Chapter 6
Hydroclimatic Conditions and Patterns

6.1 Introduction

6.1.1 Science Question

The water levels of the Great Lakes are determined not only by the conveyance of their connecting channels, but also in large part by the climatic conditions and patterns in the basin. Therefore, the key science question addressed by the Study related to the St. Clair River issue is:

- *How has climate affected the change in lake level relationship between Lake Michigan-Huron and Lake Erie?*

This question was investigated through an integrated approach focused on comparative and statistical hydrologic data analyses. From an assessment of the literature and consultation with experts, the Study shaped its hydroclimatic modelling strategy (Lee and Pietroniro, 2008). The strategy, which was independently peer-reviewed, focused on over-lake precipitation, basin runoff and lake evaporation as the major contributors to the net basin supply (NBS).

Lake level relationship between the lakes varies over time, and as a result the hydroclimatic projects undertaken in the Study focused broadly on the post-dredging period of 1962-2005 with a closer focus on the period from 1996 to 2005. It is known that there was dredging for the 8.2 m (27 ft) navigational channel project from 1958-1962, which changed the conveyance of the St. Clair River, and it has been assumed that the river regime has remained constant over the period from 1962 to the present. Since 1962, there has been a continuous drop in the change-in-fall relationship between Lake Michigan-Huron and Lake Erie and a drop in levels of Lake Michigan-Huron and Lake Superior (see Figure 6-5 later in this chapter).

6.1.2 Assessing Uncertainty

Addressing the key science question requires a thorough understanding of the water balance of the Great Lakes. The water balance is an accounting of all water entering and leaving a given lake. As noted in Chapter 2, (NBS can be calculated using two approaches:

Component Method

The component method determines NBS directly from its component contributions, (*i.e.*, over-lake precipitation, lake evaporation, groundwater and basin runoff). The mathematical equation for this method is:

$$NBS = P + R - E + G \quad \text{(Equation 1)}$$

Where:
P is over-lake precipitation,
R is basin runoff to a Great Lake,
E is evaporation from the lake surface, and
G is net groundwater flux into a Great Lake.

All terms are expressed in monthly flux estimates of m^3/s-months (ft^3/s-months) (or other time periods)

The groundwater flux is considered small and well within the uncertainty of the other three major components.

Residual Method

The residual method determines NBS indirectly by accounting for the inflow to the lake, its outflow, and net change in storage or water level, for a period using the following equation:

$$NBS = O - I + \Delta S - \Delta ST + D_o - D_i + C_{use} \quad \text{(Equation 2)}$$

Where:
O is the outflow from a Great Lake,
I is inflow from an upstream Great Lake,
ΔS is change in water storage of the Great Lake
ΔST is change in water storage caused by thermal expansion or contraction of water
D_o is diversion of water out of the Great Lake or its basin, and D_i is diversion in,
C_{use} is consumptive use of Great Lake water
All terms are expressed in m^3/s-months (ft^3/s-months) (or other time periods).

Consumptive uses, like the groundwater component, were not considered further in the investigations, given their relatively small effects on the water balance and the fact that they were within the uncertainty of the major components.

Researchers have quantified Great Lakes water balances for many decades, and hundreds of water balance studies have been done. However, uncertainties in estimates of the major components of the water balance in such a large system can vary dramatically, leading to uncertainty in the overall water balance. Many different methods have been employed over the decades, based on limited databases, which may have introduced various biases into previous computations. These uncertainties mask or confound an understanding of changes in the various water balance components. Addressing this uncertainty and upgrading the methods, data and models used for analysis are key elements of the hydroclimatic projects of the Study. Several methods used here to assess uncertainty include comparative analysis, Monte Carlo simulation and bootstrapping techniques. Comparative analysis compares two or more sets of data, generally developed independent of one another. Monte Carlo simulation is a statistical technique in which an uncertain value is calculated repeatedly using randomly selected "what-if" scenarios for each calculation. Uncertain quantities in the model are replaced with approximate numbers to see how uncertainty affects results. Bootstrapping is the technique of estimating statistical properties by measuring those properties when sampling from an approximating distribution. This can be achieved by re-sampling (with replacement) from the original dataset. The method most applicable to each of the hydroclimatic projects was used and is briefly described in the following sections.

6.1.3 Overview of Approach

To address the St. Clair River issue, the Study first undertook an assessment of the contemporary estimates of the water balance, their uncertainty and methodological approaches. This step included an overall understanding and updating of existing residual and component NBS estimates used in the current management strategies by both the U.S. and Canada. The U.S. Army Corps of Engineers (USACE) and Environment Canada compute the residual supplies. The component supplies are computed by the U.S. NOAA Great Lakes Environmental Research Laboratory (GLERL).

For the residual supplies, this included adjusting the St. Clair River and Niagara River flows for updates to stage-discharge relationships, correcting beginning of month lake elevations for gauge changes and glacial isostatic adjustment, and ensuring system mass balance. For the component supplies, it included inspection and correction of computational errors and inclusion of all available hydrometeorological observations. A comparative analysis of the residual and component NBS was concurrently undertaken to better understand where differences in the data occurred and the causes of these differences.

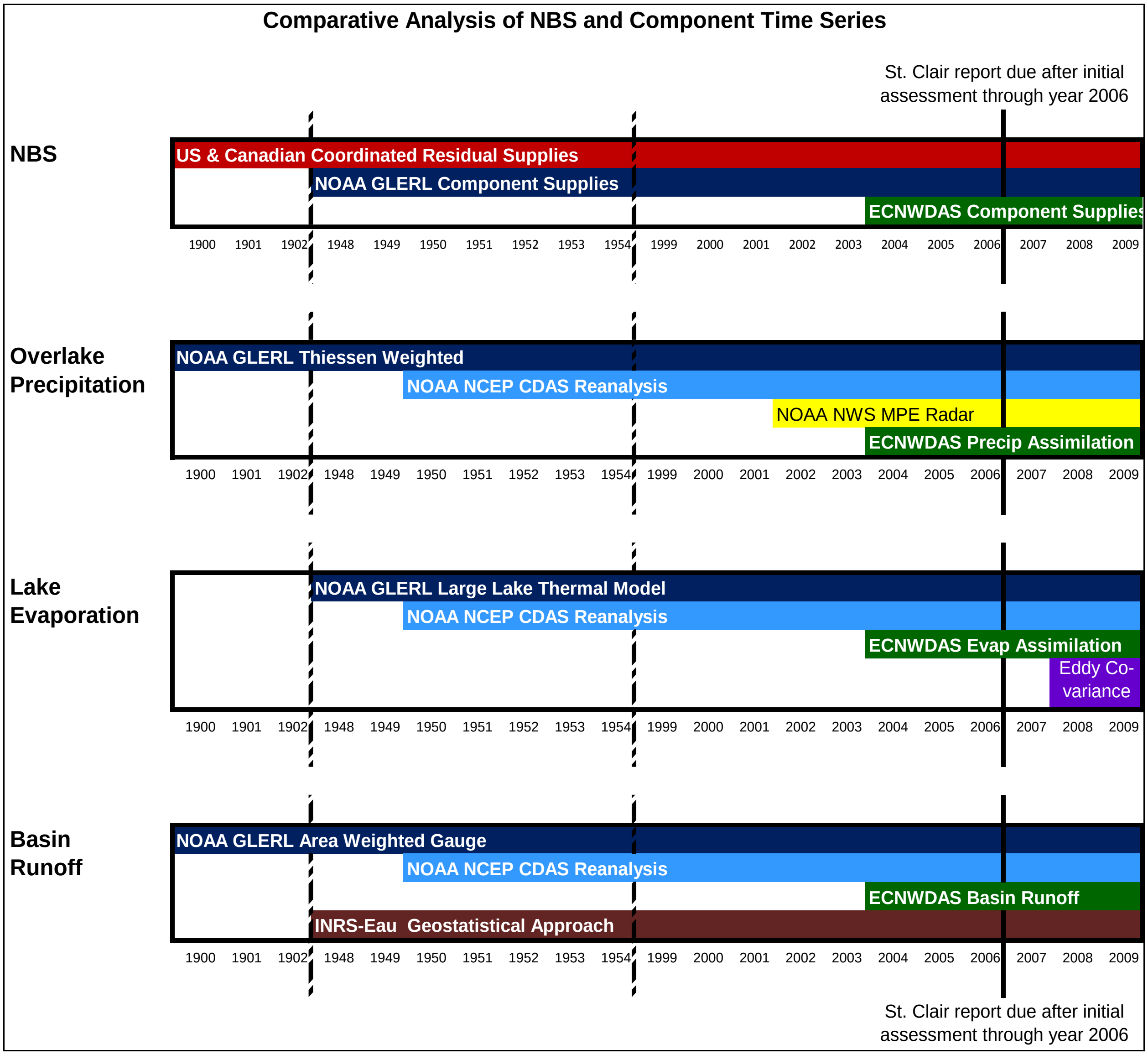
As part of the comparative analysis, exhaustive statistical analysis was also performed on the water balance data to explore trends (a gradual rate of increase or decrease over a period of time), shifts (an abrupt increase or decrease at a point in time) and change-points (the point in time where a change in trend or shift occurs in the data). These results were then inspected to determine, if possible, whether they were artifacts of the data or whether they reflected true physical phenomena such as a change in conveyance or climate patterns. With respect to changes in conveyance and based on findings reported by Quinn (2008 a-e), there were three possible significant events that could have resulted in erosion of the river bed. They were the 1973-1974 record high lake levels, the 1984 ice jam, followed by the 1985-1986 record high lake levels.

While the complete assessment of the NBS components was underway for the Lake Superior part of the Study, several projects focused specifically on closing the water balance to better determine what portions of the change in fall between Lake Michigan-Huron and Lake Erie were due to climate and conveyance. The accelerated timeline of the Study did not permit waiting until conclusion of the complete NBS assessment; however the two simultaneous efforts informed each other and the water balance projects reported here used the best estimates available at the time each specific study was conducted. Multiple revisions of the datasets occurred during the Study period and thus several of the specific projects reported here used different data revisions.

The third major focus of the Study was the investigation and development of new monitoring and modelling approaches to estimating the major components of the NBS – over-lake precipitation, basin runoff and lake evaporation. New computational and sensing technology offers the opportunity to improve upon current Canada and U.S. operational methods for computing NBS. The new technology includes current numerical weather and climate models that use data assimilation techniques to derive the components of the water balance. These independent models complement the existing quasi-operational modelling system developed by the GLERL, and are being used to assess and pinpoint potential deficiencies in modelling approaches and further refine the water balance estimates. The models are primarily the National Center for Environmental Prediction CDAS reanalysis (NCEP CDAS), Environment Canada's Numerical Weather and Data Assimilation System (ECNWDAS), and the Canadian Regional Climate Model (CRCM). In addition, new technology such as weather radars and eddy covariance towers are being used to measure precipitation and lake evaporation. Figure 6-1 illustrates the data available for the comparative analysis. Note the different lengths of time for which the data series are available. The residual NBS have the longest record, beginning in 1900. The GLERL component supplies are available from 1948 onward, while the new modelling and monitoring techniques have much shorter records for comparison.

Section 6.6 discusses projects still in progress and additional planned projects.

Figure 6-1
Net Basin Supply and Components Comparative Assessment Timelines



6.2 Comparative and Statistical Hydroclimatic Data Analyses

6.2.1 Comparative Analysis of Water Balance Data

The comparative analysis of pertinent Great Lakes water balance data was undertaken primarily by Quinn through a series of applied studies (2008a-e). Given that water supplies to the Great Lakes can be computed by two independent methods (residual and component), Quinn's analysis provided the opportunity to identify differences between these methods for insight to both climate and channel conveyance changes. Quinn (2008a-e) also investigated the uncertainty inherent in the data and made recommendations on improvements to the computational procedures.

Ideally, the two independent methods should arrive at the same NBS estimates. However, Quinn (2008a) found that the residual NBS computations for Lake Michigan-Huron began deviating from those of the GLERL component NBS beginning in about 1970. A second shift appears to have occurred shortly after 1985 in the residual NBS. He attributes the 1970 shift to an apparent change in the Thessalon lake level gauge that affected the change-in-storage computations (Quinn and Southam, 2008). He attributes the 1985 shift to issues related to estimated flows for the St. Clair River and possibly the Detroit River that both appeared about 1985 (Quinn, 2008b). Further, he points out problems with an inconsistent water balance between the St. Clair River and Detroit River due to the interagency flow coordination procedure (Quinn, 2008c) and potential changes in the channel conveyance in the St. Clair River that may have occurred between 1971 and 1989 (Quinn, 2008d).

Quinn (2008e) also found issues with the Lake Erie residual NBS computation, not only due to problems associated with the St. Clair and Detroit River inflows, but also due to problems associated with Niagara River outflows and change-in-storage computations.

In response to Quinn's findings and other considerations, the data have been revised for the residual NBS. Specifically, the following changes were made:

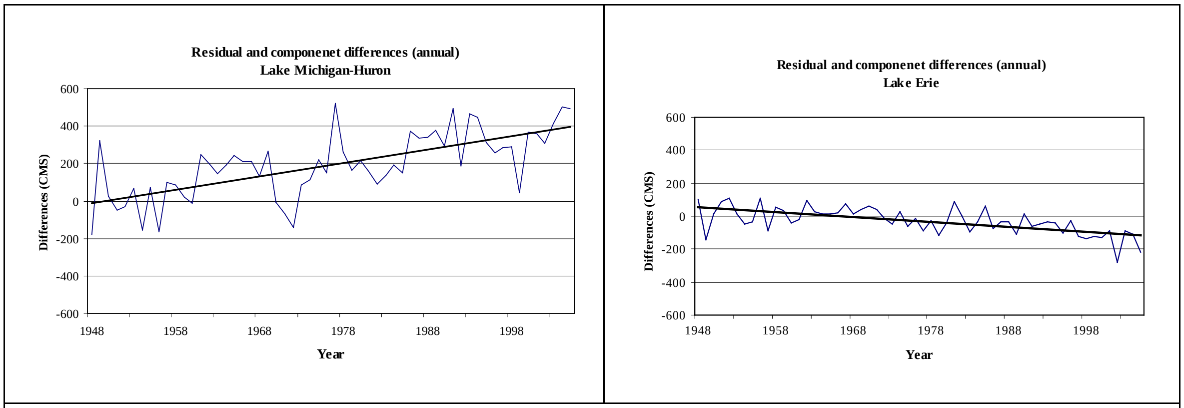
- recomputed NBS based on metric levels, flows and diversions;
- used actual month lengths to convert changes in storage in metres to cubic metres per second;
- revised the outflow from Lake Erie by separating the Niagara River flow and the Welland Canal diversion, and estimating Niagara flows from 1961 to present based on better gauged estimates of the outflow from the Maid of the Mist pool;
- revised previously coordinated St. Clair River and Detroit River flows in light of changes in conveyance reported by the hydraulics technical work group; and
- revised Lake Erie beginning-of-month and change-in-storage data using Cleveland water level gauge data instead of Fairport data from 1992 to present.

Quinn (2008a, e) demonstrated that earlier versions of GLERL component NBS datasets also contained significant errors. Quinn discovered several computational errors in the basin runoff component that were corrected and some anomalies in the lake evaporation component for 2001-2006 that have subsequently been addressed by GLERL. He also noted that declines in the streamflow and precipitation gauging networks have introduced uncertainties in the component

NBS that contribute to the differences found between the two computational methods. The ongoing monitoring and modelling projects may help to resolve some of these issues.

Annual differences in the GLERL component and residual NBS for Lake Michigan-Huron and Erie are plotted in Figure 6-2. The plot shows the annual differences (component NBS minus residual) NBS for Lake Michigan-Huron and for Lake Erie. A simple trend line in the differences for each of the lakes is shown for illustrative purposes.

Figure 6-2
Differences in Annual Average Monthly NBS (m^3/s) for Lake Michigan-Huron and Lake Erie since 1948



Note: Differences are calculated as component minus residual NBS values.

6.2.2 Statistical Analysis of Hydroclimatic Data

Extensive statistical analysis of the hydrologic and climate data was undertaken by Ouarda *et al.* (2009) to identify climate trends, change-points and other statistical anomalies to discern their relationship to the change in lake level relationship between Lake Michigan-Huron and Lake Erie. Statistical analysis was applied to each lake's monthly and annual water supplies and lake levels, water supply components (over-lake precipitation, basin runoff, and lake evaporation), connecting channel flows, air and water temperature, change in storage and the change in fall between Lake Michigan-Huron and Lake Erie. The period of record evaluated was 1948-2005 for most data, but when available, a longer record was used, primarily for lake levels and channel flows. Only component NBS estimates were used, because of problems identified with the residual NBS related to the St. Clair River conveyance change.

For trend detection, two methodologies were used: the original Mann-Kendall (MK) nonparametric test (Mann, 1945; Kendall, 1975) and the Trend Free Pre-whitening modified Mann Kendall (TFPW_MK) nonparametric test (Yue *et al.*, 2002). The latter test prevents the autocorrelation evident in most Great Lakes hydrologic data from influencing the long-term trend assessment and is presented here (*i.e.*, the effect of the prior year's hydrologic regime persisting into the following year). For the change-point analysis, the Bayesian method was used (Seidou and Ouarda, 2007).

Net Basin Supplies

While no long-term monotonic trends were discernable in annual NBS to Lake Superior, Lake Michigan-Huron and Lake Erie exhibited a weak increasing trend over the period of record (see Tables 6-1). This trend was supported by increasing trends found in watershed runoff and over-lake precipitation, while lake evaporation (and similarly, air temperature) showed no statistically significant long-term trend. However, an upward trend in maximum air temperature was found for the Lake Superior basin. This is not meant to imply that there are no observed changes in temperature or water balance components. Rather, this indicates that statistically, there is no significant monotonic increase in many of these variables over and above the observed natural variations seen during the full analysis time period.

Table 6-1
Trend Detection Results for the Great Lakes NBS, 1948-2005
(TFPW_MK test)

Lake	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Annual
SUP	0	0	0	0		0	0	▿		0	0	0	0
HGB	0	0	0	0	▵	0	0	0	0	0	▵	▵	0
MHG	0	0	0	0	0	0	0	0	0	0	Δ	0	0
MIC	0	0	0	0	0	0	▿	0	0	0	Δ	0	0
STC	0	0	0	0	0	Δ	Δ	Δ	Δ	Δ	▵	0	0
ERI	0	0	0	0	0	0	0	▵	Δ	0	Δ	0	0
ONT	0	0	0	0	0	Δ	0	0	Δ	Δ	Δ	0	Δ

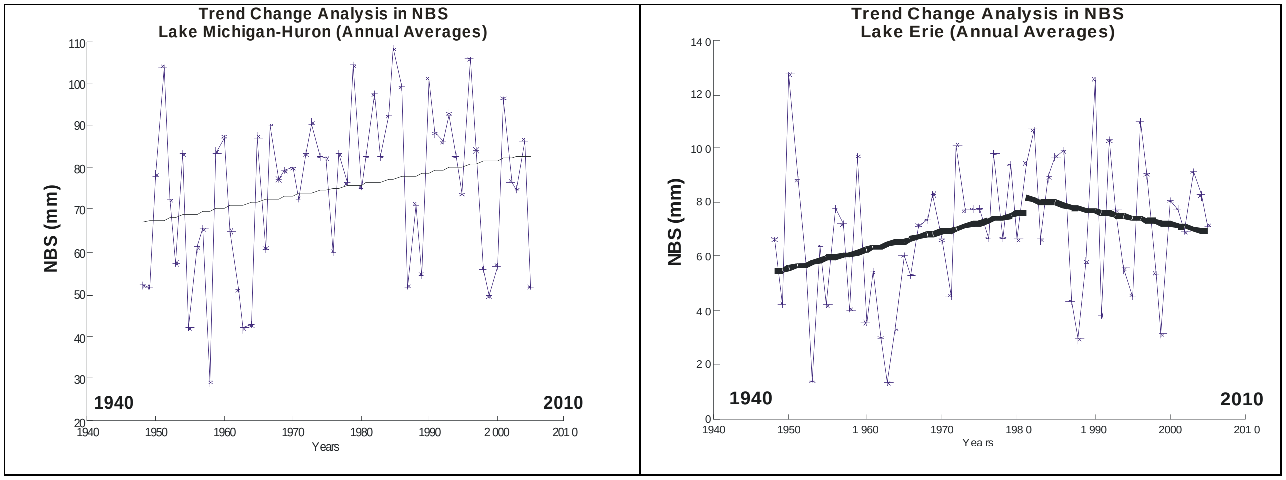
Key to Table 6-1:

0 : Acceptance of the null hypothesis (no trend).
Δ : Upward trend significant at 5% significance level.
▵ : Upward trend significant at 10% significance level.
∇ : Downward trend significant at 5% significance level.
▿ : Downward trend significant at 10% significance level.

However, change-point analysis revealed more pronounced trends (increasing and decreasing) throughout the record on shorter (decadal) timescales. Lake Superior again distinguished itself by having a rising trend in water supplies from 1948 to 1966, and declining supplies thereafter. No change-point was detected for Lake Michigan-Huron NBS, with only a slight rising trend as outlined in Figure 6-3a. Lake Erie exhibited a rising trend from 1948 to 1981, followed by a slight declining trend through 2005 (see Figure 6-3b). These results support other meteorological and climatological evidence that Lake Superior's climate tends to be distinct from that of the lower lakes (Assel *et al.*, 2004; Quinn, 1981; Hodgkins *et al.*, 2007). Stow *et al.*, (2008) also provided indirect evidence of regional climate driving lake level change when they compared standardized changes in Great Lakes water levels to those of three seepage (closed basin) lakes located in the same region and found them highly correlated.

Figure 6-3
Change-Point Analysis of Annual Net Basin Supplies

a) Lake Michigan-Huron b) Lake Erie



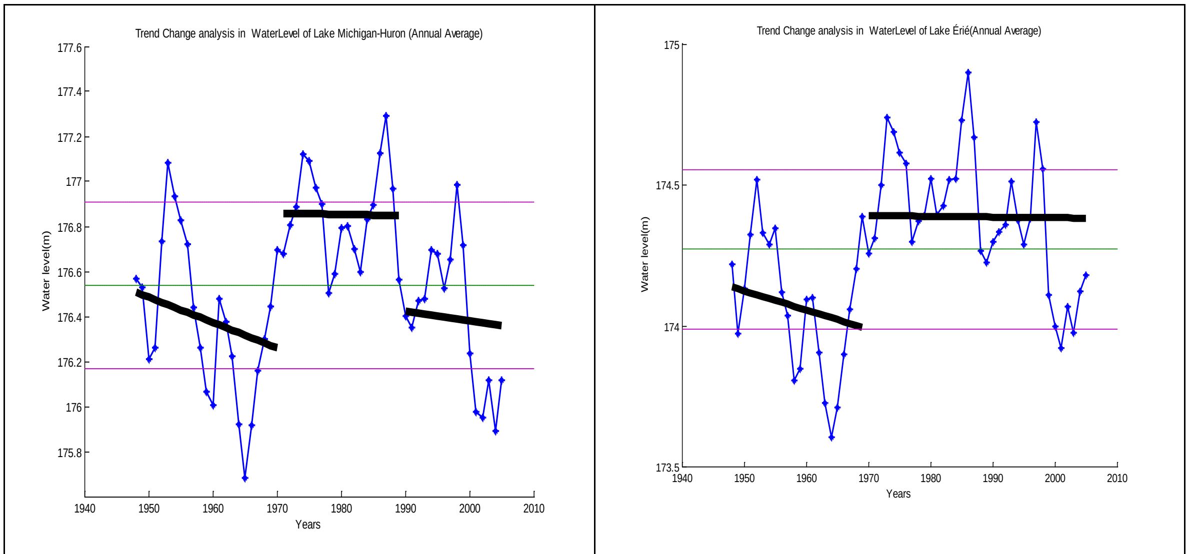
Note: No change-point was found for Lake Michigan-Huron, one change-point was found for Lake Erie (1981).

Lake Levels

Annual lake levels for 1918-2007 were statistically analyzed for trends and change-points considering the correlated variables of air temperature and overland precipitation. By considering these latter variables, change-points due to climate were removed, leaving those related to the hydraulics of the system or other factors related to measuring water levels. The analysis showed that Lake Superior annual water levels exhibited no significant trend when analyzed over the period of record, whereas Lake Michigan-Huron and Lake Erie showed upward trends in annual water levels over the period of record. The results obtained from the Bayesian change-point detection method showed that there were a single change-point in Lakes St. Clair and Erie in 1969 and two change-points in 1970 and 1989 for Lake Michigan-Huron (see Figure 6-4a). Given that a range of probable dates of change (instead of a unique date) should be taken into consideration, 1969-1971 can be considered as the range of a common change-point for all Lake Michigan-Huron, Lake St. Clair and Lake Erie. No change-point was detected in Lake Superior water levels.

With respect to Lake Michigan-Huron, the change-points in 1970 and 1989 are consistent with findings from Quinn's comparative analysis of NBS (Quinn, 2008a-e) and the conveyance changes reported in Chapter 5. Significant upward trends in the Lake St. Clair and Lake Erie water levels occurred after the change-point, while Lake Michigan-Huron showed an upward trend after the 1970 breakpoint followed by a downward trend after the 1989 breakpoint. The increasing shifts in water levels followed by decreasing trends suggests that water levels in the Great Lakes are now higher (compared to the first half of the twentieth century) but that they are on a declining course. Additional statistical analysis on net total supplies (NTS) (Section 6.3.1) shows that though there have been upward trends in NBS, there has been a persistent decline in NTS that has resulted in the declining lake levels.

Figure 6-4
Change-Point and Trend Analysis for Water Levels
(Accounting for correlations with precipitation and air temperature)
a) Lake Michigan-Huron and b) Lake Erie



(a)	(b)

Note the change-points for Lake Michigan-Huron in 1970 and 1989 and for Lake Erie in 1969.

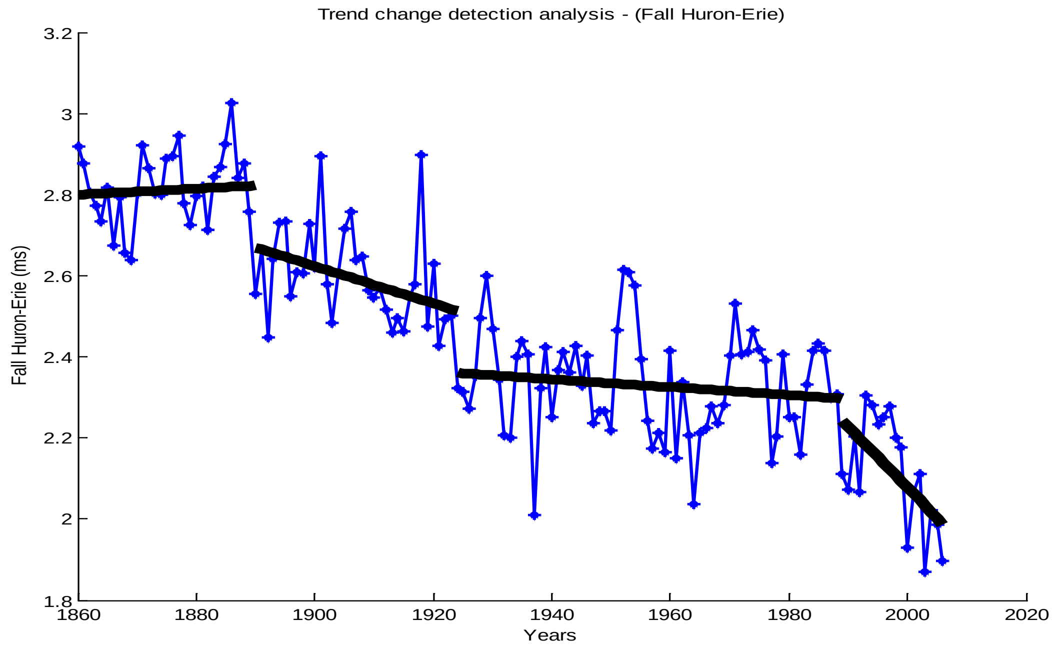
Connecting Channel Flows

The initial statistical analysis of the connecting channel flows for the period of record (1900-2006), adjusted for serial correlation, revealed no long-term trend for the St. Marys River, the St. Clair River and Detroit River flows. Subsequently, computational issues in the coordinated flows and water level data were recognized and are documented in Chapter 5. Re-analysis of the trend and change-point statistics is pending, as a result of the revision of the flows.

Change in Fall

A statistical analysis of the change in fall between Lake Michigan-Huron and Lake Erie (1860-2005) was also conducted. Change-points were found in 1888, 1923, and 1988. After each breakpoint, downward shifts with downward trends were exhibited, with the trend post-1988 being noticeably steeper than the prior periods (see Figure 6-5). The change points in 1888 and 1923 could be correlated with human activities: in 1888, the Edison Sault hydropower diversion station was completed in the St. Marys River; and 1923 could be associated with the deepening of the St. Clair River channel to 6.4 m (21 ft), that was carried out in 1920 and 1921.

Figure 6-5
Change-Points in the Fall between Lake Michigan-Huron and Lake Erie
(1888, 1923 and 1988)



6.3 Impact of Climate on Lake Levels

6.3.1 Water Balance Assessment

For further insights into climate effects on water levels, a simple water balance assessment for Lake Michigan-Huron and Lake Erie was carried out using coordinated monthly water supply values. These data included beginning of month lake levels, connecting channel coordinated flows and GLERL component estimates for over-lake precipitation, basin runoff and lake evaporation. These data were divided into both five-year segments and annual averages.

To understand the historical context, available data for 1900-2005 were used in assessing deviations in NBS and NTS for Lake Michigan-Huron and Lake Erie. Deviations from the mean are expressed as the percent difference between the 1900-2005 mean NBS and NTS estimates and the estimated values for that given year. Figure 6-6 shows total deviations from 1900 to 2005 (as a percentage of the mean) for both Lake Michigan-Huron and Lake Erie. The plots show marked deviations in recent years for Lake Michigan-Huron and corresponding low water levels. Similar lake level drops and deviations are also noted through the measurement period, including the deviations and low lake levels noted throughout the 1930s. Water levels in Lake Erie have recovered in recent years, and are similar to what they were in 1900. As of April 2009, water levels on Lake Michigan-Huron have recovered to nearly historically average conditions.
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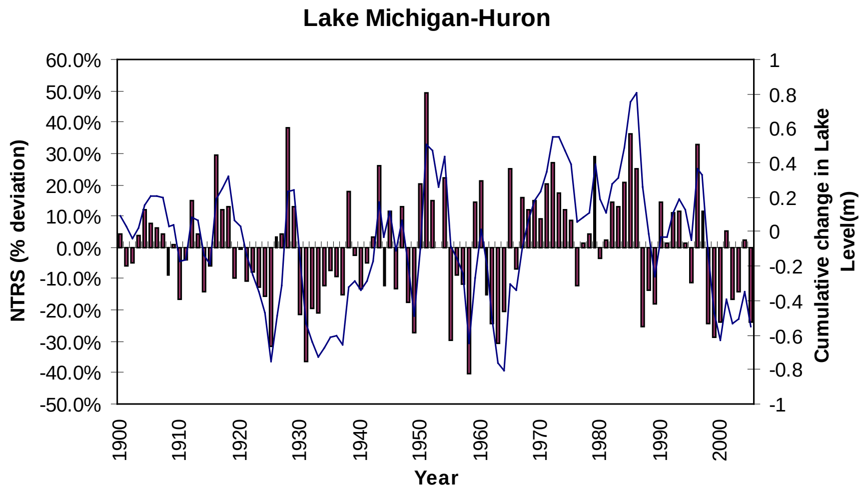
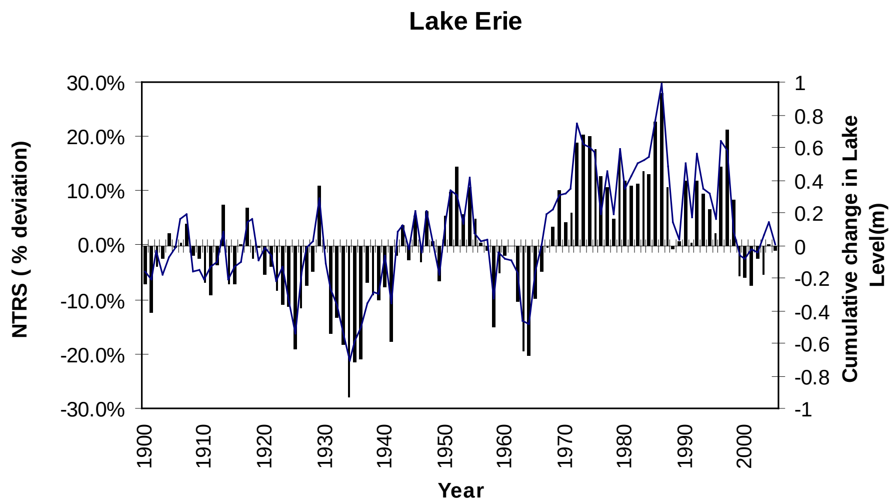
Figure 6-6
Annual residual NTS Deviations from the Mean for Lake Michigan-Huron and Lake Erie
(1900-2005)



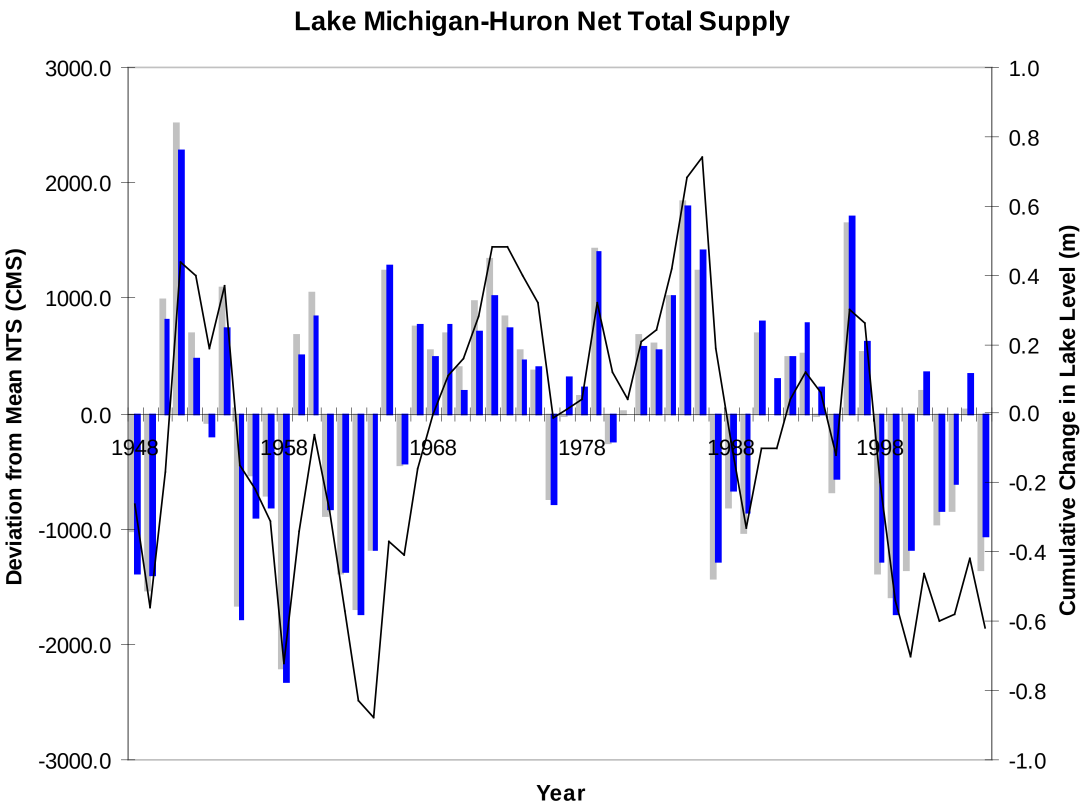


Note: Low NTS deviations observed from 1998 to 2005 for Lake Michigan-Huron. Cumulative changes in lake levels (metres; blue lines) are plotted on the right hand axis.

Both residual and component NTS estimates represent the total inflow into Lake Michigan-Huron and Lake Erie, respectively. As noted in Figure 6-6, there appears to be a prolonged period of negative deviations (*i.e.*, water supply deficits) from the mean for NTS within the last ten years, since about 1998. This coincides with the prolonged drought that occurred in western North America and began about the same time. Supplies into Lake Erie are shown to be less variable and result in more stable lake levels.

Inherent in the residual NBS and NTS estimates noted above are any biases or errors in flow or lake level estimates that are used to calculate the residual supplies. As discussed and shown earlier in Figure 6-2, two independent methods for estimating NBS have been available since 1948. Although minor differences in NTS using either component or residual estimates for Lake Michigan-Huron can be observed, the overall supply into the lake shows a long period of negative (deficit) supplies compared to the long-term mean, with a resulting drop in lake level. This does not imply that the lake level drop is completely attributable to hydroclimatic factors, but it does support independent observations and computations that these deficits are a contributing factor to lake level declines. As discussed in section 6.3.2, these factors do explain a large proportion of the observed changes. Figure 6-7 highlights the NTS estimates using both component and residual estimates for Lake Michigan-Huron, showing that both residual and component methods are fairly close in their computations and that they are synchronous with lake level fluctuations, partly explaining changes throughout the period of record (1948-2005).

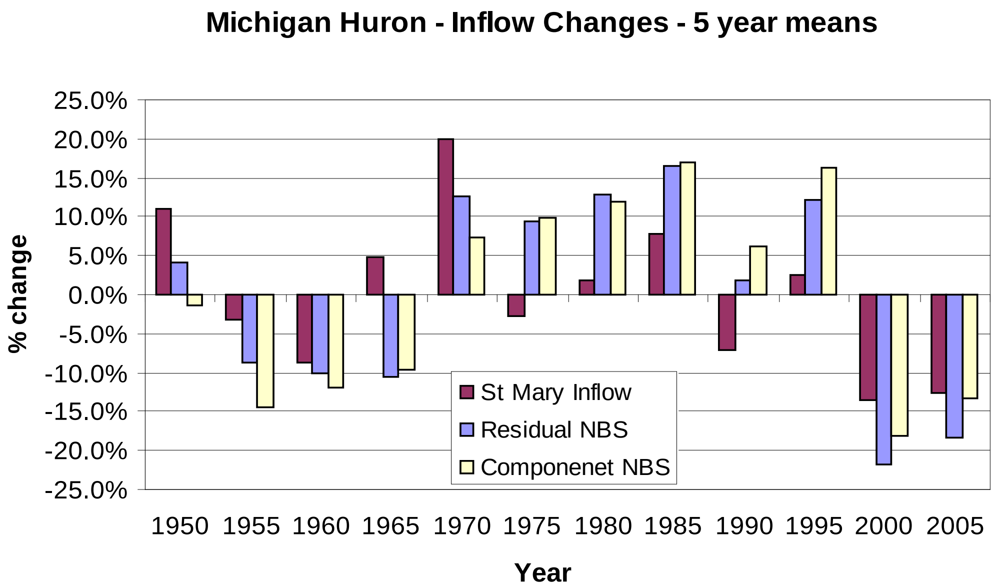
Figure 6-7
Annual Net Total Supply (CMS) for Michigan-Huron 1948-2005



Note: Both component (light gray bars) and residual NTS estimates (St. Marys River flow + NBS; blue bars) are shown. Changes in lake level (metres; black line) are plotted on the right axis.

To further examine the context of recent changes, five-year average estimates of water balance components from 1948 to 2005 (Figure 6-8) indicate that for the last two five-year periods, there has been a substantial decrease in the Lake Michigan-Huron NTS (residual NBS plus the St. Marys River inflow), with a decrease of about 20 percent based on the 40-year mean (1948-2008). This resulted in a significant negative water balance for the lake over that period, with an average decrease in change in storage of about 400 m^3/s (14,126 ft^3/s); a basis equating to an average increase in the rate of decline of about 1 cm (0.4 in) a month relative to average over this decade. There is some question regarding the reliability of residual NBS due to the uncertainty in St. Clair River outflows. However it could still be concluded there is a relatively strong climate signal present in explaining the deviations in Lake Michigan-Huron lake levels given that that 10-year average St. Marys River inflows (a significant portion of the NTS) are reliable and that St. Marys River inflows alone into Lake Michigan-Huron have decreased by about 13 percent over the last ten years when compared to the 40-year average. Using either component or residual NBS estimates, it is quite clear form Figure 6-8 that total water supply into Lake Michigan-Huron has decreased substantially within the last ten years.

Figure 6-8
Analysis of NTS for Lake Michigan-Huron



Note: Illustrates the upstream St. Marys River contribution along with component and residual estimates of NBS. The plot highlights significant deviations using either component or residual NBS estimates of total inflow into the lake.

6.3.2 Climate versus Conveyance

A project by Tolson (2009) looked at the distribution of change in fall (*i.e.*, decline in head difference) using deterministic and bootstrap statistical techniques given two alternative periods of climate. This project determined these climate periods in part considering the change-point analyses in Ouarda *et al.* (2009). However, Tolson considers 1987 as a more representative change-point in large part because it generates a trend in the current climate era NBS for Lake Erie that is hydraulically consistent with the change in fall difference between Lake Michigan-Huron and Lake Erie observed over time.

Deterministic approaches rely on existing observations and present the one possible scenario based on best possible estimates of NBS and conveyance. The bootstrap technique in Tolson (2009) takes a probabilistic approach to evaluate system behavior under a number of plausible alternative sequences of climate where these sequences are based on a re-sampling and re-ordering of the historical climate (NBS) record. This project concentrated on two hydraulic regimes for the St. Clair River channel conveyance (1962-1977 and 1988-2006). The project presents an initial model evaluation, deterministic assessments of contributing factors and a stochastic assessment of climate and conveyance contributions to changes in fall.

The project uses a mathematical simulation model of the upper Great Lakes (from Lake Superior to Lake Erie) to assess the relative impacts of NBS and St. Clair River channel conveyance change on the recent behavior of lake levels. The model used is the Coordinated Great Lakes Routing and Regulation Model (CGLRRM) that was originally developed by the GLERL, in conjunction with the USACE and Environment Canada. The origin of CGLRRM was the work of Quinn (1978) and then the work of Clites and Lee (1998). Today, the CGLRRM is sanctioned by all relevant agencies from Canada and the U.S. that make up the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data.

The CGLRRM was utilized to simulate lake levels (and thus the drop in head difference) in a suite of comparative modelling experiments. The first steps in the project were focused on building a robust and credible deterministic model of the Great Lakes system as follows:

- Show that the CGLRRM, using component NBS, can replicate past lake levels. Demonstrate that model predictions generate a head difference over time that tracks the observed head difference.
- Repeat step 1 with different open water lake-to-lake stage-fall-discharge equations for St. Clair River flow for the 1962-1977 and 1996-2005 periods such that two different conveyance regimes on the St. Clair River were represented.

Note that the equation for the 1996-2005 period was developed by Environment Canada to specifically represent the current conveyance regime and thus derived on the basis of recent St. Clair River flow data from 1996-2006.

Results from the modelling exercise indicated that component NBS, can reasonably replicate 1962-1977 lake levels (and lake fall behavior) with a lake-to-lake stage fall equation developed by Fay and Noorbakhsh (2004) for the 1962-1999 period. However, it was noted that in order to reasonably replicate 1996-2000 lake levels (and lake-fall behavior) a new lake-to-lake stage-fall equation developed for the 1996-2006 period was required. Reasonable predictions are achieved when the average of component and residual NBS for Lake Michigan-Huron are used for the model for the 2001-2005 period.

The deterministic modelling results are highlighted in Table 6-2 and described using three different metrics that quantify the change in head difference (lake fall) over time between Lake Michigan-Huron and Lake Erie. This was required because of the difficulty in assessing model goodness of fit given all the possible measurements and model results from which to compare. The three metrics chosen for comparison reflect the important comparison points between model results and observations.

The first metric, referred to as M1, covers the 1997-2000 period and is equal to the (1997 average lake fall) - (2000 average lake fall). M1 is an important metric because the simulated metric is not impacted by the adjustment to Lake Michigan-Huron NBS for the 2001-2005 period.

The second metric, referred to as M2, covers the 1997-2005 period and is equal to the (1997 average lake fall) - (2005 average lake fall).

The third metric, referred to as M3, is based on the three-year moving average of annual average lake fall and covers 1997 (average of 1996, 1997 and 1998) through 2004 (average of 2003, 2004 and 2005). All metrics were simulated within -6 to 13 percent of the measured values.

Table 6-2
Measured and Simulated Metrics for Assessing Change in Head Difference across Different Periods based on Annual Average Lake Levels

Metric	Period	Change in Head Measured (m)	Change in Head Simulated (96-00 conveyance with adjusted NBS) (m)	Simulation Error in (m)
M1	1997-2000	0.28	0.32	0.04
M2	1997 -2005	0.35	0.33	-0.02
M3	1997– 2004	0.29	0.27	-0.02

Once reasonable simulations for existing lake levels were achieved, the next effort focused on undertaking various deterministic runs. These runs varied one model input factor at a time and then compared the simulated change in head differences. To attempt to quantify the possible effect of a change in conveyance, the model was run by using the deterministic results above and then run again assuming no change in the stage-fall equations. The result from this analysis showed that the post-1977 conveyance change on the St. Clair River was estimated to cause between 22 and 25 percent of the three different metrics considered above (see Table 6-3). Climate and all other factors were therefore responsible for 75 to 78 percent of the metrics.

Table 6-3
Evaluation of Conveyance Change Effect on the Change in Head Difference Using Various Simulated Metrics

Metric	BASELINE Change in Head Simulated (96-00 conveyance with adjusted NBS) (m)	Change in Head Simulated (1962-1977 conveyance with adjusted NBS) (m)	% of baseline change in head difference due to conveyance change (brackets are % attributed to other factors)
M1	0.32	0.24	23 (77)
M2	0.33	0.26	22 (78)
M3	0.27	0.20	25 (75)

Note Metric M1 is based on only component NBS while the other two are influenced by the adjustment to 2001-2005 Lake Michigan-Huron NBS inputs.

The third step focused on assessing the relative contribution of both climate (e.g., NBS) change and conveyance change from a stochastic perspective that considers alternative sequences of NBS. Alternative sequences of NBS were sampled using a moving blocks bootstrap approach (Efron and Tibshirani, 1993) and thus functioned to maintain the spatial correlation of NBS across all the lakes. Additional metrics for quantifying the drop in head difference over time were developed and are included in the detailed analysis. The NBS sequences were analyzed to determine the two most recent eras of NBS on the Great Lakes. The modelling experiments in this step involved varying the NBS era and the equation for St. Clair River flow as described earlier.

The stochastic modelling showed that the system behavior resulting from the actual 1996-2005 NBS sequences was fairly uncommon in comparison with the distribution of possible ten-year NBS sequences sampled from the 1948-2005 period (1,000 samples). The results further indicate that even with the post-1977 conveyance change, 50 percent of the alternative NBS sequences sampled from the 1948-2005 period would have generated a drop in head difference and/or Lake Michigan-Huron levels that would have generated little concern among stakeholders as defined by:

- a minimum annual average Lake Michigan-Huron level over the 1996-2005 period that was higher than the historical low annual average from 1990; and/or
- the simulated M3 drop in head difference metric was less than 0.10 m (0.32 ft) (in comparison to 0.29 m (0.95 ft) that was observed system behaviour).

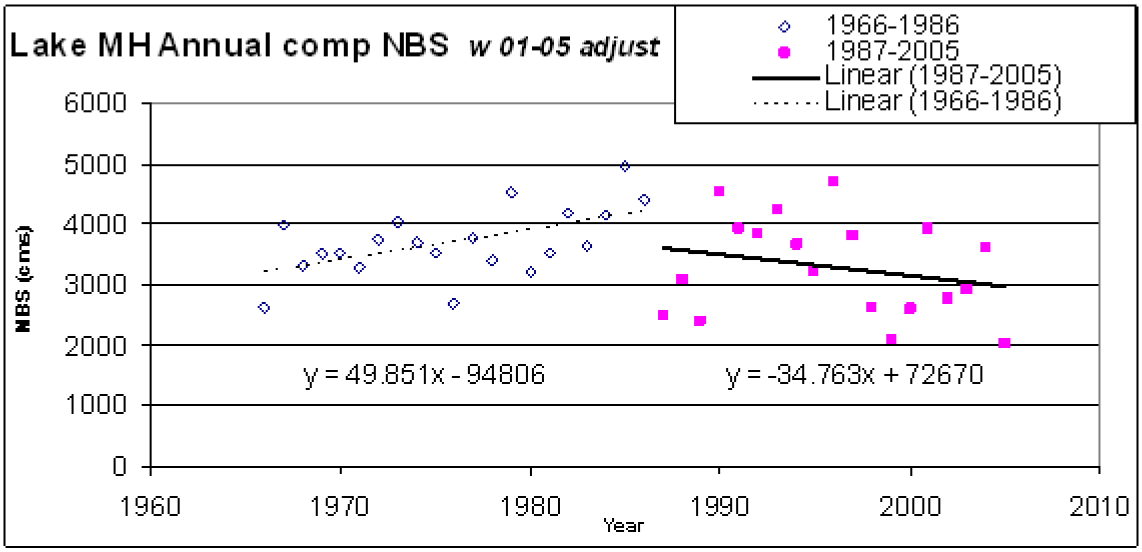
This implies that in at least half of the stochastic trials, the simulated head-difference was not influenced by the post-1977 conveyance change, but rather, highlights the rather rare occurrence of the observed NBS values.

As noted earlier, considering the work by Ouarda *et al.* (2009), two climate eras derived from change-point analysis using lake-level data were defined as 1970 and 1989. As shown in the figures, there appears to be some change in direction in trend around 1986 for NBS as well, however, this was not picked up in the change-point analysis as shown in figure 6-3(a), even though a change appears to have occurred. Figure 6-9 shows the Lake Michigan-Huron NBS tendencies based on a 1986 change-point and highlights that there appears to be some change in direction in NBS. It is interesting to note that this event coincides with, but is independent of possible conveyance changes noted by Quinn 2008(d).

To assess climate and conveyance change in the context of a simulation study in a comprehensive and objective manner required sampling these periods separately in a series of bootstrap experiments and incorporating the post-1977 conveyance change. The resulting simulations showed the average drop in head difference is estimated to be 59 percent less when the 1966-1986 climate era is sampled instead of the 1987-2005 climate era. Furthermore, only 1 of 1,000 alternative NBS sequences sampled from 1966-1986 period generated head difference behavior that could be considered equal or more extreme than the historical conditions observed from 1996-2005. Based on these results, it would appear that change in climate era is more than three times as influential as the post-1977 change in conveyance considering their impacts on the magnitude of the drop metrics.

Considering both the deterministic and stochastic findings, the post-1977 conveyance change on the St. Clair River was estimated to cause no more than one-third of the drop in head difference and more likely responsible for approximately one-quarter of the drop in head difference. Other factors (particularly climate) contribute to the substantial majority of the drop in head difference that was observed for the 1996-2005 period.

Figure 6-9
Analysis of NBS for Lake Michigan-Huron



Note: Illustrates the change in direction of potential NBS trends around 1986.

6.3.3 A Focus on the 1996-2005 Period

A more focused project was undertaken by Lee and Dahl (2009) to illustrate and quantify the contribution of the many possible factors that may have affected the change in fall between Lake Michigan-Huron and Lake Erie for 1996 to 2005. A series of lake level simulations were made to evaluate the contribution of the lakes' NBS, the Lake Superior outflow, diversions, ice and weed retardation, and changes in conveyance.

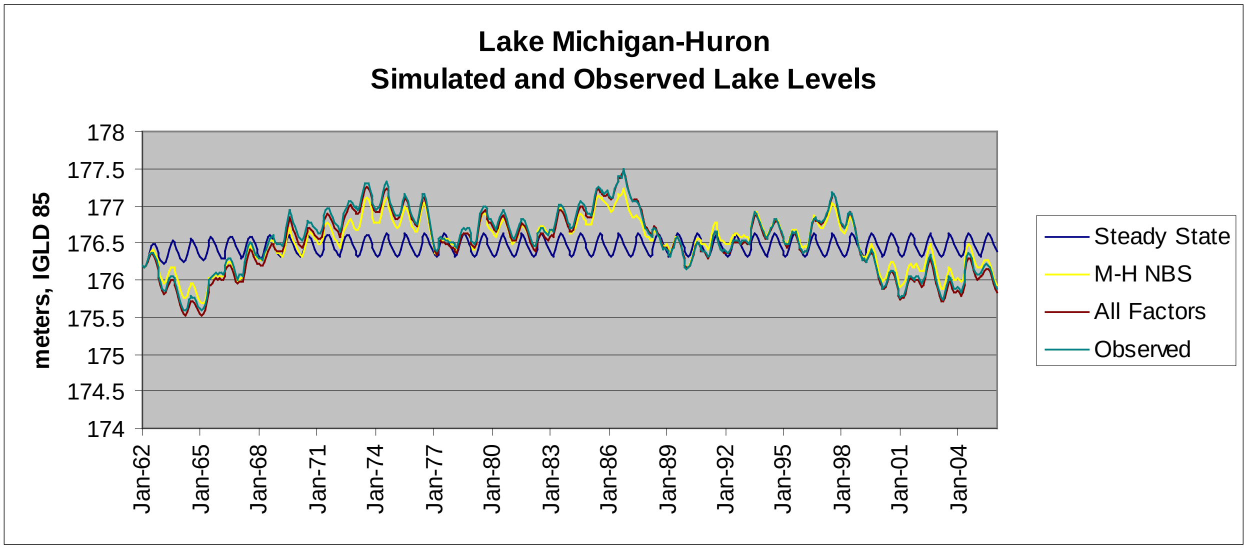
A base simulation for 1962 through 2005 was first conducted that represented long-term average hydrologic conditions using the CGLRRM. Then the influence of each factor was evaluated by repeating the base simulation with the observed values input to the simulation separately. The simulation was started with actual 1962 initial conditions and assumed St. Clair River channel conveyances as represented by the Fay and Noorbakhsh (2004) stage-fall discharge relationship.

Three simulations then looked at plausible change in conveyance scenarios:

- a scaled change in conveyance beginning in 1971 and increasing to a new channel capacity by 1989;
- an abrupt change in conveyance beginning in 1984 coinciding with the record St. Clair river ice jam; and
- an abrupt change in conveyance beginning in 1989 coincident with potential channel erosion following the high lake levels of 1986-1989.

A final simulation was made considering all of the factors including change in conveyance and compared to the recorded lake levels to verify the model's performance (see Figure 6-10). The simulations were repeated for both residual and component NBS.

Figure 6-10
Simulated Lake Michigan-Huron Lake Levels Using Residual NBS



Note: Residual NBS for a) steady-state scenario, b) the influence of Lake Michigan-Huron NBS, c) all factors and d) the observed lake level.

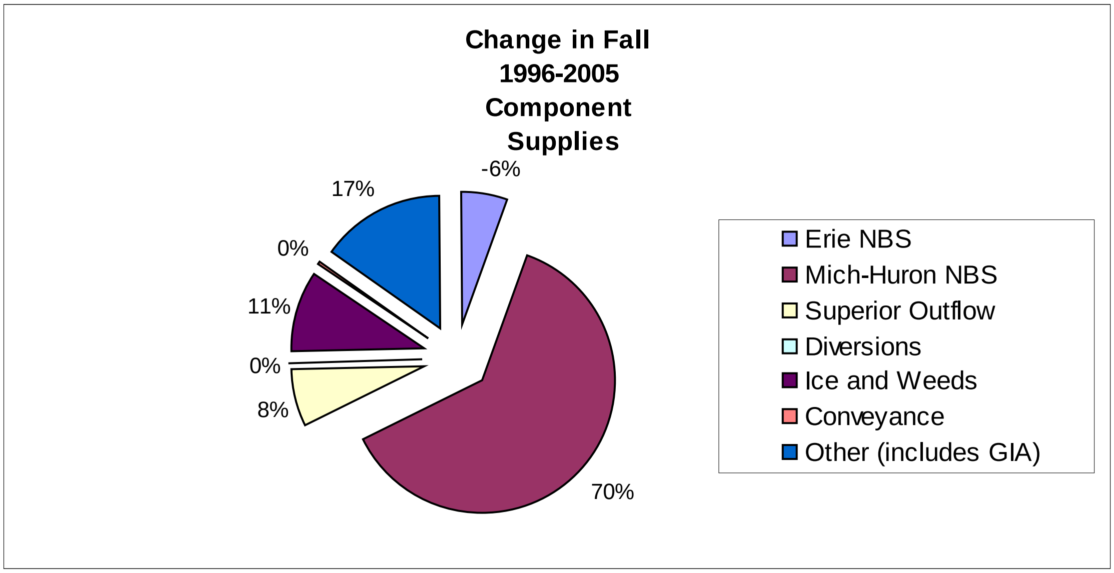
The change in fall between the lakes was then computed for each scenario and for the observed lake levels, using the 1996 and 2005 January monthly mean lake level. The percentage of the fall explained by each factor was then calculated. Figure 6-11 illustrates the percentages. The model results show that between 70 to 72 percent of the change in fall is due solely to the decline in Lake Michigan-Huron NBS. The Lake Erie NBS only contributed to less than 4 percent of the change in fall via a backwater effect on Lake Michigan-Huron's levels. The effect of Lake Superior's outflow accounts for 6 to 8 percent of the change in fall, while apparent ice and weed retardation accounts for 11 to 14 percent. Diversions from Lake Michigan-Huron had negligible effect as they were small and relatively constant.

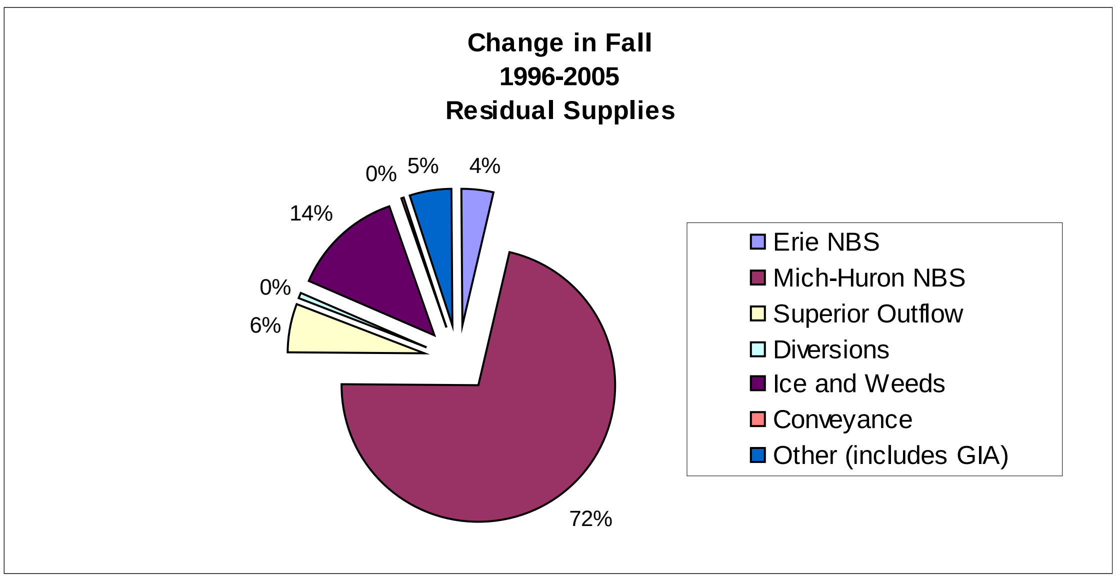
Interestingly, the simulations revealed that the change in conveyance made no contribution to the change in fall for the 1996-2005 period, confirming the stochastic analysis presented by Tolson (2009). This is because the change in conveyance occurred earlier enough for the system to reach equilibrium after the initial increase in channel flow. The majority of impact occurs within three years of the conveyance change, and this period (1989 to 1992) is before the 1996 to 2005 period being evaluated (Quinn, 1985).

An estimated 5 to 17 percent of the change in fall is attributed to other factors not explicitly accounted for in these simulations, including glacial isostatic adjustment, NBS errors and model calibration. The percentage is larger for the component supplies as the apparent weed and ice retardation factors were not re-computed for them but were instead based on the residual supplies.

Both of these modelling exercises appear to support independent earlier work done by Quinn (2008-b), which concluded a conveyance change in the St. Clair River in the mid-1980s, likely due to the record high lake levels of 1986 or a major ice jam in 1984. The Quinn study concluded that the changes appear to have taken place in two reaches of the St. Clair River, the reach from Dry Dock to St. Clair Police and the reach from the mouth of Black River to Dunn Paper. He concludes that it is possible that erosion has increased the conveyance in the river and resulted in the lowering of Lake Michigan-Huron by about 5 to 7 cm (2 to 2.6 in). The results of the Study's analysis described above are consistent with these conclusions.

Figure 6-11
Attribution of the Change in Fall between Lake Michigan-Huron and Lake Erie, 1996-2005
(top figure: component supplies; bottom figure: residual supplies)





6.4 New Modelling and Monitoring Approaches

6.4.1 Hydroclimatic Modelling and Analysis

In an effort to improve component NBS estimates, an independent model, the CRCM, was used to assess shortcomings and further refine the component water balance estimates (see Figure 6-1). The CRCM model complements the existing quasi-operational modelling system developed by the GLERL.

An initial assessment of monthly mean simulated NBS and its components using the CRCM has been completed. Early results indicate that the model reproduces the GLERL data relatively well for most months, and for each component. The largest differences are for monthly runoff estimates (see Figure 6-12). This finding is not surprising, as the routing component of the model has not yet been implemented. Annual runoff estimates agree to within 7 percent, which nevertheless still represents the largest bias of all the components of NBS.

Evaporation estimates from the CRCM, GLERL and measured evaporation (see Section 6.4.2) were examined. Comparison with measurements indicate that the GLERL model compares better in June and July than the CRCM, successfully modelling both the direction and general magnitude of evaporation and condensation. Other months (August to November), indicate that both models simulate evaporation reasonably well. While annual estimates of both models agree well, the significant monthly differences require further investigation.

In summary, initial investigations indicate the current suite of models of the component NBS show no large differences annually. However, there can be large monthly differences between the methods. The techniques being developed are providing insights into the error structure and confidence limits that can be expected from the component estimates of NBS.

6.4.2 New Observation and Monitoring Technologies

Lake Evaporation

Until recently, evaporation from Lake Superior could be estimated only as a residual of the long-term water or heat budgets or from meteorological data. A field project is currently being carried out by Spence *et al.* (2009) that directly measures evaporation over Lake Superior using an eddy covariance system. Meteorological data collection began in June 2008 at Stannard Rock lighthouse, 38.6 km (24 mi) southeast of Manitou Island (Figure 6-13).

Comparison of these direct measurements with evaporation estimates generated by the GLERL and CRCM models can identify strengths and weaknesses in each method of lake-wide evaporation estimation. Observed data suggest that the atmosphere above the lake in June and July is highly stable, with most energy directed to heating the water (Table 6-4). During these months, a strong negative bias in the CRCM humidity gradient results in significant condensation over the lake. The GLERL model performs better during this period than the CRCM, but only because it overestimates water temperature. Once the evaporation season begins, both models follow the observed humidity gradients (mid-August to October). Analysis performed to date is representative of the ice-free season only; it is important to continue field observations of evaporation until data from an entire year are available for comparison with the models.

Figure 6-12
Comparison of GLERL and CRCM Models
(Computed monthly NBS and over-lake precipitation, basin runoff and lake evaporation for 1998-2005)

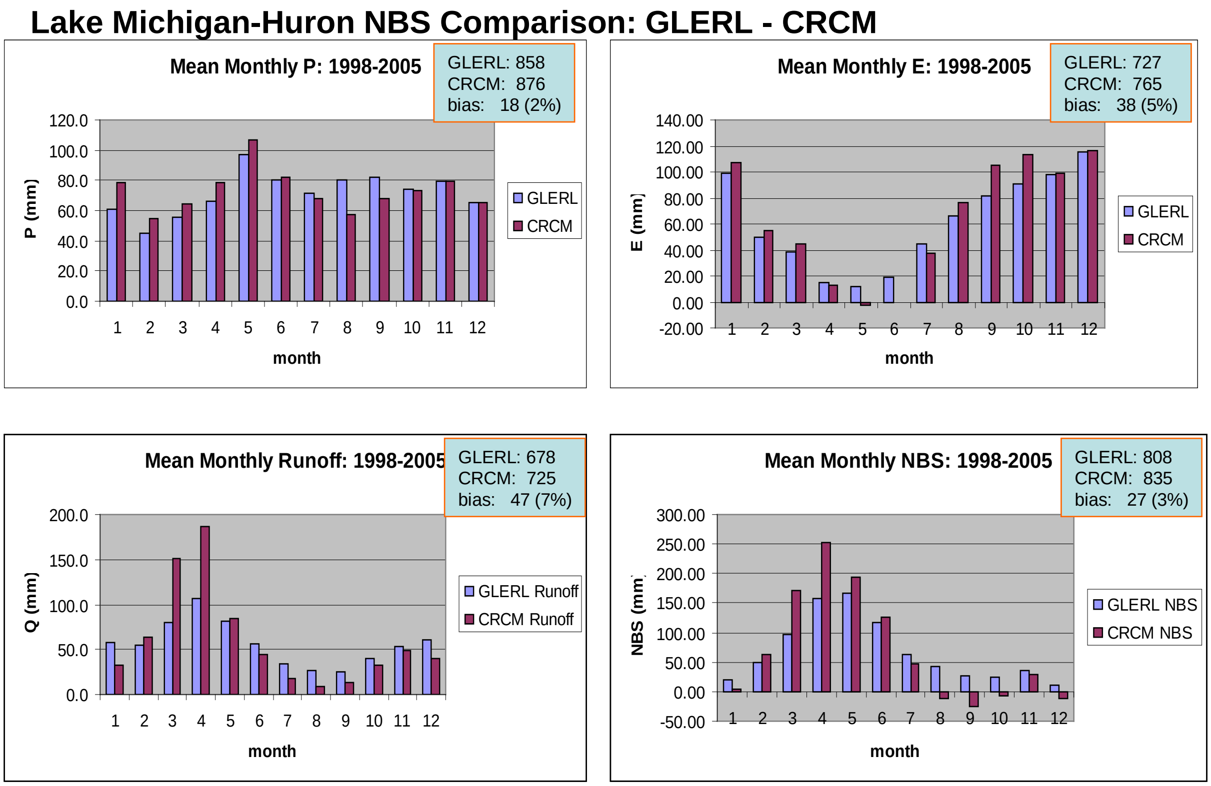
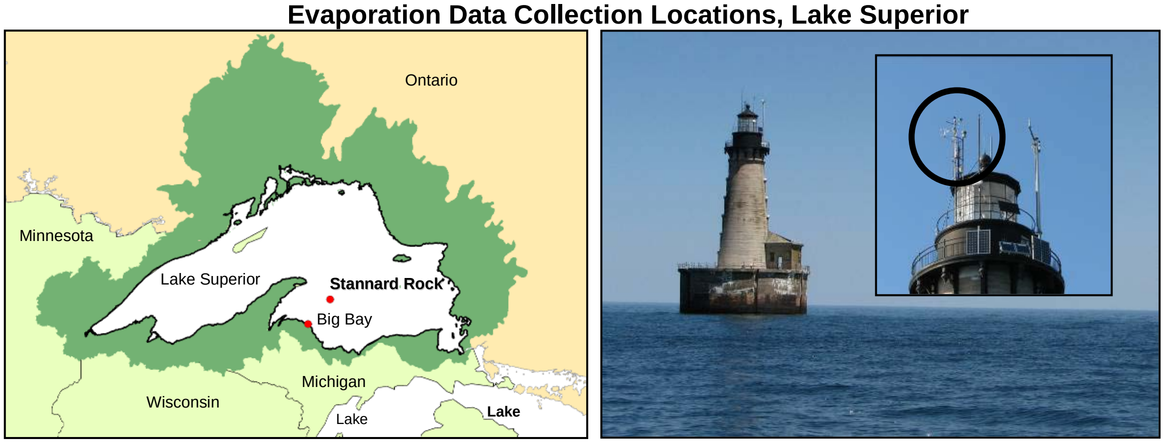


Figure 6-13
Evaporation Data Collection Locations, Lake Superior



Note: Left: Lake Superior and its watershed in dark green. Notable locations are denoted by the red dots. At right, a picture of the Stannard Rock lighthouse with an inset image of the eddy covariance and meteorological sensors.

Table 6-4
Monthly Evaporation Rates, 2008
(mm)

Month	Observed	Extrapolated	GLERL	CRCM (Stannard)	CRCM (Superior)
June	-3.0	-2.4	-1.2	-24.7	-19.9
July	1.8	1.2	5.9	-15.8	-10.9
August	14.9	20.3	28.3	16.3	22.2
September	55.6	62.8	51.9	54.0	61.0
October	76.9		83.1		
November	18.2		32.9		

Over-lake Precipitation

DiMarchi (2009) estimated the error in estimates of over-lake precipitation for each lake. Over-lake precipitation estimates from the National Center for Environmental Prediction Multi-sensor Precipitation Estimates Stage IV product were compared to values derived by GLERL's Thiessen interpolation method. Tests reveal a high correlation between MPE and GLERL estimates for the 2002-2006 period. However, the MPE product does not provide full radar coverage for some lakes (see Figure 6-14) and there are inconsistencies on how NOAA National Weather Service personnel quality control or even consider precipitation over-lake and over Canada in preparing the Stage IV product. Precipitation estimates for Lake Superior and Lake Huron will require integration of Canadian radar products. Table 6-5 shows that the Lake version of GLERL estimates is better than the Land version and does not show relevant bias.

Figure 6-14
Average 2002-2006 Precipitation During Summer Months
(mm/day)

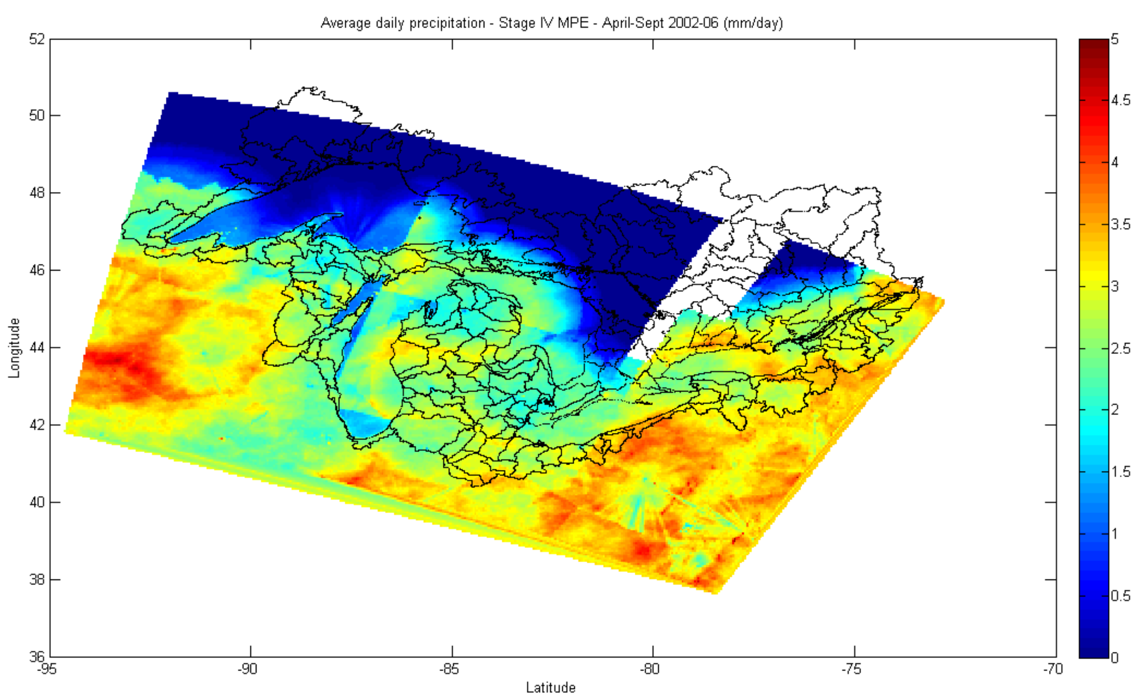


Table 6-5
Comparison of Lake-Wide Mean Monthly Precipitation Estimates

	Lake Ontario	Lake Erie	Lake Michigan	Lake Huron*
MPE*/TPLake				
Bias (%)	-0.97	-2.7	-4.2	9.6
Correlation	0.93	0.96	0.97	0.79
C.I. 2.5%	-31%	-24%	-21%	-27%
C.I. 97.5%	27%	23%	58%	83%
MPE*/TPLand				
Bias (%)	6.80	-2.3	-1.0	10.3
Correlation	0.91	0.88	0.96	0.78
C.I. 2.5%	-25%	-42%	-22%	-30%
C.I. 97.5%	52%	39%	84%	93%

Note: Estimates by MPE (only partially available for Lake Huron); GLERL Thiessen Polygons – Lake, and GLERL Thiessen Polygons– Land: percentage bias, correlation, RMSE/average MPE, and Confidence Interval boundaries for GLERL Thiessen Polygons (January 2002-December 2006).

Runoff Estimation

DeMarchi (2009) also assessed the uncertainty in GLERL's methodology for lake-wide river runoff estimates by assessing the error derived from:

- area-weighting measured flows of nested basins to a downstream gauged location (same-basin error); and
- area-weighting measured flows between gauged basins (inter-basin error).

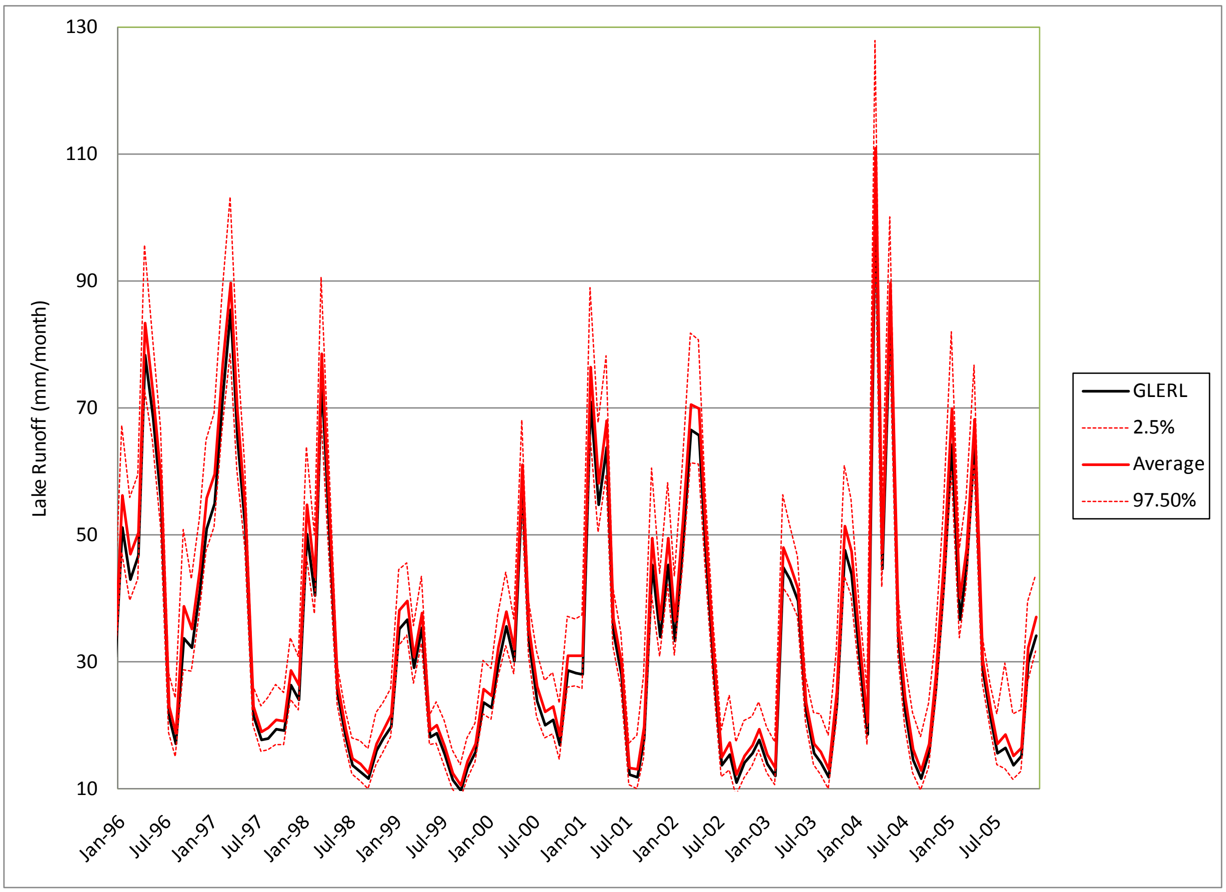
It was shown that inter-basin error is potentially the largest source of uncertainty within the GLERL model. The total runoff estimation and relative uncertainty is obtained by combining the measured data and the same-basin and inter-basin errors in an uncorrelated way in a Monte Carlo analysis (Figure 6-15). GLERL estimates are relatively accurate for the Lake Erie and Lake Michigan basins, where hydrometric gauge density is highest, but more uncertain and affected by a significant bias for the other lakes (Table 6-6).

Table 6-6
Relative Differences between Monte Carlo Simulation and GLERL Estimates
(1966-2005)

	Lake Erie	Lake St. Clair	Lake Huron	Georgian Bay	Lake Michigan	Lake Superior
2.5%	-8.11%	-13.21%	-8.86%	-10.26%	-3.46%	-12.25%
Average	2.60%	6.70%	6.66%	6.09%	6.83%	5.72%
97.5%	17.03%	37.22%	28.04%	31.93%	20.26%	29.62%

Ouarda *et al.* (2009) propose to develop a new technique for prediction of streamflows at ungauged sites based on regional flow duration curves (FDCs) and nonlinear spatial interpolation techniques. This project will consist of two parts. The first will involve the reconstruction of daily historical streamflow time-series for all ungauged basins using spatial interpolation techniques. Climatic and physiographic basin characteristics will be used to establish regional estimation models using a stepwise regression method. FDCs at ungauged sites will be estimated using a regional parametric approach. The second part of this project will develop an optimal approach for predicting daily streamflows at ungauged sites using neighbourhood regionalization techniques. A comprehensive evaluation of existing approaches of regional FDC estimation and a comparison of a spatial interpolation method with drainage area ratio methods will be performed. This project will lead to the development of a real-time streamflow prediction tool for ungauged basins within the Great Lakes basin.

Figure 6-15
Total Runoff to Lake Huron Estimation and Relative Uncertainty, for 1996-2005



6.5 Discussion on Results of Hydroclimatic Analyses

In responding to the science question *How has climate affected the change in lake level relationship between Lake Michigan-Huron and Lake Erie?,* the various projects indicate that climate has played the dominant role, while channel conveyance and glacial isostatic adjustment have had a smaller effect. A significant decline in water supplies to Lake Michigan-Huron over the past decade has resulted in its lake levels declining relative to Lake Erie levels. The hydroclimatic projects have revealed the need for more careful estimates and continual monitoring and analysis of Great Lakes water supplies and connecting channel flows. This will become especially important as part of an ongoing adaptive management effort to deal with the emerging but, as yet, unknown effects of climate change. New procedures and techniques for doing so are under development and evaluation.

6.6 Additional Work

Although significant progress was made on the hydroclimatic projects given the accelerated time line to report on the St. Clair River issue, additional work still remains. The additional work is focused on undertaking the detailed analyses required as part of the development of a new Lake Superior regulation plan, and does not affect the results shown to date with respect to the influence of hydroclimatic factors on the decline in head difference between the lakes. This additional work includes the following projects:

Comparative Analysis of Net Basin Supplies

With respect to the comparative analysis, a re-assessment of the residual NBS, computed with the new flow estimations (St. Clair, Detroit and Niagara Rivers), remains to be completed. Likewise, a similar re-assessment of the component supplies is pending the completion of improved hydroclimatic models, better geospatial methodologies for computing watershed runoff and over-lake precipitation, and the lake evaporation uncertainty analysis and field studies. A final re-assessment and revision of the hydrologic data (channel flows and NBS) will be completed and published.

Statistical Analysis and Teleconnections

Although most of the work has been completed on the statistical analyses of the hydrologic data, work is still progressing on assessing trends in lake ice cover and linking large-scale atmospheric circulation patterns to water supplies (teleconnections). Upon completion of these efforts, the stochastic water supplies (Fagherazzi *et al.*, 2005) generated for the International Joint Commission's Lake Ontario-St. Lawrence River Study will be re-assessed by the Study and revised, if necessary. This sequence of 49,995 years of stochastically generated water supplies will be used to test and evaluate proposed Lake Superior regulation plans.

Climate Change Sequences

In addition to the stochastic water supplies for plan evaluation, the Study will develop climate change sequences. An expert workshop was conducted in July 2008 to explore current methodologies and approaches. Work is in progress on preparing regional models (GLERL's Coupled Hydrologic Atmospheric Research Model and the Canadian Regional Climate Model) for global climate model down-scaling experiments of both present and future climates. The climate sequences will be used to develop an understanding of current and plausible future projections of Great Lakes water availability.

6.7 Key Points

- Climate is the main driver of the lake level relationships between lakes and over time. Although the water levels of the Great Lakes in the latter half of the twentieth century have been higher compared to the first half, there has been a persistent decline in NTS to Lake Superior and Lake Michigan-Huron over the past two decades. This has led to declining lake levels.

- The change in conveyance is only responsible for 25-33 percent of the change in fall between Lake Michigan-Huron and Lakes Erie from 1986 to 2005. Most of the effect of the change in conveyance occurred within three years of the conveyance change with this period ranging from 1989 (assuming a change in 1986) to 1992 (assuming a change in 1989).

- The climate was by far the major contributing factor for the 1996-2005 period. The temporary effect of earlier changes in conveyance on lake levels were shown to have little impact by this time. A substantial decline in Lake Michigan-Huron NTS was the primary cause of the change in lake level relationship to Lake Erie.

- New monitoring and observation methods are required to better estimate the water supplies to the lakes. New methods based on weather radars, direct sensing of lake evaporation and better estimates of basin runoff are being investigated by the Study.

- New hydroclimatic models are required to better predict climate effects on lake levels. The use of regional climate models to improve prediction of NBS is being advanced by the Study.