Chapter 4

Hydroclimatic Conditions: Past, Present and Future

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Lake Superior Regulation:
Addressing Uncertainty in Upper Great Lakes Water Levels

Final Report to the International Joint Commission

by the
International Upper Great Lakes Study

Chapter 4 examines how hydroclimatic processes affect Great Lakes water supplies and water levels, with a focus on the possible impacts of climate variability and climate change on future water levels.

4.1. Study Approach to Hydroclimatic Analysis[1]

A main task of the International Upper Great Lakes Study (the Study) was to assemble a broad range of hydroclimatic sequences to test the *robustness* of the candidate regulation plans – the capacity to meet regulation objectives under plausible future water level conditions – to replace plan **1977A** (see **Chapters 5** and **6**). This effort relied, in turn, on a hydroclimatic database that has been expanded and improved since the last major study of Great Lakes water levels in 1993 (Levels Reference Study Board, 1993). Despite these improvements, much of the science that underpins the plan formulation and evaluation by the Study is still challenged with uncertainties. Recognizing this challenge, the Study sought to reduce these uncertainties.

4.1.1 Science Questions

A major task of the Study was to examine the hydrology and climate of the upper Great Lakes, focusing on changes to the contemporary hydrology affecting the levels of the lakes and the impacts of future climate variability and change. The Study addressed two primary science questions:

- *What are the historical estimates of the net basin supply (NBS[2]) in the upper lakes and how have any potential changes to the water balance components affected the level of the lakes?*
- *What potential impact could variations in the climate system have on any future regulations of the Upper Great Lakes?*

The first science question was extensively investigated in the Study's first report to the International Joint Commission (IJC), ***Impacts on Upper Great Lakes Water Levels: St. Clair River***[3], which examined the physical processes and possible ongoing changes in the St. Clair River. The Study expanded on this previous work for this final report.

1 This chapter is based on peer-reviewed work undertaken by the Study's Hydroclimatic Technical Work Group (TWG) See the TWG's final report for more information on the methodology and analysis (International Upper Great Lakes Study, 2012).
2 Net basin supply (NBS) is the net amount of water entering a lake, consisting of the precipitation onto the lake minus evaporation from the lake, plus groundwater and runoff from its local basin, but not including inflow from an upstream lake. Time series of NBS are crucial as they are necessary to simulate water levels and flows and evaluate the impacts of the candidate regulation plans.
3 Available at the Study's website: www.iugls.org

4.1.2 Hydroclimatic Analytical Framework

The Study's analytical framework for conducting the hydroclimatic statistical and modelling studies consisted of three themes:

1. understanding the water balance of the Great Lakes (section 4.2);
2. assessing the reliability of historical recorded and estimated data, and increasing understanding of potential NBS conditions through the use of paleo-information[4] and stochastic[5] analysis (section 4.3); and,
3. addressing the plausibility and scope of climate change impacts on NBS using established down-scaling techniques and - new modelling work (section 4.4).

Figure 2-2 in **Chapter 2** illustrates these three themes in the Study's hydroclimatic analytical framework.

Based on this analysis, the Study developed contemporary and future NBS scenarios. These scenarios, in turn, supported other key analyses of the Study:

- testing the performance and robustness of a wide range of candidate regulation plans (**Chapters 5** and **6**); and,
- analyzing the role that adaptive management can play in helping interests in the upper Great Lakes basin better anticipate and respond to future extreme water levels (**Chapter 9**).

4.2 Theme 1: Understanding the Water Balance of the Great Lakes

The first theme of the hydroclimatic analysis involved assessing the validity of existing methodologies used to determine contemporary estimates of the water balance. Although the existing conventional methodologies used for estimating water balance components have proven relatively successful in the past, questions remain regarding measurement uncertainties associated with the principal components of the Great Lakes water balance (*i.e*., precipitation, evaporation and runoff). To address these questions, the Study sought to improve accuracy and consistency in NBS estimates, including the modification of existing models, development of new models, collection of new data, and improvement of a range of methodologies that have been used for lake level estimation. These analyses were also fundamental to ensuring that any potential future climate outcomes could be understood and attributed to past changes. This attribution required historical estimates of the water balance elements to be as bias-free[6] as possible and to have uncertainty bounds associated with each element.

[4]*Paleo* – a combining form meaning "old" or "ancient," especially in reference to former geologic time periods, used in the formation of compound words, as in *paleo-hydrology*.
[5]*Stochastic* – statistics involving or showing random behaviour. In a stochastic simulation, the common statistical properties of a historical series of streamflows or lake levels (*e.g.*, mean, standard deviation, variance) may be randomly rearranged to create a new 'synthetic' series of plausible flows and lake levels, based on those measured properties.
[6]Bias- refers to a systematic (*i.e.*, not random) difference between a quantity and a prediction of this quantity.

4.2.1 Residual and Component NBS

The two most commonly used methodologies for Great Lakes water balance accounting are:

- the *residual method*, which is more indirect and is based on change in storage of the lake; and,
- the *component method*, which directly computes NBS by specifying the water balance through a quantification of the components of the hydrological cycle for each lake, and accounting for all inflows and diversions.

Residual NBS

The residual method of estimating NBS requires accurate records of the inflow, outflow, the net change in storage (as expressed by the change in water level over a given time period), as well as the major diversions into and out of the lake. Change in storage due to thermal expansion and contraction, minor diversions and estimates of consumptive use are normally assumed negligible when compared to the other larger elements of the water balance.

The coordinated residual Great Lakes NBS database is maintained by the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (CCGLBHHD). The simplicity of the residual method, which relies primarily on water level measurements as the principal source of data, allows for residual NBS to be computed for the historical period of 1900 to present. For these reasons, residual NBS sequences have typically been used for operational and regulation planning purposes. For the Study's analysis, historical residual NBS sequences were deemed more suitable for both plan formulation and adaptive management purposes. A methodology was also developed as part of the Study to derive residual NBS supplies from historical data for the period 1860-1899 (Quinn, 2010), providing additional insight into the full range of NBS scenarios that have been experienced in the relatively recent past. The estimates of historical NBS for the period 1869 to 1899 are good only for Lake Superior, however. The NBS values for the downstream lakes cannot be estimated with confidence in view of unknown connecting channel conveyances.

Residual NBS are subject to considerable uncertainty, arising primarily from estimations of change-in-storage, inter-basin inflow and outflow, and diversions; not accounting for thermal volumetric changes, consumptive use, and minor diversions adds additional uncertainty (Neff and Nicholas, 2005; Bruxer, 2010). The amount of uncertainty depends not only on the accuracy of the methods used to estimate the different terms in the residual NBS equation, but also on the magnitude of the different quantities being measured, which varies depending on the lake. For example, the total uncertainty in the residual NBS computed for Lake Superior, where there is no connecting channel that flows into the lake and where the flow out of the lake makes up a relatively smaller proportion of the overall water balance, may be relatively small. By contrast, the uncertainty in NBS is greater for a smaller downstream lake such as Lake Erie, where the inflows and outflows are large in relation to the NBS, because relative errors in these terms are magnified (Quinn and Guerra, 1986; Neff and Nicholas, 2005; Quinn, 2009; Bruxer, 2010).

Furthermore, because NBS is computed indirectly using the residual method, these estimates cannot be used in the context of climate projections, where the physical processes that describe the interaction between climate and the different components of the hydrological cycle are required.

Equation for Calculating Residual NBS

$NBS = O - I + \Delta S - \Delta ST + D_o - D_i + C_{use}$

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

Understanding Component Supplies

The component method estimates NBS directly from its component contributions (*i.e*., overlake precipitation, basin runoff, lake evaporation and groundwater). Component supplies have traditionally been calculated using methods outlined by the Great Lakes Environmental Research Laboratory (GLERL) and have served as the basis for comparison against residual supplies for many years (Croley, 2008).

Since each primary component exhibits unique differences, relative to the methodology used for estimation, different techniques are commonly used to reduce errors and uncertainties. For overland *runoff*, computational estimates remain as one of the greatest sources of uncertainty in the calculation of component NBS for the Great Lakes. Daily streamflow information is essential for the adequate calculation of the overland runoff component as well as the management of the Great Lakes system in general. Monte Carlo analyses, in which the uncertainty of each error sources is simulated by randomly generating an ensemble of alternative and equally likely discharge, indicates that monthly runoff is slightly higher than estimates currently used to determine computed runoff. Investigations revealed that improvements in the estimates of discharge at gauge locations, application of better techniques extending discharge per unit area measured at downstream gauges to the entire watershed, and advances in determining basin-wide average discharge in gauged and ungauged water sheds could significantly reduce uncertainty in the calculation of component NBS.

Equation for Calculating Component NBS

$NBS = P + R - E + G$

Where:
P: overlake precipitation;
R: basin runoff to a Great Lake;
E: evaporation from the lake surface; and
G: net groundwater flux into a Great Lake[7].
All terms are expressed in m^3/s-months (ft^3/s-months) (or other time periods).

[7] The groundwater component has relatively small effects on the water balance and is also well within the uncertainty of the major components. Thus, the groundwater impacts were not considered further in the Study.

Overlake *precipitation* estimates can also introduce significant error into the overall water balance. Recent analysis has shown that estimates of overlake precipitation from the United States National Center for Environmental Prediction (NCEP) Multi-sensor Precipitation Estimates (MPE) Stage IV products can correctly identify areas of high and low precipitation for most of lakes Ontario, Erie, St. Clair, Michigan, and part of Lake Huron (DeMarchi *et al.*, 2009). These estimates can reduce uncertainty and error in determining precipitation amounts.

Until recently, *evaporation* from the Great Lakes was not measured, but rather was indirectly estimated as a residual of the long-term water or heat budgets, or modelled using meteorological data as input. The Study undertook investigations to directly measure evaporation at specific locations on Lake Superior and Lake Michigan-Huron using eddy covariance systems (Spence *et al.*, 2009), with the goal of improving overall lake evaporation estimates. Data collection began in June 2008 on Lake Superior at Stannard Rock Lighthouse (Figure 4-1), and in September 2009 on Lake Michigan-Huron at Spectacle Reef. Comparison of these direct measurements with evaporation estimates generated by models identified strengths and weaknesses in each method of lake-wide evaporation estimation. The IJC has committed to continuing field observations at different locations throughout the Great Lakes over multiple years, which will greatly improve the observational dataset and the theoretical models based on those data.

Figure 4-1
Gauging Station, Stannard Rock Lighthouse, Lake Superior

Inset - image of the eddy covariance and meteorological sensors

GLERL Model Estimates of NBS

GLERL model estimates of historical NBS from 1948 through 2008 were one of the component NBS estimates used by the Study. GLERL estimates each of the components using a suite of models and methods in conjunction with measured base data. Historical overlake *precipitation* is currently estimated by GLERL using observed precipitation measurements at primarily land-based gauges and extrapolating these point measurements to the lake surface using a weighting approach. Overland *runoff* has traditionally been computed using streamflow records at gauged streamflow stations, extrapolated to ungauged portions of the basin using area ratios of gauged versus ungauged basin area. Finally, a one-dimensional energy balance model, called the Large Lake Thermodynamic Evaporation Model, which was calibrated to surface water temperature and ice cover, is used to estimate lake *evaporation* from areal-average air temperature, wind-speed, humidity, precipitation and cloud-cover data. These approaches have been developed over many years and represent the first comprehensive attempt to quantify NBS components systematically in all the Great Lakes (Croley and Hunter, 1994).

MESH Model Estimates of NBS

To assess the current practices in simulating NBS, the Study applied another method for estimating component NBS. This approach is based on the coupled atmospheric hydrology modelling system developed by Environment Canada (Pietroniro *et al*., 2007). Using the surface and hydrology MESH model (Modélisation Environnementale - Surface et Hydrologie) coupled to the GEM (Global Environmental Multiscale Model) atmospheric model (Mailhot *et al.*, 2005), predictions of NBS were determined by solving both an energy balance equation and a mass balance equation on a two-dimensional grid, over both land and water (Fortin *et al.*, 2011).

Precipitation and overlake evaporation estimates were obtained from short-term forecasts (lead time of 6 to 18 hours) generated by the GEM numerical weather prediction (NWP) model. Overlake evaporation predictions were verified against observations from the Stannard Rock eddy covariance system on Lake Superior, established by the Study. Changes to the parameterization of surface roughness over water used by GEM were necessary to better fit these observations, which resulted not only in improved evaporation forecasts, but also in improved precipitation forecasts. Since a significant amount of uncertainty in NBS comes from the uncertainty in the runoff component, predicted streamflow was replaced by observed streamflow at 169 locations across the basin, corresponding to approximately two-thirds of the land portion of the Great Lakes watershed. The remaining one-third was predicted by the hydrological model WATFLOOD (WATerloo FLOOD) (Kouwen, 1988).

NBS was computed for each lake, based on estimates of overlake precipitation, overlake evaporation and runoff from the watershed. The resulting five-year hindcast (June 2004 - May 2009) of NBS for the Great Lakes were obtained and illustrated in Figures 4-2 and 4-3 as the water level responses to the cumulative effect of NBS over time.

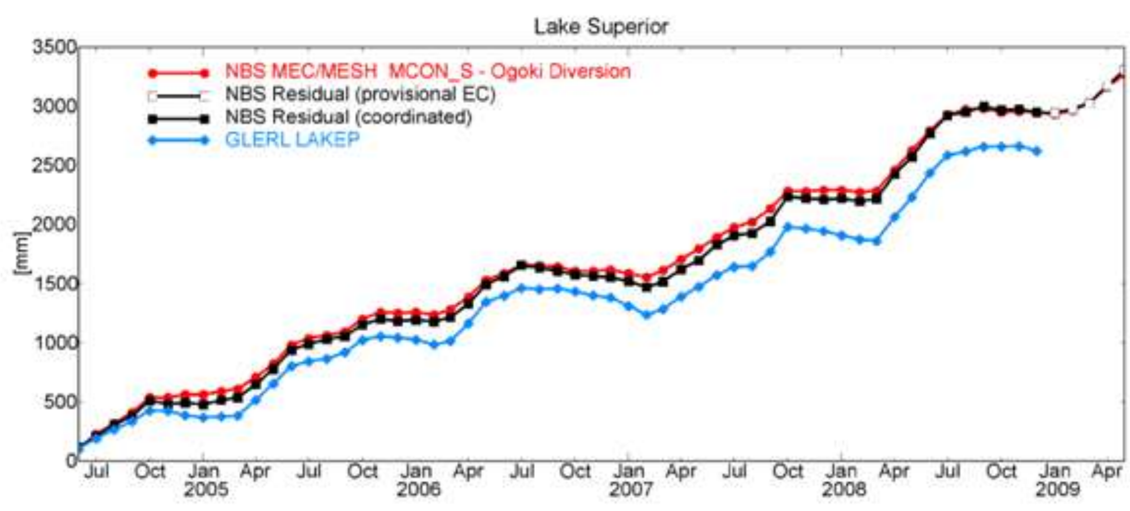


Figure 4-2
Cumulative NBS for Lake Superior
in MCON_S plotted against the coordinated and provisional residual NBS, and the GLERL NBS

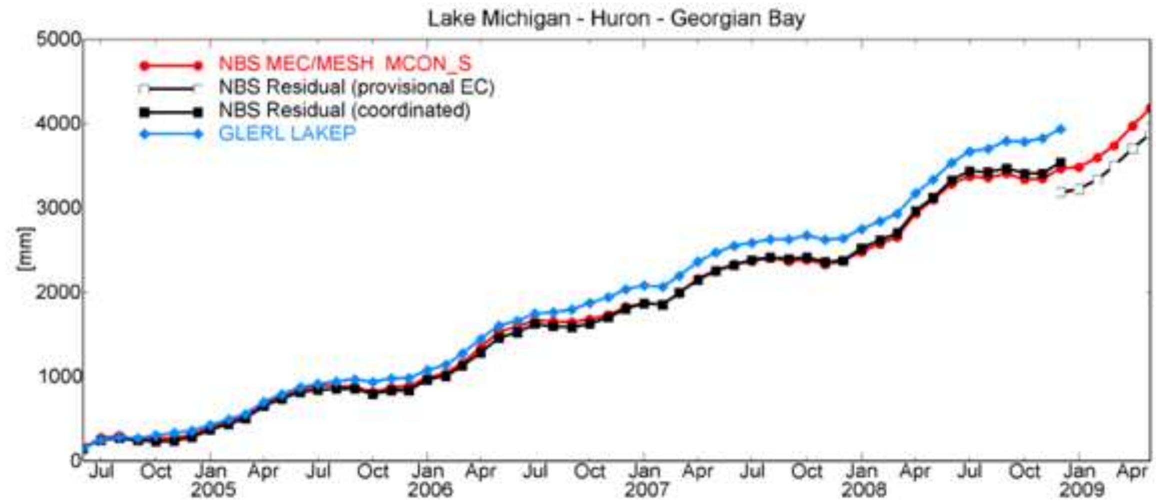


Figure 4-3
Cumulative NBS for Lake Michigan-Huron
(including Georgian Bay)
in MCON_S plotted against the coordinated and provisional NBS, and the GLERL NBS

MESH predictions of cumulative NBS (the sequence of partial sums from June 2004 to May 2009) match the cumulative sum of residual NBS very well. These data are plotted alongside the GLERL estimates. This does not prove that either estimate is correct, because each estimate was derived independently. However, it does increase confidence in NBS predictions obtained from these two methods (*i.e.*, MESH and residual NBS). However, the GLERL approach is more readily applied to long historical periods, as it requires less data, though bias corrections must be made, as discussed next.

Understanding Bias in Component NBS

The water balance analysis undertaken during the Study resulted in two existing time series of component NBS. The GLERL component NBS dataset for the 1948-2008 period was re-analyzed and updated in light of the observations and efforts over the duration of the Study. The component NBS dataset developed by Environment Canada used the MESH modelling with improved estimates from observations. GLERL's dataset extends back to 1948, which is very useful for assessing trends and detecting shifts in components of NBS, thus helping understand changes in NBS. However, while GLERL component NBS correlates well with coordinated residual NBS, it does not have the same long-term average. As noted above, at least over the short-term, the MESH estimates also correlate well and do exhibit less systematic bias.

Environment Canada's dataset based on the MESH model extends back only to 2004, but agrees slightly better with residual NBS than the GLERL dataset for this same period. In particular, the five-year mean of MESH component NBS is closer to the five-year mean of residual NBS for all lakes. Cumulative NBS comparisons confirm this. These results increased the confidence that the Study had in NBS estimates obtained from the MESH component and residual methods. In addition, it was also shown that compared to evaporation measured at Stannard Rock on Lake Superior, GLERL component NBS shows a significantly higher evaporation rate (Fortin *et al.*, 2011). Furthermore, overlake precipitation estimates are obtained from near-shore stations, many of which are automated, and it is recognized that precipitation gauges are negatively-biased (Goodison *et al.*, 1998). This bias is stronger for snowfall than rainfall and much stronger at exposed sites such as near-shore stations. The GLERL uncertainty estimates for precipitation and runoff also confirmed the potential for bias (DeMarchi *et al.*, 2009). Therefore, there were reasons to believe that GLERL component NBS could be substantially affected by biases (Figure 4-3).

It was not possible within the timeframe of the Study to perform the level of analysis, revision and subsequent validation of the GLERL component NBS models that would be required to correct for all potential sources of bias, measurement error and model error, and uncertainty uncovered as a result of the Study's efforts in this area. Future scientific research and development at GLERL, including analysis and application of the latest generation of regional climate models (RCMs) will focus on these priorities (*e.g.*, Holman *et al.*, 2012; Gronewold *et al.*, 2011).

Nonetheless, by comparing GLERL and MESH component NBS estimates for the most recent period of record, it was possible to estimate a bias correction and compute a bias-corrected estimate of component NBS back to 1948. The Study referred to this third estimate of component NBS as a *back projection* of MESH component NBS (MBP). A plot of cumulative NBS, computed backward from December 2008, shows that the MBP agrees better with residual NBS than the GLERL component NBS for all lakes (Figure 4-4). These MBP data were used to show the improvement in water balance closure shown in Lake Superior and Lake Michigan-Huron.

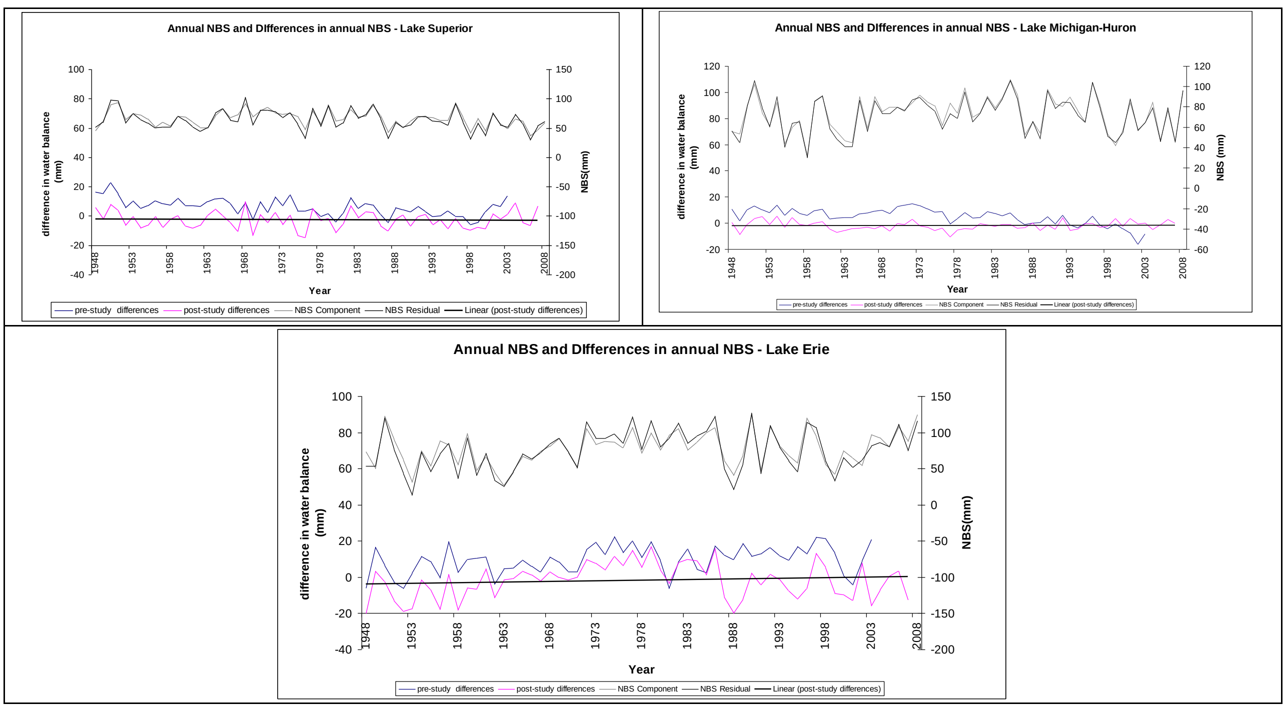


Figure 4-4
Sequences of Cumulative Residual NBS and GLERL Component NBS
(before and after bias correction, 1948 to 2008)
Cumulative NBS computed backward from 2008 to 1948.

Using this back-projected information, a time-series of precipitation, evaporation and runoff for each of the upper lakes was generated. Table 4-1 highlights these components for the 1948-2008 period. Estimates are monthly over the surface area of the lake. The data in the table represent the current best-estimate of the mean values of the individual components. DeMarchi (2011) also derived estimates of both bias-correction and confidence intervals (uncertainty) using linear regression and Monte Carlo analysis.

Table 4-1
Average Annual Water Balance Components of the Upper Lakes (1948-2008)

Note: derived from the final version of the GLERL estimates as mm over the lake

Lake	Method	Overlake Precipitation mm/year	Evaporation mm/year	Runoff mm/year	NBS mm/year
Superior	Component (GLERL)	789.2	605.6	616.4	799.2
	Component (MBP)	859.3	531.1	468.5	796.7
	Residual	n/a	n/a	n/a	774.9
Michigan-Huron	Component (GLERL)	840.8	655.1	721.1	906.8
	Component (MBP)	895.4	661.5	648.7	882.6
	Residual	n/a	n/a	n/a	860.0
Erie	Component (GLERL)	924.2	925.5	813.9	812.6
	Component (MBP)	973.1	933.8	770.1	809.4
	Residual	n/a	n/a	n/a	765.4

Table 4-1 presents a summary of component estimates using the component and residual methods. One of the goals of the Study was to reconcile the differences in results when using the two methods. A number of observations can be made. First, there is good agreement between the two component approaches, with MBP producing slightly lower estimates. Second, there are significant differences between these approaches for each component and from lake to lake. Third, the MBP component estimates are closer to the residual method estimates.

While the NBS estimates by the GLERL and MBP methods provide reasonable convergence with the residual NBS, it is clear that efforts are still required for reconciling each of the components. It is also apparent that offsetting errors bring the overall estimates closer together. Time limitations within the Study did not allow for further analyses that could prove helpful. These include calibrating the GLERL model with the observed evaporation data in Lake Superior and Lake Michigan-Huron, and continuing the hindcast back to 1997 from 2004 using the MESH model in an effort to better understand and reconcile component estimate differences.

4.2.2 Estimating and Addressing Uncertainty in the Component NBS Sequences

The uncertainty in component NBS was assessed through the collection of new observational data, through improved model parameterizations, and through comparisons of both the GLERL and MESH component NBS estimates with the residual NBS estimates. Applying the evaporation measurements and comparing the results of complementary modelling systems, the Study sought to quantify the uncertainty in the estimates more systematically. (For more information on the methodology, see DeMarchi *et al.*, 2009; DeMarchi, 2011; and IUGLS, 2012.)

1. Lake Evaporation

Monthly level evaporation estimates from Environmental Canada's MESH model were compared with GLERL Large Lake Thermodynamic Evaporation Model for the period from June 2004 to May 2009. The distribution of the residuals between the GEM and the adjusted GLERL values is fitted with a probability distribution to determine the uncertainty band. Evaporation estimates were generally successful in replicating GEM results and bias was strongly reduced or even eliminated (IUGLS, 2012).

2. Overlake Precipitation

Nearly all precipitation gauges in the Great Lakes region are located on land, making overlake precipitation estimation difficult and susceptible to error. The lack of offshore precipitation gauges also makes a direct evaluation of overlake precipitation estimate uncertainty challenging. The strategy adopted by the Study was to compare available estimates of overlake precipitation from a number of sources and assess any differences that are identified.

GLERL overlake precipitation estimates (derived using Thiessen polygon interpolation) were compared to improved estimates of overlake precipitation that included the use of weather radar and/or forecast data, including the NCEP's MPE Stage IV product and the MESH system's CaPA product (DeMarchi *et al.*, 2009). It was shown that MPE can correctly identify areas of high and low precipitation for most of lakes Ontario, Erie, St. Clair, Michigan, and part of Lake Huron. Using these estimates can reduce uncertainty and error in determining precipitation amounts. Thus, these data may prove useful for improving GLERL overlake precipitation estimates in the future. It was also shown that there were significant differences between the GLERL precipitation estimates and those obtained from the other two precipitation estimates, which showed better agreement, suggesting a bias in the GLERL precipitation estimates.

Monthly level precipitation estimates from Environmental Canada's CaPA were compared with GLERL overlake and overland estimates for the period June 2004 to May 2009. The distribution of the residuals between the MESH and the adjusted GLERL values was fitted with a probability distribution to determine the uncertainty band. It was found that the adjusted overlake precipitations estimates succeeded in replicating the MESH results and that the bias was eliminated (IUGLS, 2012).

3. River Runoff

Computational estimates of runoff remain as one of the greatest sources of uncertainty in the calculation of component NBS for the Great Lakes. Of the three components of the Great Lakes NBS, river runoff is potentially the most accurately measured, but large portions of the lake basin are ungauged. In addition, the proportion of the basin that is ungauged has increased in recent years, notably for lakes Superior and Erie (Table 4-2). This further exacerbates the uncertainty in overall estimates of runoff from the Great Lakes basin.

Table 4-2
Percentage of Ungauged Basin Area, by Lake

Year	Lake Superior	Lake Michigan	Lake Huron	Lake Erie
1992	34 %	24%	34 %	25%
2008	40%	25%	38 %	42%

1992: modified from Lee, 1992
2008: adapted from DeMarchi *et al.*, 2009

The Study evaluated three types of errors associated with estimating basin runoff in the GLERL approach (DeMarchi *et al.*, 2009):

- errors in the observed discharge estimates at gauged locations;
- errors caused by extending the discharge per unit area measured at the most downstream gauge in a sub-basin to the remaining ungauged portion of a sub-basin; and,
- errors caused by extrapolating the lake's basin-wide average discharge per unit area in the gauged portion of the basin to ungauged sub-basins.

These sources of uncertainty were investigated using Monte Carlo analysis. This analysis indicated that not only is monthly runoff computed using this method subject to a high degree of uncertainty, but that there are systematic errors in the computed runoff. Investigations also revealed that improvements in the measured discharge estimated at gauged locations, application of more sophisticated techniques for extrapolating discharge measured at gauged locations to the ungauged portions of the drainage basin, and other advances in determining basin-wide average discharge in gauged and ungauged watersheds could significantly reduce uncertainty in the calculation of runoff and component NBS.

4.2.3 Assessing Historical Trends

An assessment of hydrological trends can provide information relative to what happened in the past, revealing changes and previously undetected events. Trend and change-point analyses conducted in the first part of the Study provided valuable insight into what had transpired within the upper Great Lakes. The analyses revealed events and apparent shifts in the hydroclimatic regime that significantly added to existing knowledge. Following this same line of analysis, the Study addressed variations and trends in component NBS.

Given annual and monthly supply sequences, it is possible to analyze the three important component NBS terms and examine for trends. As noted by Gronewold and Fortin (2011), mean annual overlake precipitation is higher than mean annual overlake evaporation. More importantly, mean annual runoff is higher than the mean annual net overlake precipitation. On an annual basis, the ratio of net overlake precipitation to NBS is, on average, about 20 percent for lakes Superior and Michigan-Huron, about 1 percent for Lake Erie and about 10 percent for Lake Ontario. As is apparent, the contribution of net overlake precipitation is much smaller than runoff. Thus, it is critical to accurately assess the runoff component. Figure 4-5 shows annual mean net overlake precipitation (precipitation minus evaporation, or P-E), runoff, and component NBS for each lake from 1948 to 2008. The findings indicate a general decrease in annual net overlake precipitation for lakes Michigan-Huron and Superior over the last several decades, with a noticeable increase in the frequency of negative net overlake precipitation for these two systems from roughly 2000 to 2008. On Lake Ontario, 2007 was the first year, for the period 1948-2008, with negative net overlake precipitation.

Further analysis of the net precipitation shows that overlake precipitation in all cases is generally increasing largely in step with increasing lake evaporation, leading to a small year-over-year change to the net precipitation. This is easily demonstrated when contrasting Lake Superior and Lake Michigan-Huron as show in Figure 4-5. In the case of Lake Superior, annual precipitation appears relatively steady, while there appears to be increasing evaporation.

Lake Michigan-Huron also shows an increasing evaporation trend since 1948 with what appears to be a corresponding trend towards increased overlake precipitation. This evaporation trend has been documented on a number of occasions and is largely attributed to decreasing ice-cover (Assel, 2009, IUGLS, 2009). These trends are important when trying to establish the context for future NBS sequences. The best possible unbiased estimates described earlier were used to examine the trends and they do provide an important context for the Study. In general, there is an increasing evaporation in all of the lakes since 1948. However, the Study also determined that in most cases (except Lake Superior), this is coincident with increases in precipitation over lakes. These findings appear to be consistent with estimates provided in the regional climate assessment (discussed next) and confirm that while there are changes in both precipitation and evaporation, the net impact to NBS is not as great as noted in previous studies.

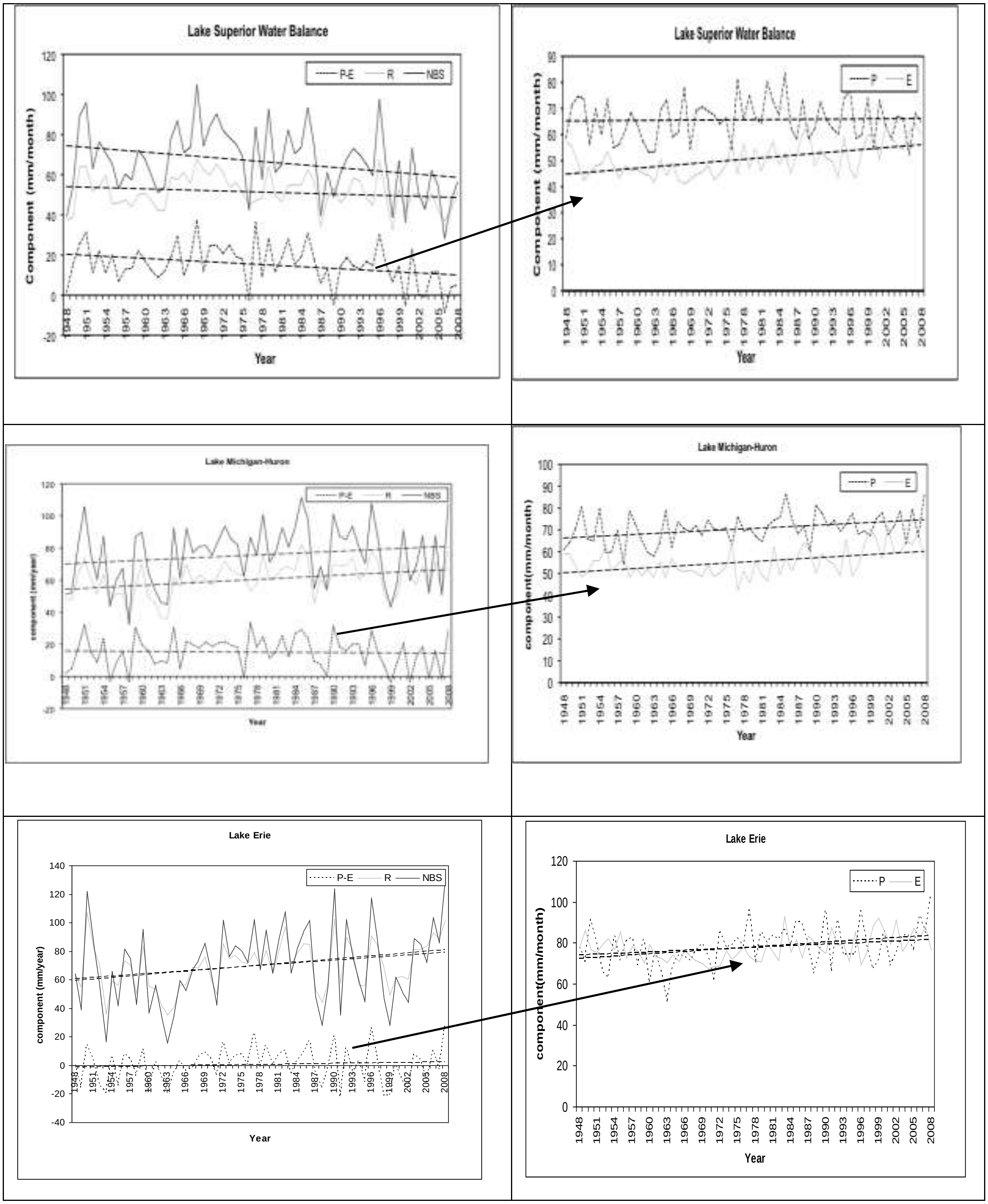


Figure 4-5
Annual Mean Net Overlake Precipitation, Runoff, and Component NBS
(1948 to 2008) Note: derived from Gronewold and Fortin, 2011

Understanding the Water Balance: Summary

The first theme of the Study's hydroclimatic analysis involved addressing the need to improve understanding of the water balance in the upper Great Lakes basin.

Questions remain regarding uncertainties associated with the principal component estimates of the Great Lakes water balance (*i.e*., precipitation, evaporation and runoff). The Study addressed this uncertainty through the collection of new observational data, improved model parameterizations, and comparisons of both the GLERL and MESH component NBS estimates.

Applying the evaporation measurements and comparing the results of complementary modelling systems, the Study sought to quantify the uncertainty in the estimates more systematically. This analysis found that:

- lake evaporation estimates were generally successful in replicating GEM results and bias was strongly reduced or even eliminated;
- adjusted overlake precipitations estimates succeeded in replicating the MESH results and that the bias was eliminated; and,
- computational estimates of runoff remain one of the greatest sources of uncertainty in the calculation of component NBS for the Great Lakes, exacerbated by the large proportion of the lakes basins that is ungauged.

Improvements in the runoff estimates at gauged locations, application of more sophisticated techniques for extrapolating discharge measured at gauged locations to the ungauged portions of the drainage basin, and other advances in determining basin-wide average discharge in gauged and ungauged water sheds could significantly reduce uncertainty in the calculation of runoff and component NBS.

In assessing historical trends in NBS, the Study concluded that evaporation has increased in all of the lakes since 1948. However, the Study also determined that except for Lake Superior, this increase in evaporation is coincident with increases in precipitation over the lakes. That is, while there are changes in both precipitation and evaporation, the net impact to NBS is not as great as noted in previous studies.

4.3 Theme 2: Assessing the Reliability of Historical Recorded and Estimated Data

In the second theme of the hydroclimatic analysis, the Study assessed the representativeness of historical variations and estimated data to provide insights into the potential impacts of climatic extremes and possible future trends. It was determined that a broad range of scientific approaches, in addition to climate modelling, should be explored to provide information relative to possible future climate scenarios. This would provide a greater range of possible conditions for consideration and alert investigators to any inconsistencies between model projections and the climates of the past. Two such approaches were paleo-investigations and stochastic hydrological analysis

4.3.1 Paleo-analyses

The Study examined paleo-sequences extending back more than 1,000 years to provide insight as to possible climate extremes in the future. Paleo-lake levels have been derived by dating submerged tree stumps and ancient beach ridges (Baedke and Thompson, 2000; Wilcox *et al.*, 2007) and reconstructed tree ring data (Quinn and Sellinger, 2006; Wiles *et al.*, 2009). Initial investigations focused on existing paleo-data, primarily tree ring and beach ridge data, as well as older measurements and climate transposition studies to examine extreme high and low lake levels that have likely occurred over the past 1,000 years. These data were used to examine potential extremes for water resource analysis and regulation studies. The information was indexed to modern reference points, such as modern chart datum levels, and the historical high and low lake levels for each of the upper Great Lakes, to the extent possible (Quinn, 2010).

The resulting analyses enabled an extrapolation of prehistoric Great Lakes water levels over the past 1,000 years. Figure 4-6 illustrates the wide range of possible lake levels (maximum and minimum) for Lake Superior, based on these findings. Comparable figures were produced for lakes Michigan-Huron and Erie, and exhibited similar ranges of levels.

Additional paleo-modelling (Brown, 2011) using a stochastic simulation framework (Prairie *et al.*, 2008) was employed to generate NBS sequences. This method consisted of a non-homogeneous Markov chain model simulating the hydrological state using the Palmer Drought Severity Index (PDSI) (Palmer, 1965) reconstructed data, and k-Nearest Neighbor[8](k-NN) to resample observational NBS magnitudes conditioned on the hydrological states. Using this methodology, 500 sequences of 100 annual NBS values were generated.

An important facet of the paleo-simulation framework was the ability to investigate the persistence of dry and wet spell years, which is a more important factor in lake regulation than a single year maximum or minimum lake level. The replication of persistent dry and wet spells is a vital link for long-term water management. Figure 4-7 illustrates the relative frequencies of uninterrupted dry and wet years from the random 500 simulations for the upper Great Lakes (Brown *et al.*, 2011). The bar graphs generally indicate that there is a longer persistence of wet spell years than for dry spell years for all the lakes. Although the relative frequencies are not significant, a dry spell of six or seven years statistically scored the highest for each lake. For a wet spell, there are slight differences among the lakes, but generally the model's highest frequency lies between six to eight years' duration. The data also show that dry and wet

[8]The k-nearest neighbor algorithm (k-NN) is a method for classifying objects based on closest training examples in the feature space.

periods of 10 to 15 years duration show up relatively frequently in the paleo-record, and need to be considered as part of any planning scenarios. This indicates the capability of PDSI reconstructed data to show the magnitude and duration of high and low epochs of NBS that were not observed during the period of historical record since1860 for Lake Superior. The modelling effort was able to replicate a variety of high and low sequences that have occurred in the past, based on paleo-data, and which provide a better sense of estimating the likelihood of extreme lake levels and their persistence over time.

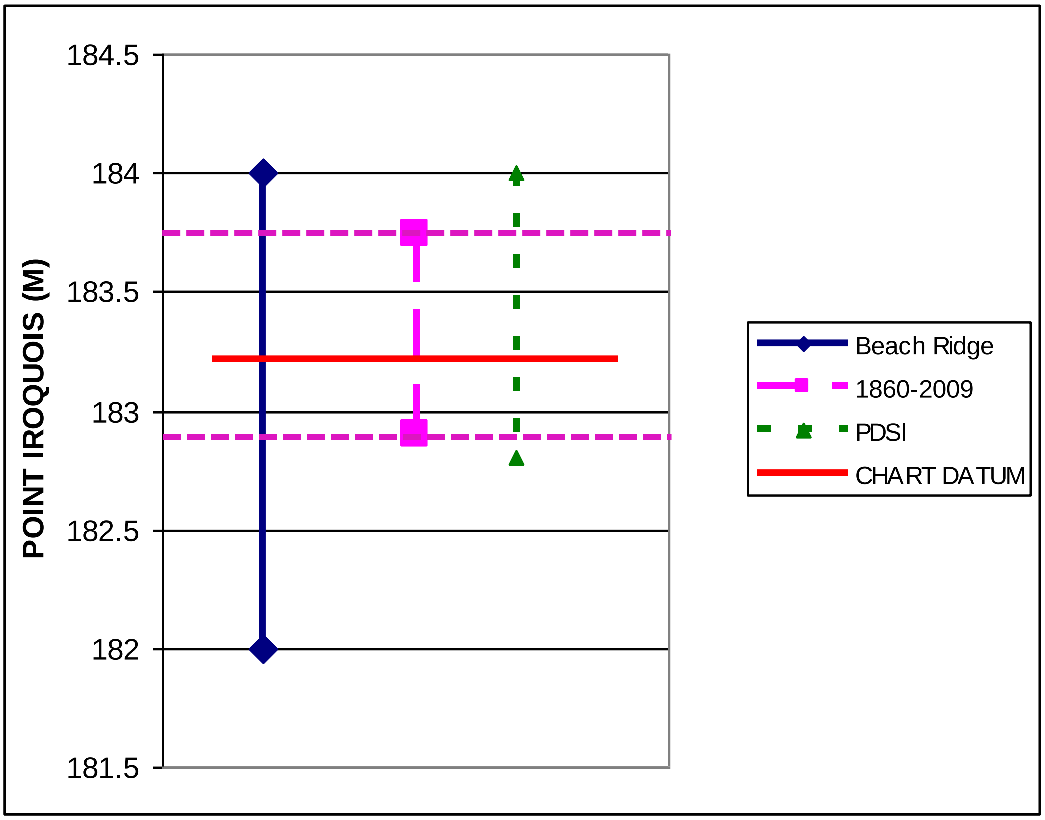


Figure 4-6
Estimated Levels of Lake Superior, Based on Paleo-data

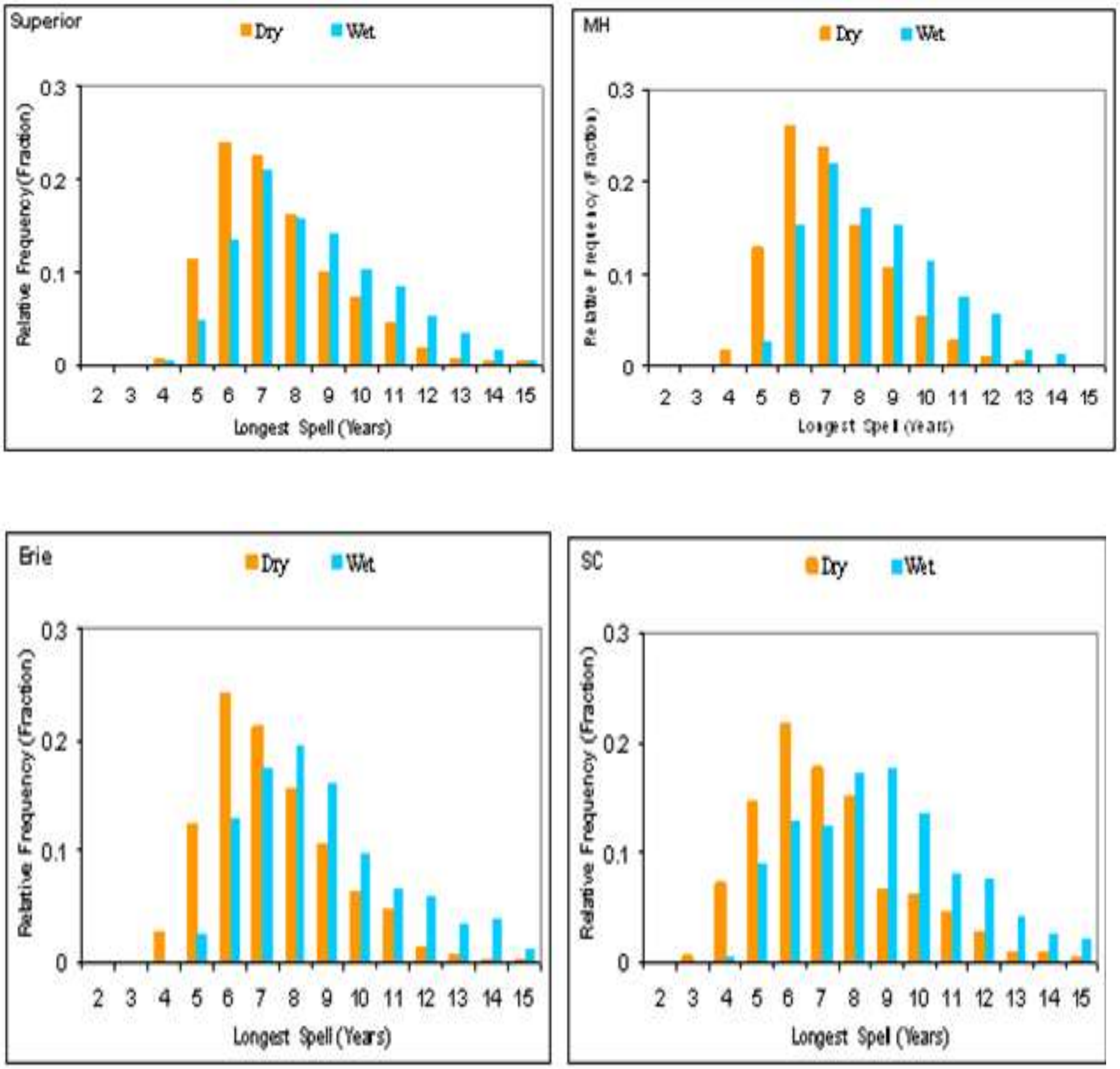


Figure 4-7
Relative Frequencies of Uninterrupted Dry and Wet Years, by Lake

4.3.2 Stochastic Models

Stochastic simulation of multivariate hydrological variables is routinely used to assist in evaluating alternative designs and operation rules, particularly where the historical record is relatively short or the risk of project structural failure is relatively high. The performance of a given regulation plan can be estimated by simulating the behavior of a water resources system using sequences of inputs that are long enough to contain a large number of potential hydrological scenarios that could occur in the future, including rare and potentially catastrophic events.

To obtain a greater understanding of the long-term variability of the past, whose modes might be extended into the future, the Study developed four stochastic models for plan formulation purposes. The stochastic series produced a wide range of plausible sequences of NBS not seen in the relatively brief historical record. (For detailed information on the models, see IUGLS, 2012).

CARMA Model

An initial stochastic model of current historical climate record was developed, using the Contemporaneous Shifting Mean – CARMA Model (CSM-CARMA) at the annual level and a temporal annual-monthly disaggregation scheme. The temporal and spatial characteristics of the revised Great Lakes Residual NBS data base (1900-2008) were used with revised CSM-CARMA model parameters to generate a new data base, including all the lakes, for the Study (Fagherazzi, 2011). NBS sample statistics and the corresponding routed levels and outflows were compared with observed characteristics which verified that the generated NBS, as well as the routed levels and outflows series, reproduced the characteristics of the historical series very well. A resulting series of 55,000 annual and monthly NBS combinations, representing the randomly reconfigured statistical properties of the current climate was provided for plan formulation and evaluation.

NL-ARX Models

Two approaches combined contemporary climate data with longer-term inter-annual and decadal climate oscillations, such as the El Nino Southern Oscillation (ENSO). This was done using a non-linear auto-regressive model (NL-ARX) to develop two alternative stochastic models where the apparent shifts in the mean of annual NBS was explained using climate-related variables (Lee *et al*., 2011). Shifts relate to a modelling assumption that the future NBS will exhibit the statistics of the past, and that the underlying process that produced the historical record is not changing over time. In this work, the shifts are presumed to be tied to climate indices. These approaches resulted in a series of 50,000 synthetic NBS values for plan formulation and evaluation.

Changed Climate NL-ARX Model

The final stochastic modelling technique utilized the stochastic NL-ARX model above to generate stochastic sequences of annual NBS with climate change-affected predictors produced by GCMs (Seidou *et al.*, 2011). The outputs of the third generation of the Canadian General Circulation Model (CGCM3), under two climate scenarios representing moderate and high emissions of greenhouse gases, were used to calculate future values of the predictors. The model generated 500 sequences of 100 years (corresponding to years 2001-2100) for each of the two scenarios.

Assessing the Reliability of Historical Recorded and Estimated Data: Summary

The second theme of the Study's hydroclimatic analysis involved assessing the representativeness of historical variations and estimated data to provide insights into the potential impacts of climatic extremes and possible future trends.

Paleo-analyses enabled an extrapolation of prehistoric Great Lakes water levels over the past 1,000 years. The results identified a wide range of possible lake levels (maximum and minimum) for lakes Superior, Michigan-Huron and Erie.

Additional paleo-modelling was employed to generate 500 sequences of 100 annual NBS values. The modelling effort was able to replicate a variety of persistent high and low sequences that have occurred in the past, based on paleo-data, and which provide a better sense of estimating the likelihood of extreme lake levels and their persistence over time.

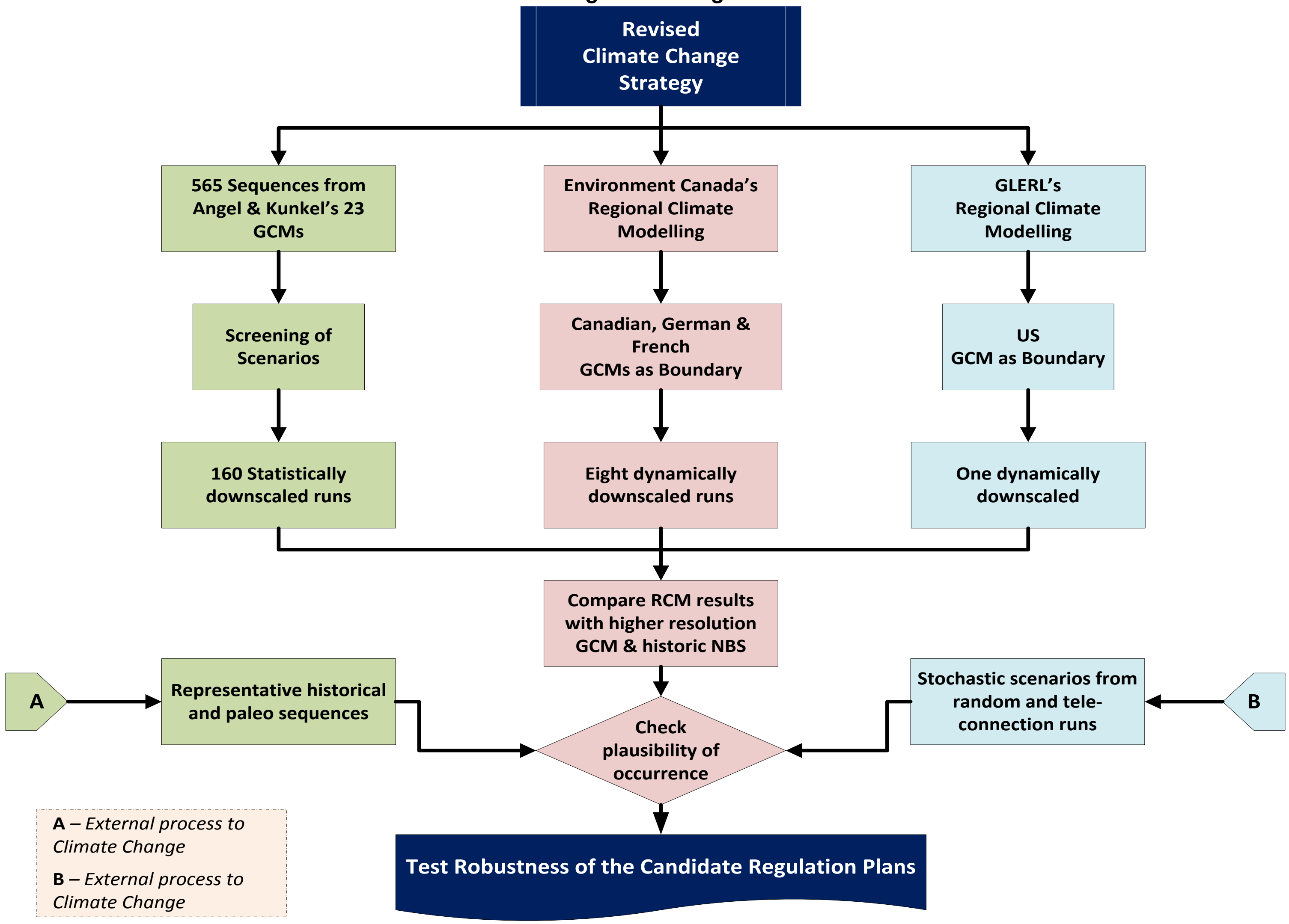
To obtain a greater understanding of the long-term variability of the past, four stochastic models were used to produce a wide range of plausible sequences of NBS not seen in the relatively brief historical record.

4.4 Theme 3: Assessing the Plausibility and Scope of Climate Change Impacts

Anthropogenic forcing of the climate system due to increasing concentrations of carbon dioxide and other gases are likely to lead to increased probabilities that by sometime in the 21st century the climate state in the upper Great Lakes basin will be outside the envelope of historically-observed conditions (IPCC 2007). The third theme of the Study's hydroclimatic analysis involved addressing the plausibility and scope of climate change impacts on NBS and water levels in the upper Great Lakes basin.

Figure 4-8 illustrates the Study's climate change modelling framework. As illustrated, the Study employed a number of approaches to address the possible impacts of climate change, including evaluating the validity of numerous model runs from GCMs and the applicability of utilizing the entire dataset or a subset of the runs. In addition, two RCMs were utilized to assess and derive down-scaled climate scenarios and current and future NBS sequences.

Figure 4-8
Climate Change Modelling Framework



4.4.1 GCM Climate Modelling

To fully encompass estimates of the future climate of the Great Lakes, the Study first evaluated output of 565 model runs from 23 GCMs compiled by Angel and Kunkel (2009). The model runs utilized future emission scenarios B1, A1B, and A2 representing relatively low, moderate, and high emissions, respectively. Scenario A2 corresponds most closely to recent experience and International Energy Agency projections (International Energy Agency, 2007). The Study considered both the validity of the model runs and the applicability of utilizing the entire data set or a subset of the runs.

The analysis used the GLERL model to calculate NBS and lake levels for the current climate (covering the period 1970 to1999), using the input variables of maximum, minimum, and mean temperature, precipitation, humidity, wind speed, and solar radiation. For each of the GCM runs, change functions expressed as the difference between the current climate and each of the future time slices (2005-2034, 2035-2064, and 2065-2094) were calculated.

Table 4-3 presents a summary of the results. The 50th percentile represents the projected change in lake levels where one-half of the scenarios predicts a greater difference while the other half predicts a lower difference for Lake Michigan-Huron. It is noted that 5 percent of the outcomes are lower than the 5th percentile and 5 percent of the outcomes are higher than the 95th percentile. Hence, these values are not the extremes.

In addition, it was noted that the results of the simulations varied widely for a single model, depending on the starting boundary conditions. Only a small number of models were run successively to determine the sensitivity and internal variability of model runs on initial conditions. These multiple runs bias the overall results shown in Table 4-3. Finally, in order to convert the precipitation forecasts for each of the models, a considerable degree of bias correction was needed, so as to convert the predictions to current values, often by a factor of five or six. The bias-corrected precipitation then had to be routed through the GLERL model and then the coordinated Great Lakes routing model. Hence the values shown in Table 4-3 are indicative rather than predictive.

Table 4-3
Estimated Lake level changes for Lake Michigan-Huron at the 5th, 50th and 95th percentiles
(in metres)

Year	*5th*	*50th*	*95th*
B1 Emission Scenario			
2020	-0.60	-0.18	0.28
2050	-0.79	-0.23	0.15
2080	-0.87	-0.25	0.31
A1B Emission Scenario			
2020	-0.55	-0.07	0.46
2050	-0.91	-0.24	0.40
2080	-1.43	-0.28	0.83
A2 Emission Scenario			
2020	-0.63	-0.18	0.20
2050	-0.94	-0.23	0.42
2080	-1.81	-0.41	0.88

Source: Angel and Kunkel (2009).

4.4.2 Canadian Regional Climate Model – CRCM

The traditional approach of perturbing observed sequences of climate variables with fixed ratios or differences derived directly from GCMs in order to run conceptual runoff and evaporation models may not capture important land surface-atmosphere feedback processes, particularly for large bodies of water such as the Great Lakes (Mackay and Seglenieks, 2011).

The Study evaluated dynamical down-scaling using series GCMs boundary conditions with the Canadian RCM (CRCM) nested within these GCMs. The CRCM runs consisted of two different approaches:

- a multi-model, multi-member "ensemble" approach, based on data from eight simulations of the CRCM driven by three different GCMs; and,
- a high-resolution approach in which one of the eight simulations was further down-scaled using a variant of the CRCM known locally as the Great Lakes Canadian Regional Climate Model (GL-CRCM), developed for the Study.

CRCM Ensemble Runs

It is recognized that averaging the results of a multi-model, multi-member "ensemble" approach to analyzing the climate system – in which several simulations are generated, differing in some small way, such as through slightly perturbed initial conditions or different parameterization schemes – tends to produce better results than any individual simulation (*e.g.*, Hagedorn *et al.*, 2005; Tebaldi and Knutti 2007).

The Ouranos Climate Simulation Team[9] operationally produces CRCM simulations on the North American grid based on a number of driving GCM simulations, and archive monthly results for general use. The Study used precipitation, evaporation, and runoff data from eight of these simulations and derived estimates of NBS were inputted directly into the CGLRRM. Results were based on a 45-by-45 km (about 28-by-28 mi) horizontal resolution grid.

CRCM – High-Resolution Runs

To evaluate the GL-CRCM model performance in a future climate, it was important to evaluate the model under a current climate sequence. The most important difference running a current or future state relates to the nature of the forcing data applied at the lateral boundary conditions.

To perform climate change experiments relying on an RCM, the atmospheric lateral boundary conditions must be provided by a GCM. In the Study, the driving GCM was the Canadian CGCM3.1v2 (Scinocca *et al.*, 2008). Data were first down-scaled using the Ouranos version of the CRCM (CRCM4.2.3) over a North American grid of about 45-by-45 km (about 28-by-28 mi) horizontal resolution. This version of the CRCM did not include streamflow routing, but did have a simple lake model, which the driving GCM did not. Finally, results from the CRCM were used to drive the GL-CRCM on a 22.5-by-22.5 km (about 14-by-14 mi) horizontal resolution grid.

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[9] Ouranos is private, non-profit consortium of the Government of Quebec, Hydro Quebec, Environment Canada and Quebec universities on regional climatology and adaptation to climate change. Ouranos provides Canadian regional climate simulations and is a source of North American regional climate simulations. The GCM boundaries established by Ouranos were employed in the RCM for the Study.

Bias Removal

Climate models generally simulate bias in water balance components that could have serious and lasting effects on any estimation of water level. If the nature of the bias is more or less time invariant, then the models can still be used to estimate changes in future climate with respect to present day climate. For example, if a model's simulated current climate is too wet over the Great Lakes region, and its simulated future climate is even wetter, then the model is suggesting an increase in precipitation (P) in the future: $P_{current}$ and P_{future} may be poorly simulated but $\Delta P = P_{future} - P_{current}$ might be quite reasonable and this information can be used to estimate changes in NBS and lake level. As is noted earlier, this "delta" approach is commonplace in most climate projections. In fact, all of the historical studies cited here have used this approach as a way to down-scale. The problem arises when the projected precipitation is substantially under-or over- predicted by the parent GCM, and the bias-correction requires the analyst to increase precipitation by a factor of five or more to adjust for actual present day values. This large adjustment of 500% brings into question whether this is a 'bias' or a systematic error in the GCM model.

In the Study, the bias-correction procedure made adjustments on NBS itself rather than on individual components. This approach is different from the cited literature, where typically, atmospheric forcing variable were bias-corrected using a delta approach. Mackay and Seglenieks, (2011) note the drawbacks of the more established methods and the benefits of bias-correcting NBS. The necessity for bias correction of climate model results for water resource applications is well known (*e.g.,* Wood *et al.*, 2004). However, it has been noted (Mackay and Seglenieks, 2011) that "there is no guarantee that the approach taken in these previous studies – that is, perturbing observed current climate precipitation and temperature with fixed ratios or differences deduced from simulation – does not disrupt interdependencies between these variables. Any such disruption could certainly distort water supply estimates."

By dynamically down-scaling using the GL-CRCM approach and bias-correcting the NBS rather than the individual components, two possible problems were avoided. First, one-way coupling of models (as in the approach taken by Angel and Kunkle, 2010, and previous climate change studies) prevented any possibility of feedback between small-scale surface processes and the overlying atmosphere. Secondly, NBS sequences in the more traditional methods were derived from calibrated conceptual models. These calibrations may not be valid in a future climate regime, and there is no possible way to test for this. Thus, by using a two-way coupled dynamical down-scaling, modelling system, internal water balance components were at a minimum internally consistent.

Observed (monthly residual) and bias-corrected simulated annual NBS results for lakes Superior, Michigan-Huron and Erie are shown in Table 4-4. These differences appear to be within the range of differences of historical estimates between the GLERL and EC models (1948-2008) differences

	Superior	**Michigan – Huron**	**Erie – St. Clair**
Overlake Precipitation	5 %	2 %	10 %
Lake Evaporation	-9 %	-1 %	-9 %
Runoff	-9 %	7 %	-2 %
NBS	8 %	9 %	21 %

Table 4-4 Relative Bias Between GLRCM and GLERL
Observed estimates of mean annual NBS and its components (results summarized from MacKay 2008 with updated GLERL values) for 1998 – 2005. $NBS = P_L - E_L + Q$, where P_L is overlake precipitation, E_L is overlake evaporation, and Q is runoff.

To compare projected future NBS results with the present, the Study used summarized monthly means and standard deviations for the current (1962-1990) and future (2021-2050) climate periods as presented in Table 4-5. On average, the Study found that the mean monthly NBS for Lake Superior will increase by less than 1 percent, while that for Lake Michigan-Huron will decrease by about 2 percent. On the other hand, the reduction in NBS for Lake Erie is more substantial, at about 8 percent. For all the lakes, increases in monthly standard deviation are larger, ranging from 7 percent for Lake Erie to 22 percent for Lake Superior.

NBS	Observed = GLRCM 1962-1990	GLRCM 2021-2050	Change
Superior	67.9 (70.5)	68.3 (86.3)	0.4 (15.8)
Michigan – Huron	74.8 (69.7)	73.2 (79.2)	-1.6 (9.5)
Erie	82.7 (106.6)	74.9 (113.8)	-7.8 (7.2)

Table 4-5 Monthly NBS mean (standard deviation) Statistics for Bias-corrected Simulation (1962-1990, and 2021 – 2050) (mm over lake)

To put these results in context with the previous work, water level estimates using the CCLRGM lake-routing model were also derived. Simulated lake levels for the current climate period for lakes Michigan-Huron and Erie indicated a small positive bias with respect to observed: 2 cm (about 0.8 in) and 7 cm (about 2.8 in) respectively (IUGLS, 2012). In addition, the current climate standard deviation is significantly underestimated for these lakes. Ensuring that the mean and standard deviation of simulated NBS matches the observed does not guarantee that mean and standard deviation lake levels will also agree with observed. Levels will depend somewhat on the actual sequence of NBS, which could never be captured by a climate model unless it was forced with observed data (which is not possible in a climate change experiment). However, it is possible that some of this bias could be removed with model improvements.

Table 4-6 summarizes the final bias-corrected version of the estimates NBS components for the current climate period (1961 – 1990) from the simulations. This calibration formed the basis for calculating NBS for the representing Study's design period of 2040. The annual pattern is similar for overlake and overland precipitation. The ARPEGE model is drier than the other models on a consistent basis, while the ECHAM5 model is typically wetter for lakes Superior and Michigan-Huron. The lake evaporation shows the greatest deviation between the GLERL and CRCM data. These results suggest that the eight simulations are all qualitatively reproducing the gross features of the average seasonal cycle in NBS components. Though the sample is small, it appears that results of the CRCM when driven with the ARPEGE model tend to be on the dry side, while those driven with the ECHAM5 model tend to be on the wet side, with the CGCM intermediate between the two. Nevertheless, all of the simulations show bias, which is clearly evident in the computed mean annual NBS results.

Table 4-6
Summary of Observed (GLERL) and Simulated Average Annual NBS Components for 1961-1990

Component	Lake	GLERL	CGCM	ECHAM5	ARPEGE
Lake Precipitaton (mm over lake)	Superior	796.5	663.3	783.6	554.2
	Michigan/Huron	840.7	782.5	862.3	626.4
	Erie	931.8	972.6	971.5	749.2
Lake Evaporation (mm over lake)	Superior	584.0	452.5	454.0	441.1
	Michigan/Huron	630.1	627.6	622.6	619.0
	Erie	896.5	750.2	742.2	728.2
Land Precipitaton (mm over land)	Superior	821.1	675.4	786.6	594.6
	Michigan/Huron	854.5	809.1	889.1	654.9
	Erie	919.7	976.6	988.7	782.0
Land Evaporation (mm over land)	Superior	408.6	458.8	450.0	454.6
	Michigan/Huron	511.1	536.1	542.6	505.0
	Erie	563.7	644.6	647.1	590.7
Runoff (mm over land)	Superior	412.5	216.8	337.6	140.5
	Michigan/Huron	343.4	272.8	346.0	151.5
	Erie	356.1	329.8	340.6	191.8

Explanation: Simulated results are labeled by the driving GCM. Results from simulations driven by GCMs with more than one ensemble member are averaged to highlight differences in driving GCM. The values in column 3 are the average values for the GLERL based components in mm for the period of 1961-1990 representing observations. Columns 4 through 6 are based on CRCM simulations using different GCMs: CGCM (Canadian),consisting of five ensemble members; ECHAM2 (German) consisting of two ensemble members; and an experimental GCM, ARPEGE (French), with one ensemble member.

4.4.3 Coupled Hydrosphere Atmospheric Research Model – CHARM

The Study also assessed future climate variability through the use of the Coupled Hydrosphere-Atmosphere Research Model (CHARM) (Lofgren and Hunter, 2011). CHARM is a regional climate model that simulates both the atmosphere and the land and lake surfaces in the Great Lakes basin. The model includes full interaction between the surface and the atmosphere and calculates runoff on a 40-by-40 km (about 25-by-25 mi) grid. CHARM model simulation of overland temperatures, overland precipitation, overlake precipitation, surface water temperature, and evaporation revealed somewhat similar results as the CRCM analysis.

The experimental model runs involved two time slices of simulation, representing the historical years of 1964-2000 and future projections for 2043-2070. These were run under observed carbon dioxide concentrations during the historical period and under the A2 emission scenario (IPCC, 2000) in the future.

NBS simulation results are shown in Figure 4-9. The figure depicts an increase in NBS during the late spring and early summer in the Lake Superior and Lake Michigan-Huron basins. Notable increases still occur during December and January, while decreases occur during the fall in the Lake Superior basin.

Results from Lofgren and Hunter (2011) also showed that the air temperatures over the land portions of the basin increase in a highly consistent way throughout the year and in all basins. The precipitation changes (*i.e.*, the differences between future and current values) generally increase, but are variable by month and basin. One of the consistent changes is that increases in precipitation occur more strongly over the land near the lakes during the summer and directly over the lakes during the winter, shifting to the areas in which they naturally occur more during those seasons because of static instability of the atmosphere. The lake surface temperatures increase during all seasons, with the greatest increase during the summer. The evaporation from the lakes shows slight increases, governed by available energy and limited by the moistening of the atmosphere that accompanies increased evaporation. The changes in NBS due to increased greenhouse gases are generally small increases. As in the case of the CRCM runs bias-correction procedures for NBS were applied.

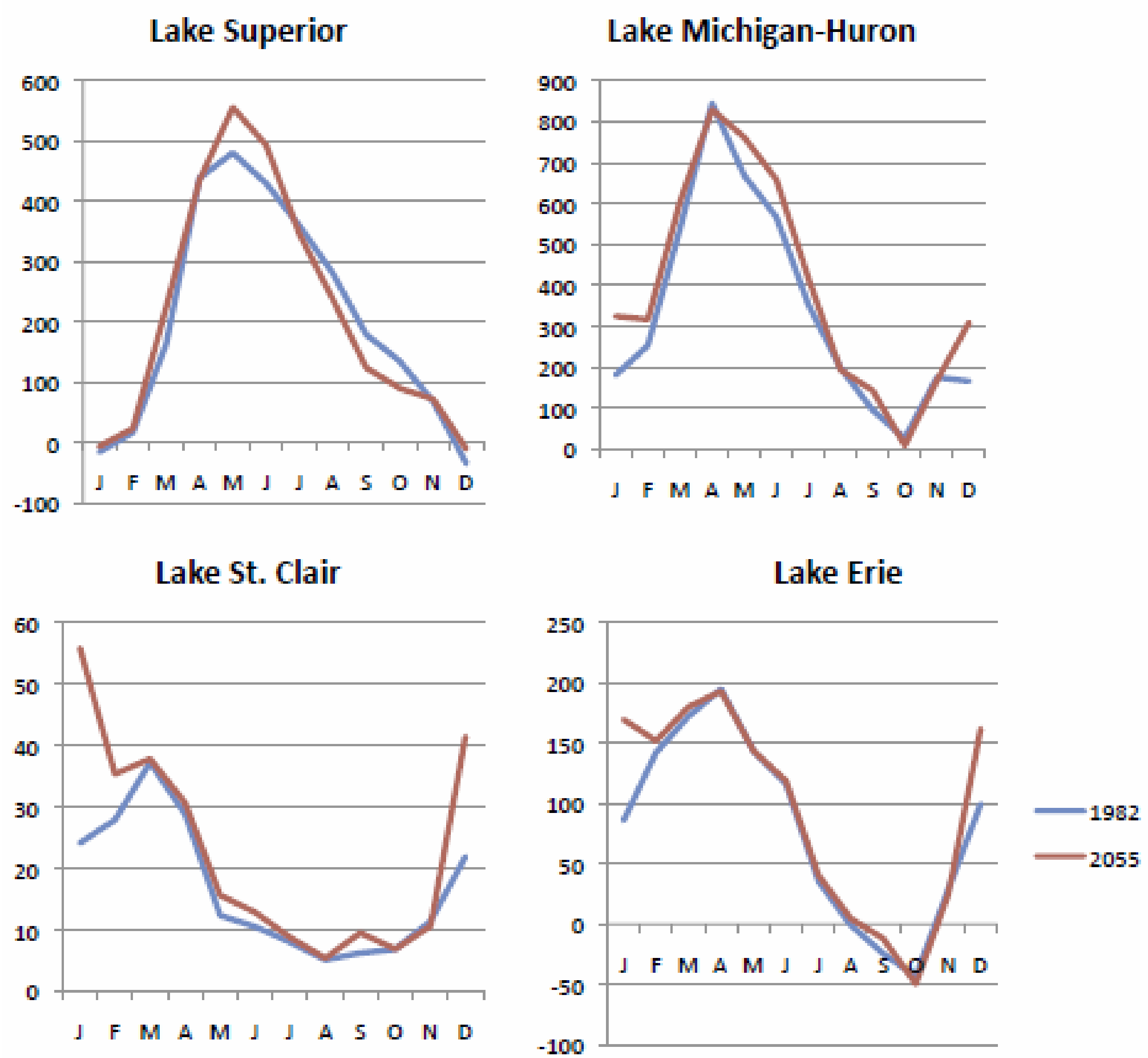

Figure 4-9
Climatological NBS(x l0 m^3/s)
CHARM 1982 and 2055 time slices

4.4.4 Integration of Results

The Study's hydroclimatic analysis has advanced the understanding of climate change science and analysis in general and, in particular, the application of climate science to the Great Lakes setting. Figure 4-10 illustrates the integration of the Study's hydroclimatic analysis.

The table shows the changes in the NBS for the design period of year 2040, comparing the results of statistically down-scaled GCMs with results of dynamical down-scaled GCM projections. The statistical modelling results are more varied for different model resolutions. For example, from the 160 different runs, the NBS of Lake Superior varies from a decrease of 245 mm (about 9.7 in) for a fine resolution of 1.4 degrees to an increase of 159 mm (about 6.3 in) for a coarse resolution of 4.53 degrees. For the eight dynamical down-scaled computations, the corresponding changes were a decrease of 135 mm (about 5.3 in) and an increase of 85 mm (about 3.3 in) at a resolution of 1.9 degrees. (Resource constraints limited the number of dynamical runs used in the analysis.)

Statistically Down-scaled GCM Projections

The GCM projections suffered from a lack of validation with the historical record. Nonetheless, the projections did inform the decision-making process. In particular, the projections described a range of possible future climates that included significant increases and decreases in mean NBS. The results were based on a future climate that is generally consistent with current understanding of the climate system and expectations of climate change.

Dynamical Down-scaled GCM Projections

As noted in 4.4.2, dynamical down-scaling approaches use a RCM that takes boundary conditions from GCM projections as inputs and fully resolves the climate conditions, including local feedbacks, at a much higher resolution over a smaller area. They appear to be of particular value over the lakes because the lake dynamics (including thermal dynamics in the lakes) affecting the local climate are included in the regional models but not in the GCMs. A drawback of higher resolution is that the computational intensity of the regional simulations often limits the number of runs that can be performed and the length of those runs. The regional climate runs also exhibited differences with mean climate in historical runs with respect to NBS and the individual components. In both cases, only NBS bias corrections were applied to allow for the individual components to remain coupled to the atmospheric and land-surface dynamics being simulated by the coupled model. A statistical bias correction was required to produce realistic historical NBS values from the RCM runs, and this same correction was applied to future projections. The results showed smaller differences from statistical down-scaling from the same GCMs.

Stochastic NBS Sequences

In contrast to visions of the future provided by GCMs, stochastic or statistical approaches use the historical record of NBS as the basis for creating NBS series that are representative of the future. The stochastic NBS sequences are compromised by the reliance on an assumption of stationarity. There are clear physical reasons for doubting the validity of that assumption (Milly *et al.*, 2008). However, due to the limitations in the GCM projections for the Great Lakes region, it is clear that at present there is no satisfactory representation of future climate on that time span. A sound principle, therefore, is to make decisions in such a way as there is not a constraining reliance on assumptions of the future using any specific approach.

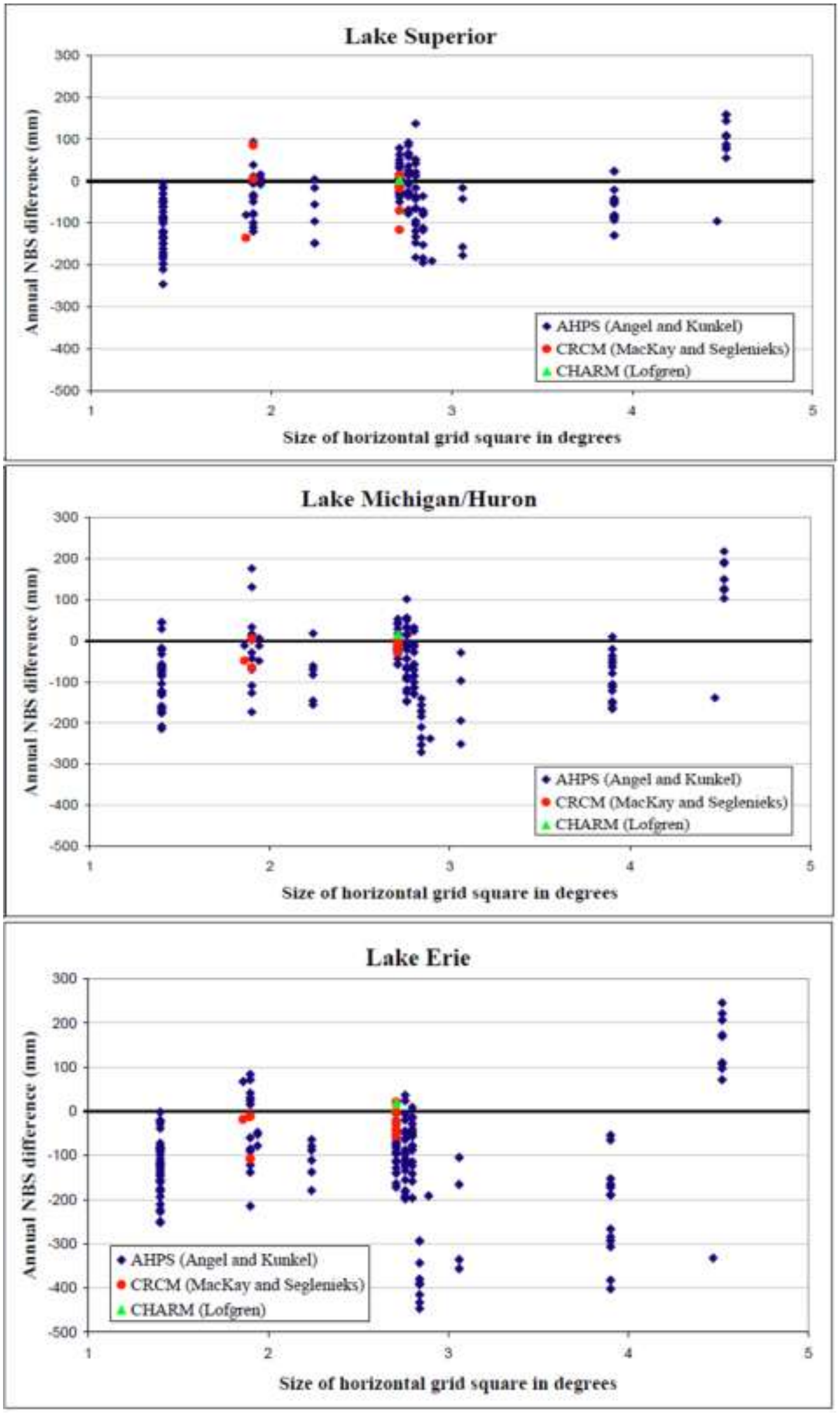

Figure 4-10 Comparison of Statistically and Dynamically Down-scaled Model Results

Assessing the Plausibility and Scope of Climate Change Impacts: Summary

The third theme of the Study's hydroclimatic analysis involved assessing the plausibility and scope of climate change impacts on NBS using established down-scaling techniques and new modelling work.

Results of the GCM simulations varied widely for a single model, depending on the starting boundary conditions. Only a small number of the models were run successively to determine the sensitivity and internal variability of model runs on initial conditions. Finally, in order to convert the precipitation forecasts for each of the models, a considerable degree of bias correction was needed.

The Study evaluated dynamical down-scaling using series GCMs boundary conditions with the CRCM model nested within these GCMs.

Climate models generally simulate bias in water balance components that could have serious and lasting effects on any estimation of water level. The Study addressed this bias by making adjustments on NBS itself rather than on individual components.

The Study assessed future climate variability through the use of CHARM, a regional climate model that simulates both the atmosphere and the land and lake surfaces in the Great Lakes basin. The results showed considerable seasonal variation in NBS. NBS increases during the late spring and early summer in the Lake Superior and Lake Michigan-Huron basins. Notable increases still occur during December and January, while decreases occur during the fall in the Lake Superior basin.

In the near term (*i.e.*, 30 years) the stochastic NBS series provides a useful representation of future climate uncertainty. The current record of Great Lakes NBS appears continuingly stationary, marked by strong inter-annual and decadal variability, and showing no response that may be attributable to climate change. During the Study's planning period "natural variability" is likely to mask any forcing due to greenhouse gas emissions.

In terms of the limits of the Study's hydroclimatic analysis, perhaps most notable from the perspective of effective lake regulation is how little the lake dynamics on inter-annual and decadal timescales are understood. Despite best efforts, the lake levels remain almost entirely unpredictable more than a month ahead.

4.5 Application of the Findings

4.5.1 Knowledge and Products Gained from the Study

A major goal of the Study was to bring the best possible hydroclimatic science to bear on selecting a robust regulation plan. In working towards that objective, the Study included state-of-the-science climate projections from one of the largest ensembles of GCM runs ever assembled for a regional study, regional climate modelling from two separate national modelling centers, a variety of statistical modelling approaches and innovations in modelling of the lake system's responses to climate. In addition, paleo-climate data analysis, new observational ability in the form of two new eddy flux towers for open water evaporation measurement, new measurements of channel characteristics in the St. Clair River were incorporated into the Study. The findings represent major steps forward in improving understanding of the largest regulated freshwater system in the world.

Despite this effort, the current understanding of the Great Lakes system in terms of the factors that will affect the performance of a regulation plan can only be described as "fair." There is a long record of lake levels and a reasonable understanding of the regulation and NBS that produced those levels. There are numerous major modelling and data collection efforts. Nonetheless, the long record of historical observations is actually quite sparse spatially, because the greatest area of the basin is comprised of the lake surfaces. There are only spatially sparse and temporally short recorded observations in these overlake areas. Also, as discussed earlier, the greatest uncertainty in NBS is the runoff due to incomplete gauging of the land area. Thus, a comprehensive understanding of lake water balances remains elusive, despite major gains made in this Study.

Perhaps most notable from the perspective of effective lake regulation is how little the lake dynamics on inter-annual and decadal timescales are understood. On decadal time scales, there is clear evidence of temporal structure (*e.g.*, years of high levels followed by years of low levels) that could not be explained. Despite best efforts, the lake levels remain almost entirely unpredictable more than a month ahead (notwithstanding a finding of small prediction skill for predicting spring tendencies on Lake Superior only, from the preceding fall in years not affected by ENSO). Based on the historical record, there appears to be a specific range within which the lake levels are likely to fluctuate. However, paleo-records indicate a range that may have been greater. In terms of understanding the lakes system relative to lake levels, the unavoidable conclusion is that Great Lakes are a complex system whose dynamics are only partially understood.

This current state of understanding has its limitations for deriving predictions of the future. As described next, the Study used a variety of approaches to generate future climate scenarios. The approaches can be categorized generally as GCM-based and those based solely on the historical record (and paleo-climate analogs).

Table 4-7 summarizes the hydrological time series developed by the Study for the hydroclimatic analysis. The different approaches used by the Study were designed to provide an array of plausible future climate sequences for the other components of the Study, including formulating regulation plans and evaluating their performance under a wide range of sequences, and examining the potential for restoration structures, multi-lake regulation and adaptive management.

Table 4-7
Summary of the Study's Hydrological Time Series

Outcome	Product	Product Components
Analysis of Observations	Historical Residual NBS Sequences[10] 1860 - 1899	1860 - 1899
	Historical Residual NBS Sequences 1900-2008	1900-2008
	Historical Component NBS Sequences 1948-2006	1948-2006
Derived sequences from residual NBS	Stochastic Sequence of Contemporary Residual Supplies	55,000 years
	Stochastic Sequence of Contemporary Residual Supplies using ENSO indicator	50,000 years
	Stochastic Sequence of Contemporary Residual Supplies using NCEP 500 mb anomalies indicator	50,000 years
	Paleo-Sequence	1000 years
CM Driven Climate Change Scenarios	Stochastic Sequence with Climate Change emission scenario A2	500 sequences of 100 years of monthly NBS
	Stochastic Sequence with Climate Change emission scenario A1b	500 sequences of 100 years of monthly NBS
	RCM Sequence	8 Ouranos 45 km runs 2 RCM 22.5 km runs
	RCM Sequence	2 Charm 40 km runs
	Angel and Kunkel Analysis	~500 Angel and Kunkel time slices (A2, A1B, B1 emission scenarios)

[10] The estimates of historical NBS for the period 1869 to 1899 are good only for Lake Superior. The NBS values for downstream lakes cannot be estimated with confidence in view of unknown connecting channel conveyances.

4.5.2 Application of the NBS Sequences and Climate Scenarios for Decision Making

The Study's hydroclimatic analyses resulted in the development of NBS sequences for each of the upper Great Lakes that would reflect potential climate change impacts. These sequences served as critical inputs into the other key analyses of the Study.

Regulation Plan Formulation and Evaluation

As described in **Chapter 5**, of the hundreds of future climate change scenarios derived for the plan formulation and adaptive management studies, 13 were chosen for detailed plan formulation and evaluation. These 13 represented the full range of scenarios that would test the limits of any new proposed regulation plan. Thus, the scenarios allowed the Study Board to test candidate Lake Superior regulation plans for "robustness" – the capacity to meet particular regulation objectives under a variety of uncertain future water level conditions.

The work on plan formulation and evaluation directly related lake level fluctuations to critical threshold levels relevant to each of the key six interests served by the upper Great Lakes system. The Study applied performance indicators (PIs) to compare and evaluate the relative performance of each economic sector or interest under the range of historical and anticipated lake level fluctuations across all sectors and lakes.

Adaptive Management

The NBS sequences were inputs into the Study's analysis of the role that adaptive management can play in helping interests in the upper Great Lakes basin better anticipate and respond to future extreme water levels. As described in **Chapter 9**, the Study explored the relationship between future lake level fluctuations and the impacts on the key interests through the development of coping zones.

Restoration and Multi-lake Regulation

The NBS sequences developed in the hydroclimatic analysis were also available for two other areas of the Study's work, but ultimately were not used.

As described in **Chapter 7**, the Study conducted an exploratory analysis of the feasibility and impacts of non-adjustable restoration structures that would permanently raise Lake Michigan-Huron water levels. Historical residual NBS were applied to study the potential impacts of restoration over the 109-year period from 1900 to 2008. Additional scenarios were not used because of the uncertainty in future NBS and because restoration structures would have a fixed/non-adjustable effect on lake levels.

In **Chapter 8**, the Study also examined the feasibility and implications of addressing extreme high and low water levels by means of multi-lake regulation that would seek to benefit the Great Lakes-St. Lawrence River system as a whole. This analysis required NBS sequences and evaluation points downstream from Niagara Falls, including the lower St. Lawrence River. The NBS sequences developed for the Study did not extend beyond the upper Great Lakes basin, as they were intended to support work on Lake Superior regulation. Therefore, the multi-lake regulation analysis used eight NBS scenarios chosen from the 50,000-year stochastic NBS dataset produced for the Lake Ontario-St. Lawrence River Study (International Lake Ontario-St. Lawrence River Study Board, 2006). These eight scenarios were based on the same approach used in this Study, and were identified as being diverse in terms of generating a range of high and low lake levels overall as well as differentially across the Great Lakes.

4.6 Key Points

With respect to the Study's analysis of the hydroclimatic processes affecting Great Lakes NBS and water levels, the following points can be made:

- The first major task of the Study was to examine the hydrology and climate of the upper Great Lakes, focusing on changes to the contemporary hydrology affecting the levels of the lakes and the impacts of future climate variability and change. Three themes were central to Study's analytical framework:

  - understanding the water balance of the Great Lakes;
  - assessing the reliability of historical recorded and estimated data; and,
  - addressing the plausibility and scope of climate change impacts on water supplies through new modelling work.

- The Study sought to improve the accuracy and consistency in NBS estimates through modification of existing models, development of new models, collection of new data, and improvement of a range of methodologies that have been used for lake level estimation. It was concluded that the improved estimates of runoff and overlake precipitation still incorporate and introduce significant uncertainty into the overall water balance. Continued efforts in modelling coupled with improved observation techniques are needed to "close the water balance" (*i.e.*, to reduce the uncertainty to as close to zero as possible).

- Perhaps most striking from the perspective of effective lake regulation is how little the lake dynamics on inter-annual and decadal timescales are understood. Despite best efforts, the lake levels remain almost entirely unpredictable more than a month ahead.

- Based on the historical record, there appears to be a specific range within which the lake levels are likely to fluctuate. However, paleo-records indicate a range that may have been greater. In terms of understanding the lakes system relative to lake levels, the unavoidable conclusion is that Great Lakes are a complex system whose dynamics are only partially understood.

- Without substantially increased confidence in historical NBS estimates for both residual and component supplies and an understanding of the uncertainty associated with these estimates, choosing plausible futures in the context of past events is highly problematical.

- In general, GCM information introduced more uncertainties that are even more difficult to reconcile with historical data.

- Despite these uncertainties, it is clear that lake evaporation is increasing and will likely increase for the foreseeable future, likely due to the lack of ice-cover. Analysis indicates that this increased evaporation is being somewhat offset by increases in local precipitation. It will be important to ensure that further climate analysis be undertaken to explore these dynamics and provide more certainty of future NBS estimates.

- Determination of climate change impacts on NBS using RCM tools provided insights into the dynamics of the hydroclimatic systems that are unavailable with statistical down-scaling. Features such as local feedback and recycled runoff are not captured in any of the GCMs. These aspects advanced scientific knowledge in this area. Due to the limited number of RCM runs, however, the full range of impacts were not computed. Additional RCM runs are desirable for discernments of differences due to finer resolutions and parameterizations.

- In light of these continuing unresolved uncertainties, the Study focused on developing plausible scenarios of future climate change through a broad range of methods. It had confidence in the resulting scenarios in the following descending order:

    - stochastic sequences of contemporary supplies;
    - residual sequences of 1900-2008;
    - GCM-RCM sequences;
    - stochastic sequences of climate change supplies;
    - bias-corrected GCM down-scaled scenarios; and,
    - paleo-sequences.

- The stochastic NBS series provides a useful representation of future climate uncertainty in the near-term (*i.e.*, the next 30 years). Based on the Study's findings, there is no evidence that the statistics of the historical record are not representative of what can be expected within the next 30 years, the Study's planning horizon.

- The current record of Great Lakes NBS appears continuingly stationary, marked by strong inter-annual and decadal variability, and showing no response that may be attributable to climate change. Increased evaporation and related local precipitation induced by climate change (with loss of ice cover), tend to be compensating each other, resulting in small change in NBS. During the Study's 30-year time horizon in terms of implementing a new Lake Superior regulation plan, "natural variability" is likely to mask any climate forcing due to greenhouse gas emissions.

- As a result, changes in lake levels in the near-term future may not be as extreme as previous studies have predicted. Lake levels are likely to continue to fluctuate, but still remain within a relatively narrow historical range. While lower levels are likely, the possibility of higher levels cannot be dismissed.

- Beyond the next 30 years, the predictions of GCMs for more extreme water level conditions in the upper Great Lakes may hold more merit. However, due to the limitations in the GCM projections for the Great Lakes region, it is clear that at present there is no satisfying representation of future climate on that time span. The best approach, therefore, is to make decisions in such a way as there is not great reliance on assumptions of future climatic and lake level conditions.

- The plausible NBS sequences and climate change scenarios developed by the Study's hydroclimatic analysis served as critical inputs into the formulation and evaluation of candidate Lake Superior regulation plans and the analysis of the role that adaptive management can play in helping interests in the upper Great Lakes basin better anticipate and respond to future extreme water levels.

4.7 Recommendations

Based on the findings presented in this chapter, the Study Board recommends the following:

1. ***The IJC should seek to improve scientific understanding of hydroclimatic processes at work in the Great Lakes basin and the impacts on future water levels as part of a continuous, coordinated bi-national effort.***

   The Study's hydroclimatic analysis has established a new standard that should be used as the starting point for water level planning and related research conducted in the future. However, considerable work remains -- the Study's comprehensive hydroclimatic analyses using a range of approaches showed that assessing the uncertain impacts of climate variability and change on upper Great Lakes water levels will continue to be a challenging task. The Study identified important avenues to be pursued in the near- and medium-term to improve understanding of these impacts and their implications for regulation. To better link this work to planning and decision-making across the Great Lakes basin, these scientific initiatives would be most effectively undertaken in a coordinated, bi-national manner. The proposed water levels advisory board, described in **Chapter 9**, could be given responsibility for this task.

2. ***The IJC should endorse efforts to strengthen the climate change modelling capacity in the Great Lakes Region in light of the promising preliminary results gained through dynamical down-scaling.***

   The Study's strategy brought state-of-the-art modelling tools to the challenge of evaluating climate change impacts in the upper Great Lakes region. The use of RCMs with GCM-driven boundaries, while not producing differences in the final NBS estimates, provided insights into the dynamics of the hydroclimatic systems that are unavailable with statistical down-scaling. Further work on additional runs of these RCMs with GCM-driven boundaries, is needed to build on these promising preliminary results.

3. ***The IJC should endorse efforts to strengthen hydroclimatic data collection in the upper Great Lakes basin and strongly recommend ongoing government support.***

   In its first report to the IJC, ***Impacts on Upper Great Lakes Water Levels: St. Clair River***, the Study Board identified a number of specific "legacy" recommendations regarding strengthening data collection, scientific knowledge and institutional capacity (IUGLS, 2009). In this final report, the Study Board reiterates those recommendations and in particular, notes the need for support and expansion key data collection programs (*e.g.*, evaporation gauges, International Gauging Stations). Long-term data collection continues to be fundamental in improving scientific understanding of how the Great Lakes system functions and how it is – and is likely to be – affected by both natural forces and human activities.