - BOM_T)\, A_L/\Delta t \qquad (1)$$

Where: BOM_{T+1} is the beginning-of-month level at the end of the month in m
BOM_T is the beginning-of-month level at the end of the month in m
A_L is the Lake Superior surface area in m2
Δt is the number of seconds in the month
ΔS is the change in storage during the month in cms.

The lake-wide beginning-of- month water levels are computed using a number of water level gauges located around the perimeter of the lake. The computational procedure is to use either straight averaging or apply weighting factors to each gauge used in the computations. The resulting values are a function of the number of gauges in the network and the averaging or weighting factors used in the computation (Quinn and Todd, 1974). There are currently five U.S. gauges and four Canadian gauges, Figure 1. The procedure used in deriving the coordinated beginning-of-month levels is to compute a straight average of water levels at the Duluth, Marquette, Thunder Bay, Michipicoten, and Point Iroquois gauges. The GLERL beginning-of-month levels employee a Theissen Polygon network using all available gauges (Croley and Hunter, 1994). This analysis will only address the coordinated procedure.

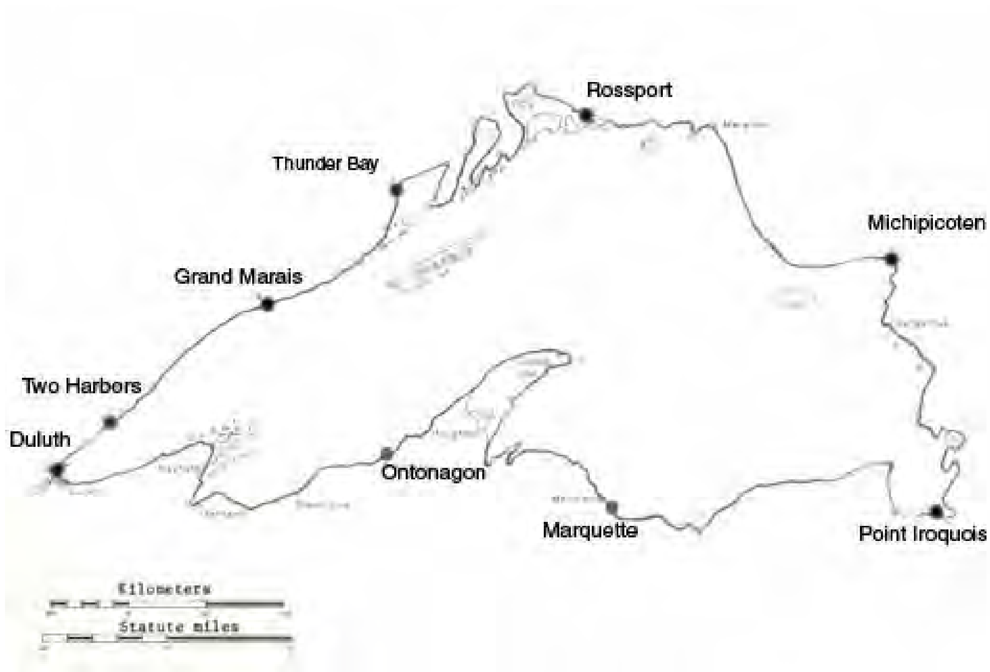

Figure 1. Lake Superior water level gauge locations.

Uncertainty Analysis

As part of the comparison between the component and residual Lake Superior net basin water supplies, it is necessary to conduct an uncertainty analysis on the change-in-storage component of the water balance. This in turn also requires an uncertainty assessment of the beginning-of-month water levels. Neff and Nicholas (2005) in their assessment of uncertainty in the Great Lakes water balance note that there is no official statement of uncertainty in the data but that they are adequate to calculate change-in-storage on the Great Lakes.

Uncertainty in the beginning-of-month water levels is due to three components:

1) The accuracy of the water level measurements
2) Does the two-day average reflect the true instantaneous level of the lake at each water level gauge?
3) Does the average of the five gauges truly reflect the lake-wide average level?

The accuracy of the water level gauges is not a significant issue. Neff and Nicholas (2007) indicate the uncertainty due to the measurements alone to be about 3mm. The other aspects are much more significant. Quinn and Todd (1974) show, for example, that the difference between weighted and averaged beginning-of-month levels for the five gauge network to average about 3 mm but with a standard deviation of 1 cm and a maximum difference of 4 cm. This is equivalent to about 1300 cms for a month.

My approach was to use the beginning-of-month levels in Quinn and Todd (1974) for the years of 1966 through 1972 to examine the standard deviations of the five gauge beginning-of-month levels and the resulting changes-in-storage. A longer period of analysis might yield slight changes, but would require a comprehensive study which could be coupled with an analysis of the averaging periods. However, this is beyond the scope of this study. Tables 1-5 list the beginning-of month water levels for each gauge. Table 6 lists the standard deviations for the five gauge averages. Table 6 lists the beginning-of-month levels for the lake-wide average values. Table 8 lists the data corrected so that each gauges would have the same average annual level as Marquette. Any gauge could be used as the base case. The purpose was to eliminate glacial isostatic adjustment and secondary factors (i.e., prevailing winds, barometric pressure influences, etc.) from the variability analysis. Table 9 lists the change-in-storage data computed from the beginning of month data.

Table 1. Point Iroquois beginning-of-month water levels (m)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1966	183.42	183.36	183.27	183.28	183.34	183.48	183.49	183.52	183.54	183.52	183.53	183.50
1967	183.33	183.31	183.23	183.21	183.34	183.42	183.50	183.50	183.56	183.43	183.43	183.33
1968	183.33	183.20	183.16	183.20	183.32	183.38	183.53	183.72	183.72	183.80	183.74	183.61
1969	183.68	183.58	183.49	183.43	183.48	183.52	183.60	183.59	183.60	183.50	183.45	183.46
1970	183.30	183.28	183.21	183.19	183.28	183.46	183.52	183.63	183.61	183.61	183.61	183.56
1971	183.47	183.46	183.46	183.37	183.52	183.63	183.71	183.68	183.64	183.59	183.65	183.60
1972	183.50	183.48	183.42	183.43	183.47	183.58	183.58	183.65	183.73	183.73	183.60	183.60

Table 2. Marquette beginning of month water levels (m)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1966	183.36	183.30	183.21	183.25	183.33	183.41	183.45	183.50	183.53	183.49	183.46	183.40
1967	183.33	183.27	183.21	183.19	183.34	183.39	183.48	183.50	183.52	183.43	183.42	183.35
1968	183.30	183.23	183.14	183.15	183.47	183.37	183.57	183.70	183.74	183.77	183.73	183.58
1969	183.54	183.54	183.47	183.38	183.48	183.55	183.58	183.58	183.58	183.49	183.45	183.42
1970	183.31	183.24	183.17	183.14	183.26	183.46	183.53	183.62	183.58	183.59	183.62	183.61
1971	183.52	183.47	183.47	183.42	183.50	183.63	183.70	183.69	183.68	183.63	183.62	183.60
1972	183.46	183.45	183.41	183.40	183.45	183.56	183.58	183.65	183.72	183.72	183.62	183.56

Table 3. Duluth beginning of month water levels (m)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1966	183.29	183.20	183.15	183.20	183.26	183.37	183.43	183.44	183.50	183.37	183.34	183.22
1967	183.28	183.20	183.19	183.17	183.39	183.35	183.44	183.47	183.45	183.42	183.39	183.35
1968	183.22	183.20	183.06	183.06	183.25	183.34	183.51	183.63	183.69	183.70	183.71	183.57
1969	183.42	183.50	183.44	183.35	183.49	183.54	183.51	183.49	183.51	183.46	183.43	183.32
1970	183.29	183.17	183.14	183.08	183.18	183.41	183.49	183.56	183.53	183.55	183.64	183.62
1971	183.52	183.34	183.33	183.42	183.47	183.61	183.64	183.65	183.68	183.65	183.52	183.54
1972	183.42	183.39	183.38	183.36	183.48	183.52	183.52	183.59	183.66	183.67	183.59	183.46

Table 4. Thunder Bay beginning of month water levels (m)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC

1966	183.37	183.27	183.25	183.28	183.31	183.42	183.49	183.49	183.55	183.45	183.40	183.32
1967	183.32	183.28	183.24	183.24	183.38	183.40	183.52	183.54	183.55	183.49	183.49	183.43
1968	183.29	183.23	183.15	183.17	183.32	183.41	183.61	183.74	183.77	183.81	183.80	183.68
1969	183.56	183.59	183.52	183.43	183.55	183.61	183.61	183.61	183.60	183.53	183.50	183.40
1970	183.35	183.30	183.24	183.18	183.29	183.48	183.58	183.67	183.62	183.61	183.70	183.69
1971	183.59	183.43	183.43	183.46	183.51	183.65	183.71	183.74	183.71	183.68	183.64	183.60
1972	183.54	183.44	183.40	183.43	183.49	183.60	183.61	183.65	183.74	183.71	183.61	183.51

Table 5.Michipicoten beginning of month water levels (m)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1966	183.43	183.37	183.30	183.33	183.36	183.49	183.51	183.54	183.59	183.53	183.55	183.53
1967	183.42	183.36	183.30	183.29	183.39	183.44	183.54	183.52	183.57	183.46	183.48	183.40
1968	183.36	183.21	183.19	183.25	183.35	183.40	183.60	183.75	183.76	183.82	183.80	183.68
1969	183.69	183.61	183.54	183.47	183.51	183.55	183.62	183.62	183.63	183.51	183.48	183.44
1970	183.31	183.34	183.24	183.21	183.29	183.46	183.52	183.66	183.61	183.61	183.67	183.65
1971	183.56	183.51	183.58	183.50	183.55	183.65	183.73	183.73	183.68	183.67	183.71	183.63
1972	183.57	183.50	183.41	183.47	183.48	183.59	183.61	183.67	183.76	183.75	183.64	183.60

Table 6. Lake Superior Beginning-of-month levels (based on 5 gauge mean) (m)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1966	183.37	183.30	183.24	183.27	183.32	183.43	183.48	183.50	183.54	183.47	183.46	183.39
1967	183.34	183.28	183.23	183.22	183.37	183.40	183.49	183.51	183.53	183.45	183.44	183.37
1968	183.30	183.21	183.14	183.17	183.34	183.38	183.57	183.71	183.74	183.78	183.76	183.63
1969	183.58	183.56	183.49	183.41	183.50	183.55	183.58	183.58	183.58	183.50	183.46	183.41
1970	183.31	183.26	183.20	183.16	183.26	183.45	183.53	183.63	183.59	183.60	183.65	183.63
1971	183.53	183.44	183.45	183.44	183.51	183.64	183.70	183.70	183.68	183.64	183.63	183.59
1972	183.50	183.45	183.41	183.42	183.48	183.57	183.58	183.64	183.72	183.72	183.61	183.55

Table 7. Standard deviation of the 5 gauge average beginning-of-month level (m)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1966	0.05	0.06	0.05	0.04	0.03	0.04	0.03	0.03	0.03	0.06	0.08	0.11
1967	0.05	0.05	0.04	0.04	0.02	0.03	0.03	0.02	0.04	0.02	0.04	0.04
1968	0.05	0.01	0.05	0.06	0.07	0.03	0.04	0.04	0.03	0.04	0.04	0.05
1969	0.10	0.04	0.04	0.04	0.02	0.03	0.04	0.05	0.04	0.02	0.02	0.05
1970	0.02	0.06	0.04	0.04	0.04	0.03	0.03	0.04	0.03	0.02	0.03	0.04
1971	0.04	0.06	0.08	0.04	0.03	0.01	0.03	0.03	0.02	0.03	0.06	0.03
1972	0.05	0.04	0.01	0.04	0.01	0.03	0.03	0.03	0.03	0.03	0.02	0.06
Ave	0.05	0.05	0.04	0.05	0.03	0.03	0.03	0.04	0.03	0.03	0.04	0.05
Max	0.10	0.06	0.08	0.06	0.07	0.04	0.04	0.05	0.04	0.06	0.08	0.11

Table 8. Standard deviation of the 5 gauge average beginning-of-month level adjusted for annual level differences (m)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1966	0.01	0.03	0.02	0.01	0.01	0.01	0.02	0.01	0.01	0.03	0.04	0.08
1967	0.02	0.02	0.01	0.02	0.04	0.01	0.01	0.02	0.01	0.03	0.02	0.04
1968	0.03	0.03	0.02	0.04	0.07	0.01	0.02	0.01	0.01	0.02	0.02	0.03
1969	0.07	0.01	0.01	0.01	0.03	0.04	0.01	0.02	0.01	0.02	0.02	0.03
1970	0.02	0.03	0.01	0.02	0.02	0.01	0.02	0.01	0.01	0.01	0.03	0.04

1971	0.04	0.04	0.06	0.04	0.00	0.01	0.01	0.02	0.03	0.04	0.04	0.01
1972	0.04	0.02	0.02	0.02	0.03	0.02	0.03	0.02	0.02	0.01	0.03	0.03
Ave	0.03	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.03	0.04
max	0.07	0.04	0.06	0.04	0.07	0.04	0.03	0.02	0.03	0.04	0.04	0.08

Table 9. Standard deviation of change-in-storage of the 5 gauge network (m).

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1966	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.04	0.03	0.04	0.08
1967	0.02	0.02	0.01	0.04	0.04	0.01	0.02	0.03	0.03	0.01	0.02	0.02
1968	0.05	0.04	0.02	0.08	0.07	0.02	0.02	0.02	0.03	0.03	0.02	0.03
1969	0.07	0.01	0.01	0.04	0.01	0.04	0.01	0.01	0.02	0.01	0.04	0.10
1970	0.05	0.03	0.02	0.01	0.02	0.02	0.03	0.01	0.01	0.03	0.02	0.05
1971	0.07	0.03	0.07	0.04	0.02	0.02	0.02	0.03	0.02	0.07	0.03	0.05
1972	0.03	0.04	0.04	0.03	0.03	0.04	0.03	0.06	0.02	0.06	0.05	0.03
Ave	0.04	0.03	0.03	0.04	0.03	0.02	0.02	0.02	0.02	0.03	0.03	0.05
max	0.07	0.04	0.07	0.08	0.07	0.04	0.03	0.06	0.04	0.07	0.05	0.10

The uncertainty of the beginning-of-month levels can be taken as either the average standard deviation from Table 8 or assume that the 95 percent confidence limit is the maximum value in Table 8 and divide that by 1.96 (Neff and Nicholas, 2005). The first case would yield a value of 0.02 m, the highest value of the averages, and the second case would also yield a value of 0.04 m for December. The first case would yield an uncertainty value of 3 cm for the change-in-storage (the square root of the beginning and end-of-month uncertainty values squared and added together). The 2nd case would yield an uncertainty value of 6 cm, a very high unlikely value.

The corresponding values from Table 9 would yield uncertainty values of 0.03 m based on the average of the standard deviations or 0.07 m if December is used. Both Tables 8 and 9 indicate that an uncertainty value of 3 cm is appropriate based upon the computed beginning-of month water levels.

The Lake Superior Surface as a plane

It has been suggested that the Lake Superior fluctuates as a semi-level plane and that the five water level gauges represent the centroid of the lake. I have not come across any literature or studies backing this position. Figure 2 shows three case studies that show this not to be the case.

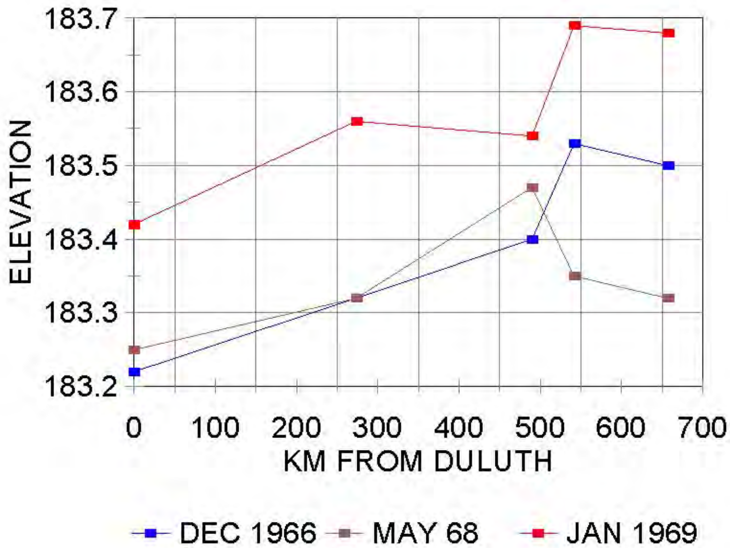

Figure 2. Beginning-of-month water levels along the axis of Lake Superior. The plotted points, from left to right are from the Gauges at Duluth, Thunder Bay, Marquette, Michipicoten, and Point Iroquois.

There are probably many examples of this type of behavior. The lake has many modes of oscillation which would induce the behavior shown above (Schwab, personal communication). This line of study should be continued in an extensive study of beginning-of-month water levels.

Conclusions

The above analysis provides an assessment of the uncertainty associated with the computation of the monthly rates of change-in-storage. This is particularly sensitive for Lake Superior where 0.01m in storage over a month is equivalent to a little over 300cms. The changes-in-storage were also found to have the highest correlation to the differences between the residual and component NBS than any other factor. Based on this assessment, I believe that ±3 cm is a good conservative value to use for the uncertainty in Lake Superior changes-in-storage. This is the value that will be used in my assessment of differences between the component and residual NBS. As noted before this assessment does not address how well the mean of the two days represents the true instantaneous values for the beginning-of-month levels.

References

Croley, T.E. II and T.S. Hunter. 1994. Great Lakes Monthly Hydrologic Data. GLERL Technical Report TM 083. Great Lakes Environmental Research Laboratory,

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

Quinn, F.H. and M.J. Todd. 1974. Lake Superior Beginning-of-Month Water Levels and monthly Rates of Storage Changes. NOAA Technical Memorandum NOS LSC R 4

Appendix 2

Methodology for Assessing Uncertainty in Change-in-Storage and Beginning-of-Month Levels for Lake Superior

Frank H. Quinn

The following is a proposed methodology for assessing uncertainty in beginning-of-month water levels and change-in-storages which appears to explain some of the differences between the coordinated and residual net basin supplies.

Change in storage from beginning-of-month levels.

The total change-in-storage can be computed as a residual from equation (1). The total change-in-storage includes both the mass change-in-storage and the change-in-storage due to thermal expansion. This is the methodology currently used for Great Lakes studies and is expressed as:

$$\Delta S_t = (BOM_{T+1} - BOM_T)\, A_L/\Delta t \qquad (1)$$

Where: BOM_{T+1} is the beginning-of-month level at the end of the month in m
BOM_T is the beginning-of-month level at the beginning of the month in m
A_L is the Lake Superior surface area in m2
Δt is the number of seconds in the month
ΔS_t is the total change in storage during the month in cms.

There has been very little work assessing the uncertainty involved is equation (1), with the exception of looking at the impact of network size and weightings (Quinn & Todd, 1974).

One possible methodology looking at the uncertainty with respect to the water level gauges used in the BOM computations is to compare the average of the BOM and EOM levels with the monthly mean. Because the storage computation assumes an average rate of change over a month, the average of the BOM and EOM levels should be the same as the monthly mean water level if the lake is uniformly rising or falling. If the NBS is front or back loaded the monthly mean will be either slightly higher or lower than the average of the BOM and EOM levels respectively. However, under nature the outflow would rise with a front loaded NBS and fall with a back loaded net basin water supply (NBS) thus tending to more closely approximate the monthly average lake level. Table 1 gives the monthly level comparison for the period 1951-2006, the period for the present gauging network. It is observed that there are monthly differences in the range of ±4 cm with an annual average range of 0 to -1 cm.

Two examples are given to illustrate the real world utility of the technique. April 1984 has a difference of 0.04m between the monthly mean elevation and the average of the BOM and EOM elevations. Figure 1 shows the increase in lake levels for the April 1984 coordinated NBS, St. Mary's flows and the Ogoki and Long Lac diversions. The figure shows both a uniform NBS and a front loaded NBS of a plus 25 percent for the first 15 days and a decrease of 25 percent of the monthly average for the last 15 days. The monthly average is also given. The differences in the monthly averages for the front and back loaded NBS are within 1 cm of the constant NBS.

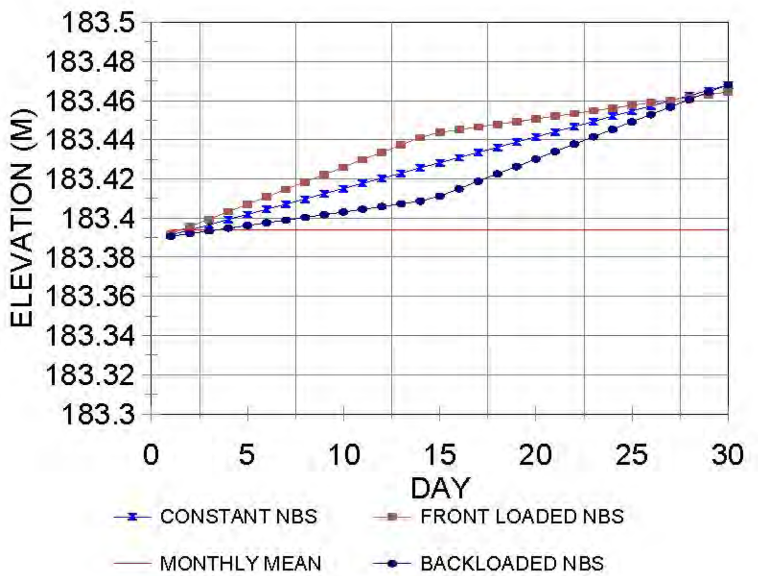

Figure 1. April 1984 daily average water level elevation with a constant, front loaded and back loaded NBS compared with the monthly mean. The beginning and ending elevations are the coordinated BOM levels.

It is also apparent that the computed elevations do not match the monthly mean leading to the observation that the BOM levels must be in error by a substantial amount. Figures 2-4, hourly water levels at the Duluth, Marquette, and Point Iroquois water level gauges, illustrate the difficulty in estimating BOM levels.

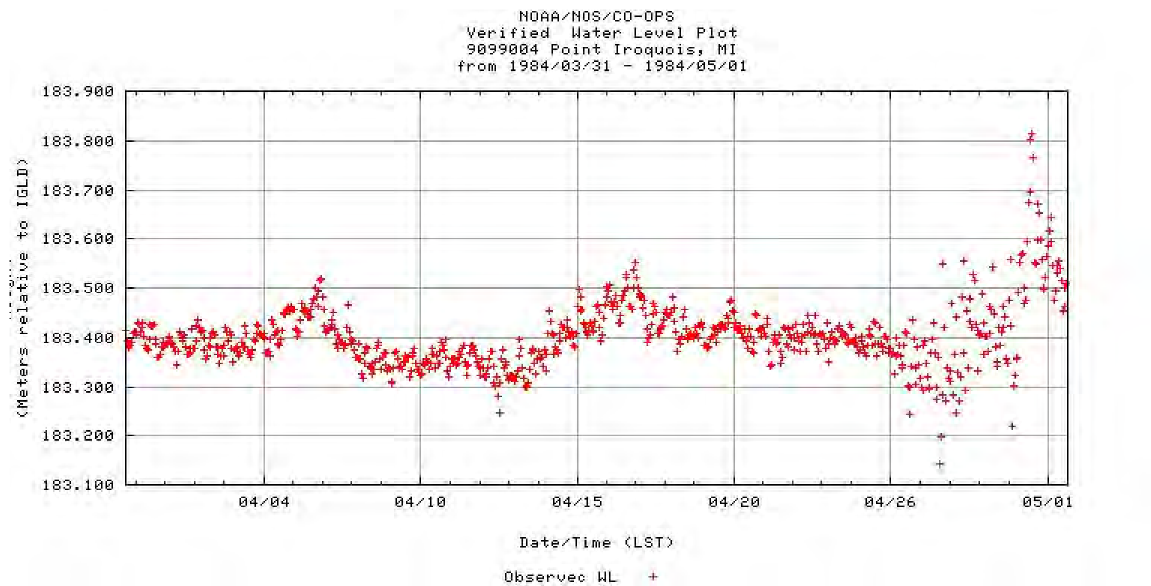

Figure 2. Hourly water levels at Point Iroquois.

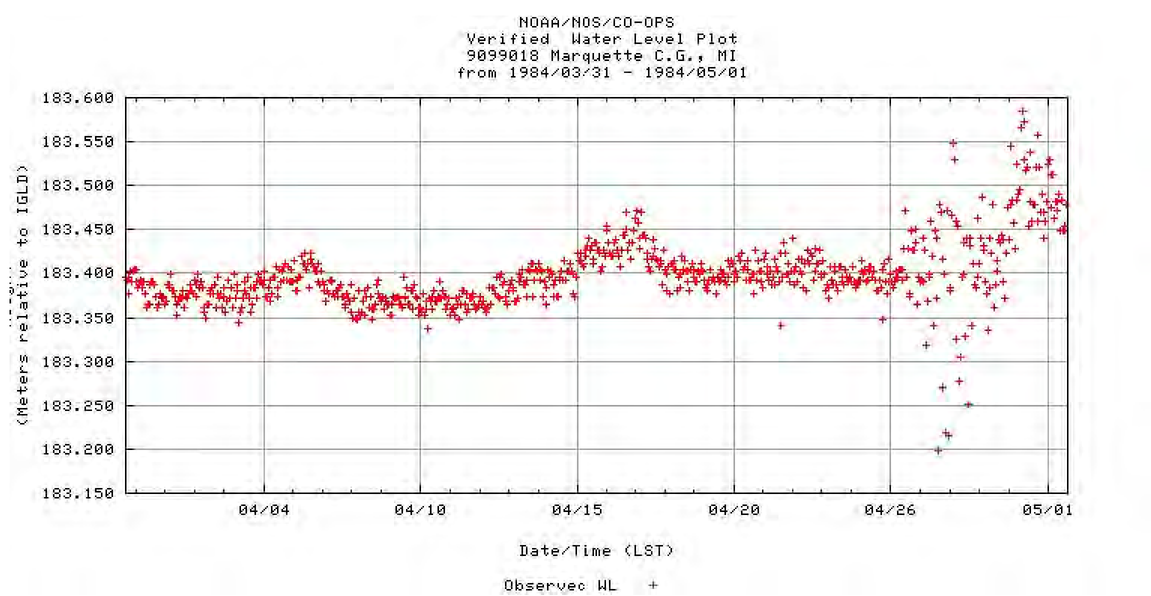

Figure 3. Hourly water levels at Marquette.

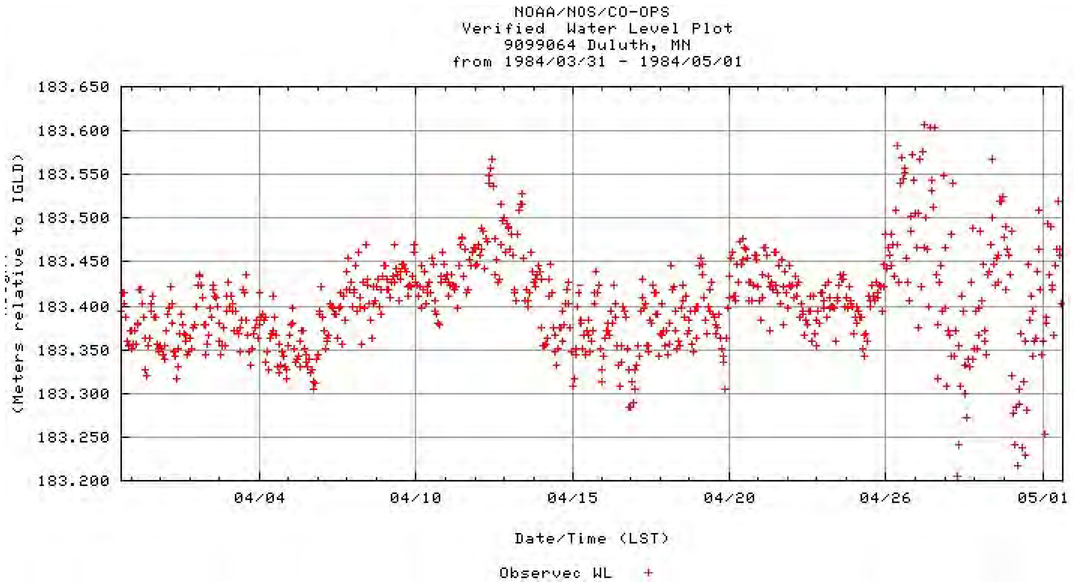

Figure 4. Hourly water levels at Duluth.

One can also observe that an uncertainty of 2+ cm in the beginning of month levels is very realistic.

The second example is for October 1985, illustrated by Figure 5. There is a clear 4 cm difference between the monthly mean and the mean of the BOM coordinated levels.

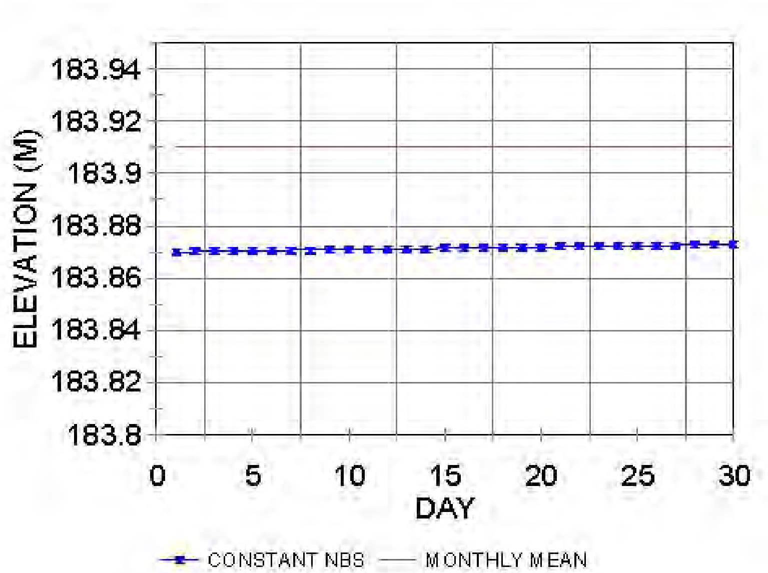

Figure 5. October daily average water level elevation with a constant NBS compared with the monthly mean. The beginning and ending elevations are the coordinated BOM level

Figures 6-8 illustrate the difficulty in estimating BOM levels. Again one or more of the BOM levels is obviously wrong. One can again observe that an uncertainty of 2+ cm in the beginning of month levels is very realistic.

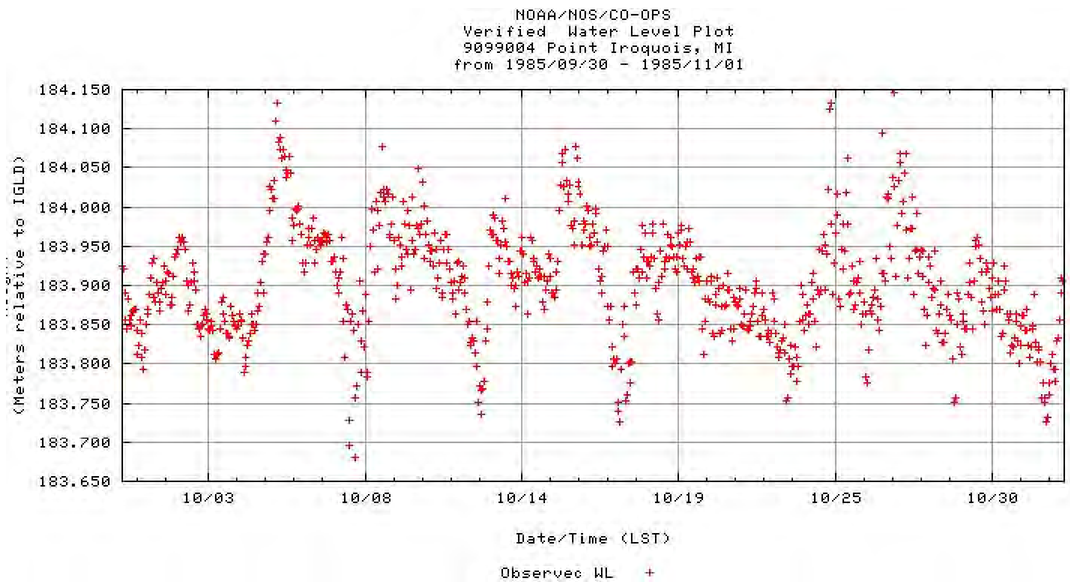

Figure 6. Hourly water levels at Point Iroquois.

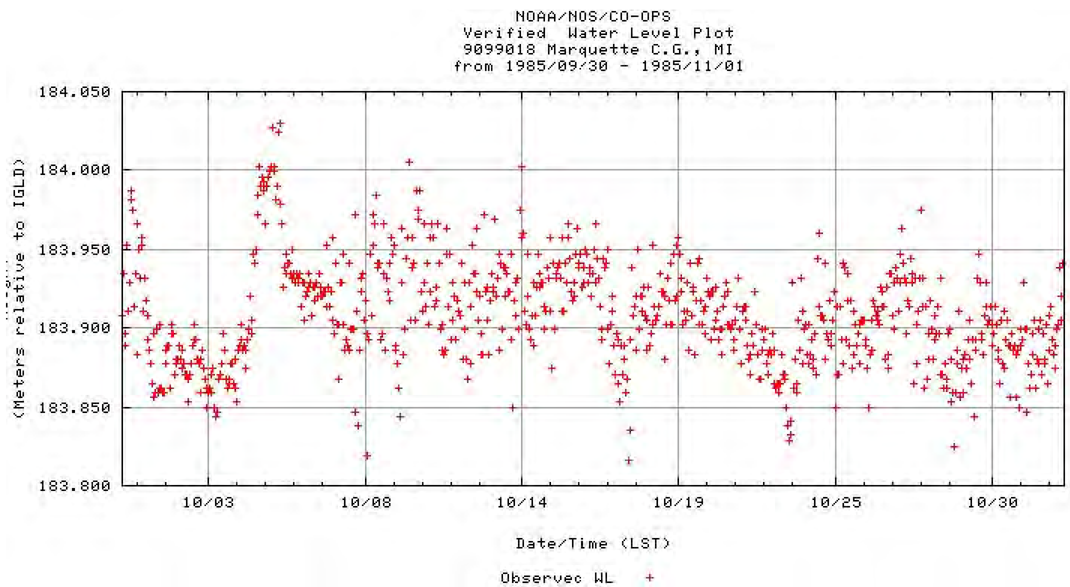

Figure 7. Hourly water levels at Marquette.

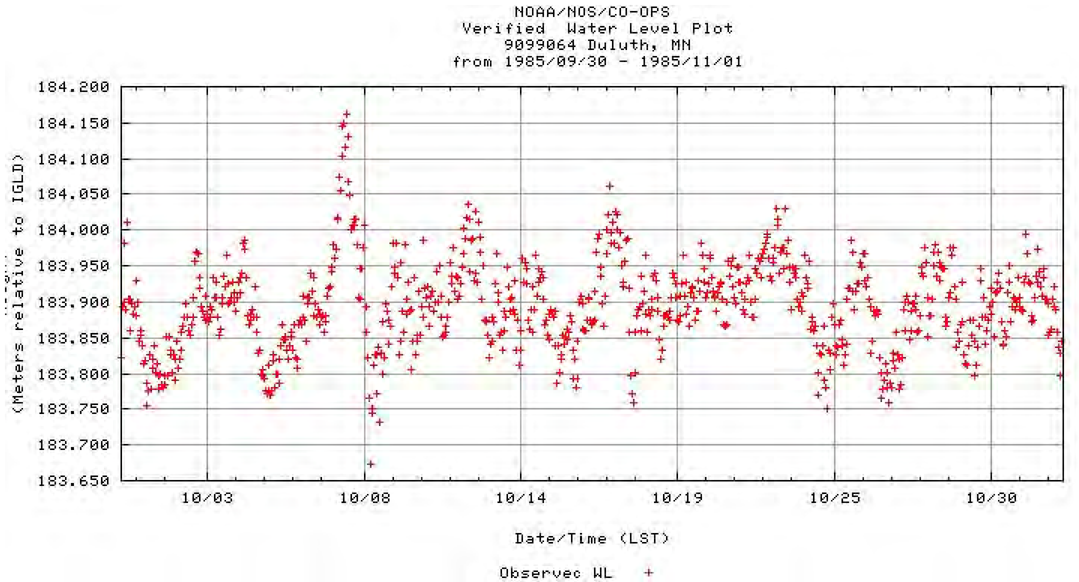

Figure 8. Hourly water levels at Duluth.

It is thus seen to be prudent and realistic, based upon the above figures, to adjust the change-in-storage computed by the coordinated BOM. This is accomplished by correcting the coordinated change-in-storage by a factor of two times the difference listed in Table 1 times 31,380 cms/m/month. The factor of two results from the fact that a BOM or EOM level must be increased by 2 cm to change the mean level by 1 cm. The correction factors for the change in storage are given in Table 2. The results are shown on a seasonal basis along with the differences between Equations (1) and (2) in Figure 9. The symmetry is readily apparent and the correlation coefficient between the two time series is -0.89. Correcting the coordinated storage by adding the adjustment gives very good agreement with the residual storage (very good agreement between the residual and component NBS) as shown on Figure 10. The monthly average differences are all less than 1 cm on the lake. Figure 11 shows the annual differences before and after correction. It indicates that the large differences and bias subsequent to the year 2000 are probable due to errors in the change-in-storage computations.

Table 1. Monthly mean water level minus the mean of the BOM and EOM levels in meters.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1951		-0.02						0.02				
1952												
1953					-0.04							
1954				-0.-4	0.02							
1955								0.02	-0.02	0.02		
1956						-0.02	0.02					
1957				-0.03								
1958	-0.02							-0.02	-0.02			
1959								-0.02				
1960				-0.04	0.02							
1961					0.02				0.02			
1962												
1963				0.02								
1964				-0.03	0.03							
1965											-0.02	
1966					-0.02							
1967			-0.02									
1968			-0.02		-0.02				0.02			
1969					0.02							
1970				-0.03						-0.03		
1971					-0.02							
1972				-0.02								-0.02
1973					0.04							
1974				-0.02		0.02						
1975				-0.03								
1976		-0.02	-0.03									-0.02
1977								-0.02			0.02	
1978							0.02			0.02		
1979				-0.03			-0.03		0.02			
1980												
1981		-0.02	-0.03									
1982					0.02		0.02			0.02		-0.02
1983					-0.03		0.02			0.03	-0.03	
1984				-0.04		0.02						
1985				-0.02						0.04	0.02	
1986												
1987					-0.02						-0.02	
1988							-0.02	0.03				
1989									0.02	-0.02		
1990				-0.03								
1991			-0.02			-0.02						
1992				-0.02	0.02		0.03					
1993				-0.02								
1994				-0.02								
1995								-0.02				
1996	-0.02			-0.04				0.02		-0.04		
1997												
1998			-0.04								-0.02	
1999				0.02			0.03					
2000		-0.02					0.02					
2001				-0.02					0.02			
2002										0.03		-0.02
2003			-0.02	-0.02						-0.02	-0.02	
2004				-0.02	-0.03					-0.02		
2005			-0.02							0.04		
2006								0.02				

Table 2. Monthly corrections to coordinated change-in-storage in cms.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1951					2397								-200
1952				2686	1117								-131
1953								1142	1192	1092			87
1954						1192	954						-20
1955				1971									-164
1956	1067							1105	1218				-79
1957								1042					-87
1958				2498	1243								-105
1959					1067				1305				198
1960													0
1961				1167									97
1962				1644	1607								-3
1963											1155		-96
1964					1356								-113
1965			1318										-110
1966			1255		1105				1180				-107
1967					1130								94
1968				1983						2046			-336
1969					1443								-120
1970				1544								1042	-215
1971					2259						1381		73
1972				-954		954							-0
1973				2071									-173
1974		-967	1996									1004	-331
1975		1017					0	1506			1243		-107
1976							992			979			164
1977				1695			1695		1130				-188
1978													0
1979		1167	1569										-228
1980					1443		979			967		-967	202
1981					1820		1017			1619	1745		-77
1982				2272		1042							-103
1983		1054		1117						2284	1531		137
1984													0
1985					1393						-992		-199
1986							1067	1582					43
1987									1004	-941			5
1988				1569									-131
1989			1230			1218							-204
1990				1142	941		1795						133
1991				1481									-123
1992				1456									-121
1993				0				-979					-82
1994	1130			2448				1004		2247			-402
1995													0
1996			2448								1130		-298
1997				1293									185
1998		1054					967						-7
1999				1356					1067				-24
2000										1958		1079	73
2001			1042	1243						1017	1356		-388
2002				1067	1619					1142			-319
2003			1305							2310			84
2004								967					81
2005													0
2006					2397								-200
Average	-40	-96	217	541	-6	-8	72	1	102	68	-89	-74	-68

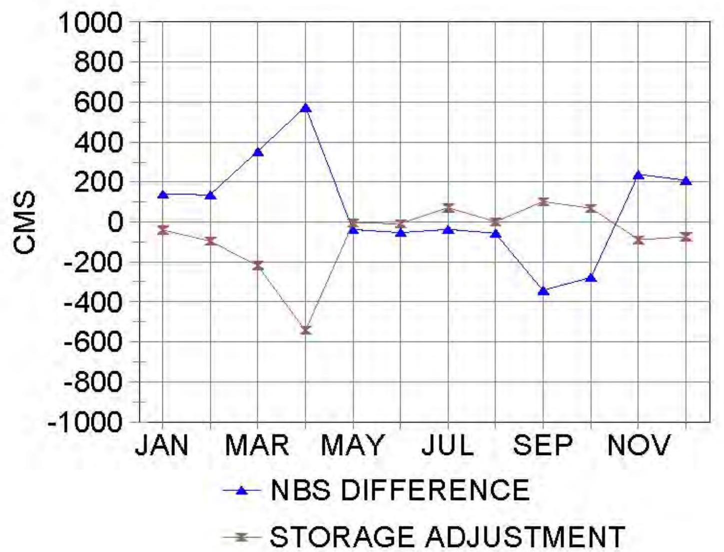

Figure 9. Computed average change-in-storage adjustment and difference between Equations (1) and (2) for the period 1951-2006.

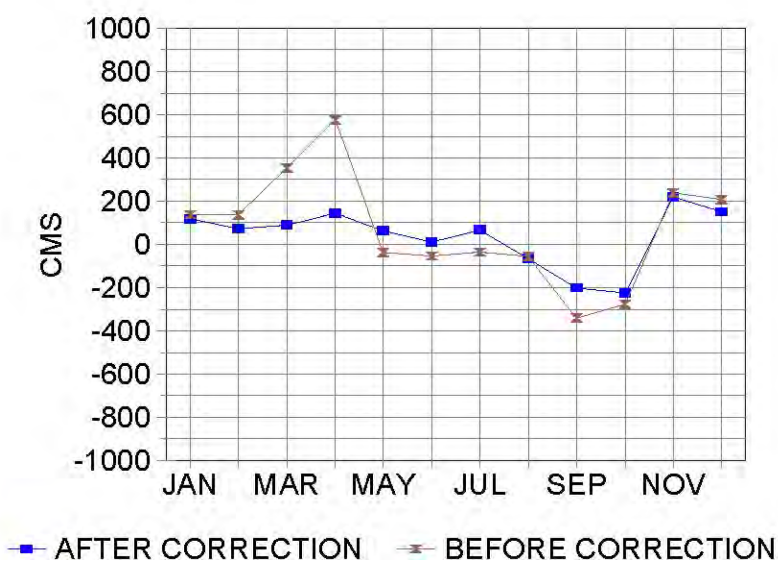

Figure 10. NBS difference before and after corrections.

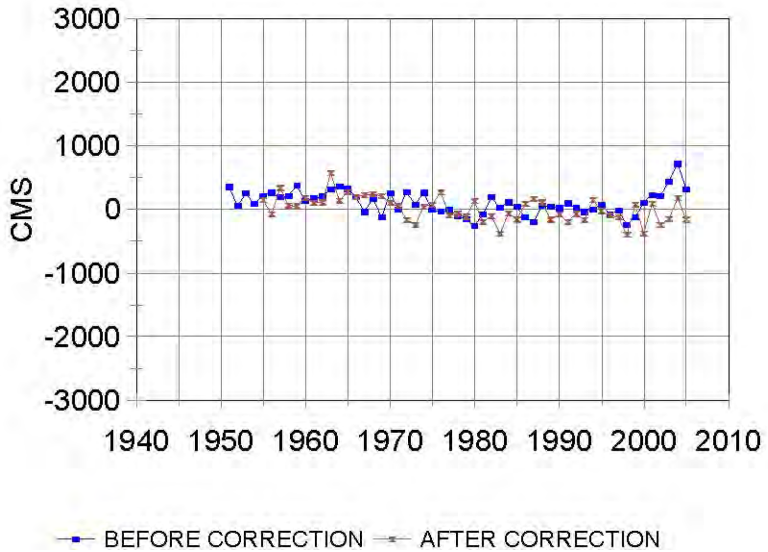

Figure 11. Annual NBS difference before and after corrections.

Conclusions

The procedure outlined above presents a methodology with a low level of uncertainty, approximately ±1 cm, for adjusting monthly changes-in-storage which may be due to erroneous beginning-of-month water levels. This analysis applies only to an assessment of the impact of beginning-of-month levels on storage computations. It does not address whether or not the water level gauges used in the computations truly represent the average lake surface level. The above and changes-in-storage that is directly applicable to the assessment of the differences between the component and residual net basin supplies. The methodology is easy to apply and accounts for major differences between the two supply series. After correcting, the monthly average differences between the component and residual net basin supplies is less than 200 cms or, less than 70 mm on Lake Superior. If this methodology is agreed to, the change-in-storage and residual net basin supplies should be recomputed.

Reference

Quinn F.H. and M.J. Todd. 1974. Lake Superior Beginning-of-Month Water Levels and Monthly Rates of Storage Changes. NOAA Technical Memorandum NOS LSC R 4

Appendix 3
Change-in-Storage Uncertainty for Lake Erie

The uncertainty in the change-in-storage and beginning-of-month levels (BOM) is one of the hardest factors to quantify for NBS comparisons. This analysis for Lake Erie builds on the prior Lake Superior analysis (Quinn, 2008). The uncertainty will be different for each lake because of their orientation, gauge locations, and response modes. The first step will be to compare the coordinated gauge network and change-in-storage with the weighted gauge network and change-in-storage (Croley and Hunter, 2008: Quinn, 1975).

The coordinated gauge network includes the following gauges: Toledo, OH; Fairport, OH; Port Stanley, ON; Port Colborne, ON. The BOM level is taken as an arithmetic mean of the 4 gauges. The weighted network consists of the following gauges: Buffalo, OH; Cleveland, OH; Toledo, OH; Port Colborne, ON; Port Stanley, ON; Erieau, ON; Erie, PA, and Marblehead, OH. Theissen polygon weights were computed for each of the stations (Quinn and Derecki, 1976). The weighted network is available for the period 1948-1990. The results of comparing the two networks are summarized in Tables 1 through 3. The high differences in January, February, and December probably reflect storm events not captured properly by the coordinated BOM.

Table 1. Weighted minus coordinated BOM levels (m).

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
AVE	0.00	0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	0.01
STD	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

Table 2. Weighted minus coordinated change-in-storage (m on the lake)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
AVE	-0.00	-0.00	-0.00	0.00	-0.00	0.00	0.00	-0.00	-0.00	0.00	0.01	0.01
STD	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02

Table 3. Weighted minus coordinated change-in-storage (cms)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL AVE
AVE	-9	-45	-2	20	-14	14	16	-30	-7	16	82	73	9
STD	197	122	114	102	78	104	107	98	97	135	163	152	23

The results of comparing the BOM coordinated levels with the monthly mean levels similar to what was done on the Lake Superior study (Quinn, 2008) are summarized in Table 4. Neither analysis, Tables 1-4, addresses how the gauges reflect what is actually happening in the lake.

Table 4. Monthly mean corrections to coordinated change-in-storage (m on the lake)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
AVE	0.00	-0.01	-0.00	0.01	0.01	0.01	0.01	0.00	0.00	-0.00	-0.00	0.00
STD	0.03	0.03	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.02	0.02	0.02

Table 5. Summary of corrections to be applied to the coordinated change-in-storage to correct for not matching the monthly mean water level with the average of the BOM levels (cms).

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
AVE	44	-68	-7	139	59	58	52	45	15	-21	-48	15
STD	279	248	225	199	177	166	133	143	141	152	171	238

The uncertainty values that I have selected to apply to the overall uncertainty analysis, based on the above results, are presented in Table 6.

Table 6. Uncertainty values

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL AVE
M	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03
cms	196	196	196	196	196	196	196	196	196	196	196	196	24

References

Croley, T.E. II and T.S. Hunter. 2008. Great Lakes Monthly Hydrologic Data. GLERL Technical Report TM 083 updated. Great Lakes Environmental Research Laboratory

Quinn, F.H. and J.A. Derecki. 1976. Lake Erie Beginning-of-Month Water Levels and Monthly Rates of change of Storage. NOAA Technical Report ERL 364-GLERL 9

Quinn, F.H. 2008 Lake Superior Net basin Supply Analysis. Upper Great Lakes study

Appendix 4

Change-in-Storage Uncertainty for Lake Michigan-Huron

The uncertainty in the change-in-storage and beginning-of-month levels (BOM) is one of the hardest factors to quantify for NBS comparisons. This analysis for Lake Michigan-Huron builds on the prior Lake Superior analysis (Quinn, 2008). The uncertainty will be different for each lake because of their orientation, gauge locations, and response modes. The first analysis will compare the coordinated gauge network and change-in-storage with the weighted gauge network and change-in-storage (Croley and Hunter, 2008: Quinn, 1975).

The coordinated gauge network includes the following gauges: Harbor Beach, MI; Ludington, MI; Mackinaw City, MI; Milwaukee, WI; Tobermory, ON; Thessalon, ON. The BOM level is taken as an arithmetic mean of the 6 gauges. The weighted network consists of the following gauges: Calumet, IL; Holland, MI; Milwaukee, WI; Ludington, MI; Sturgeon Bay, WI; Green Bay, WI; Port Inland, MI; Mackinaw City, MI; Detour, MI; Thesselon, ON; Harrisvillr, MI; Essexville, MI; Collingwood, ON; Harbor Beach, MI; Goderich, ON; Lakeport, MI. Theissen polygon weights were computed for each of the stations (Quinn, 1975). The weighted network is available for the period 1948-1990. The results of comparing the two networks are summarized in Tables 1 through 3. The high differences in January, February, and December probably reflect storm events not captured properly by the coordinated BOM.

Table 1. Weighted minus coordinated BOM levels (m).

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
AVE	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01
STD	0.05	0.04	0.04	0.05	0.05	0.06	0.06	0.06	0.05	0.05	0.05	0.04

Table 2. Weighted minus coordinated change-in-storage (m on the lake)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
AVE	0.00	0.00	-0.00	-0.00	-0.01	- 0.00	0.00	0.00	0.00	0.00	0.00	0.00
STD	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.03

Table 3. Weighted minus coordinated change-in-storage (cms)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL AVE
AVE	80	147	-189	-53	-270	-66	5	57	88	4	81	204	7
STD	820	756	485	532	458	440	470	487	466	469	610	1371	159

Table 4. Uncertainty values

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL AVE
m	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.03	0.04
cms	990	990	445	445	445	445	445	445	445	445	445	1340	159

The values in Table 4 are the values I selected to use in the uncertainty analysis. These are in general lower than the values I selected for Lake Superior. I also did an analysis of comparing the BOM coordinated levels with the monthly mean levels similar to what was done on the Lake Superior study. A summary of the results is given in Table 5. These results support the uncertainty values recommended in Table 4. Neither analysis addresses how the gauges reflect what is happening in the lake.

Table 5. Summary of corrections to be applied to the coordinated change-in-storage to correct for not matching the monthly mean water level with the average of the BOM levels (cms).

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
AVE	0	-69	-225	58	134	123	136	133	42	30	153	192
STD	237	257	669	669	611	512	453	430	550	635	699	651

References

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