Hydroclimatic Conditions: Past, Present and Future

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

Final Report to the International Upper Great Lakes Study Board

By the Hydroclimatic Work Group

March 2012
Hydroclimatic Conditions: Past, Present and Future

1.0 Introduction

The Hydroclimatic Work Group (HC WG) was established to assess changes to the contemporary hydrology affecting the levels of the lakes and to examine future climate variability and change. This report focuses on WG efforts for the development of a broad range of hydroclimatic sequences to test the robustness of candidate regulation plans with the capacity to meet regulation objectives under plausible future water level conditions.

This effort relied, in turn, on the 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 is still challenged with uncertainties. Recognizing this challenge, the WG sought to reduce these uncertainties.

1.1 Purpose and Organization

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. To address this task two primary science questions were explored:

- What are the historical estimates of the net basin supply (NBS) 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, which examined the physical processes and possible ongoing changes in the St. Clair River. The Hydroclimatic WG expanded on this previous work for this final report.

The second science question, dealing with climate variation and the influence this may have on future Lake Superior regulation, was examined through Paleo investigations, stochastic analysis and climate modeling. While the physical basis for understanding possible future climate change in extremes has largely been derived from analysis of climate model simulations, it was deemed crucial that paleoclimatic data and stochastic analyses be conducted to provide information relative to possible future events which could alert us to any inconsistencies between model projections and the climates of the past.

---

1 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.

2 Available at the Study’s website: www.iugls.org

3 Paleo – a combining form meaning “old” or “ancient,” especially in reference to former geologic time periods, used in the formation of compound words: paleobotany.

4 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, etc.) may be randomly rearranged to create a new ‘synthetic’ series of plausible flows and lake levels, based on those measured properties.
1.2 Hydroclimatic Analytical Framework

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

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

These three themes in the Study’s hydroclimatic analytical framework are presented in this report and formed the basis upon which the WG developed contemporary and future NBS scenarios. These scenarios, in turn, supported other key analyses of the overall Study.

2.0 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 WG 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\(^5\) as possible and to have uncertainty bounds associated with each element.

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,
- *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.

Figure 1 illustrates water balance accounting, for both the residual component methods.

---

\(^5\)Bias refers to a systematic (i.e., not random) difference between a quantity and a prediction of this quantity.
Through a better understanding of the water balance, Water Managers more effectively manage the waters of the Great Lakes toward improving hydrologic forecasts, ecological restoration, water conservation, navigation and hydropower operations, and many other functions which benefit our society.

**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.

**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;
- \(\Delta S\): change in water storage of the Great Lake;
- \(\Delta ST\): 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).

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 from 1900 to present 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.

In order to assess residual NBS supplies prior to 1900 a methodology was developed to derive supplies from historical data prior to 1900 (Quinn, 2010). This analysis provided significant insight into the full
range of NBS supplies that have been experienced in the relatively recent past. The methodology used to derive 1860-1899 residual NBS supplies consisted of corrected/adjusted hydrologic data, revised connecting channel stage-discharge relationships, and computed lake levels and flows reflecting current climate. The data was adjusted through a combination of change-in-storage calculations, outlet rating equations, stage-fall discharge equations, and water balance calculations. NBS sequences were developed for each Lake.

For Lake Superior three data sets were utilized to obtain the 1860-1899 supply sequence. Monthly water level data for the gauge at Marquette, Michigan were obtained from the National Ocean Survey. Monthly St. Marys River flow data for the period 1860-1899 were also available, including the discharge equations used to compute the monthly flows. The final data set included the annual Lake Superior precipitation for the period 1875-1925.

The Figure 2 shows the three and five year average annual NBS for Lake Superior. Annual values correlate well with each other and with recorded lake levels. The figure shows a very high NBS regime in the 1870s which is the largest on record. The low water regimes are all within the 1900-2006 period of coordinated data. This high NBS regime is corroborated by the annual average Lake Superior precipitation (Day, 1926) which shows an extremely high precipitation regime from about 1874-1884.

For Lake Michigan-Huron there were five data sets utilized. Monthly water level data for the gauges at Harbor Beach, Michigan and Milwaukee, Wisconsin were obtained from the National Ocean Survey. The Harbor Beach data from 1860-1874 was transferred from the water level gauge at Superior, Wisconsin. Monthly water level data for Lake St. Clair for the period 1860-1899 was available from the St. Clair Flats, Michigan water level gauge. This gauge was established in 1872. Elevations prior to that time were transferred from several other water level gauges. Published data for the St. Clair Flats gage, which was on 1903 datum, were corrected to IGLD (1985) datum by converting the data to metric units and comparing them to the Grosse Point monthly water level data for the period 1898-1907. Monthly St. Marys River flow data for the period 1860-1899 were also utilized, including the discharge equations used to compute the monthly Coordinating Committee flows. The final data set is the annual Lake Superior precipitation for the period 1875-1925.
The monthly Lake Michigan-Huron NBS average annual values are illustrated in the Figure 3. The 1860-1899 NBS data for Lake Michigan added a supply sequence slightly larger that experienced in the mid-1980s.

For Lake Erie six data sets were used. Monthly water level data for the gauges at Cleveland, Ohio and Buffalo, New York were used for the period 1860-2009 as well as the data for the gauge at St. Clair Flats, Michigan. Monthly Niagara River flow data for the period 1860-2006 were also used. The final data set is the annual Lake Erie precipitation for the period 1875-1925.

The resulting monthly average Lake Erie NBS is illustrated in the Figure 4. The figure shows a fairly constant regime from about 1890 through about 1970 followed by a high NBS regime through the present time. There also appears to be a very low NBS regime from around 1870 through 1890. The low supplies about 1888 are the lowest on record.
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).

Since 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.

Historical analyses of NBS sequences for each lake extended the historical time series by forty years, an increase of close to 40 percent. However, these estimates were deemed only applicable for only Lake Superior. The NBS values for the downstream lakes could not be used due to data inconsistencies and in view of unknown connecting channel conveyances.

**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 and Hunter, 2008).
Equation for Calculating Component NBS

\[
\text{NBS} = P + R - E + G
\]

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.  

All terms are expressed in m\(^3\)/s-months (ft\(^3\)/s-months) (or other time periods).

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 source is simulated by randomly generating an ensemble of alternative and equally likely discharge, indicated that monthly runoff is slightly higher than estimates currently used to determine computed runoff (DeMarchi et al., 2009).

In order to improve runoff estimates a new technique for prediction of stream flows at ungauged sites based on Regional Flow Duration Curves (RFDCs) and nonlinear spatial interpolation techniques was developed. This task involved reconstruction of daily historical streamflow time-series for all ungauged basins, using spatial interpolation techniques. Climatic and physiographic basin characteristics were used to establish regional estimation models using a step-wise regression method. The RFDCs at ungauged sites were estimated using a regional parametric approach where the prediction of daily stream flows at ungauged sites used neighborhood regionalization. A comprehensive evaluation of existing approaches of regional RFDC estimation and a comparison of a spatial interpolation method with drainage area ratio methods was also performed. Investigations resulted in development of a real-time streamflow prediction tool for ungauged basins which improved runoff estimates and ultimately NBS estimates.

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.

For long term quantitative assessments removal of the bias from precipitation estimates can be accomplished by merging it with daily gauge data. The approach taken was to compute the precipitation over the invalid MPE pixels as inverse square distance weighting interpolation of MPE*over valid pixels and gauge data. Given that the number of MPE pixels is much larger than the number of gauges (80,500 vs. 1,030), a simple interpolation of the nearest pixel or gauge would give a disproportionate weight to the MPE pixels. Thus, the precipitation over each invalid pixel was computed according to the following

---

6 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.
procedure: the region was subdivided into four quadrants centered on the pixel; the five nearest valid MPE pixels or precipitation gauges in each quadrant were identified; and inverse square distance weighting interpolation of the selected pixels and gauges was performed.

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 modeled using meteorological data as input. Investigations were conducted 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 5), 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. Analyses demonstrated that this methodology can lead to improved parameterization of regional climate models and may be used to improve existing models. With continuing field observations over multiple years an important step in understanding and improving observational dataset will be realized.

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 5 - Gauging Station, Stannard Rock Lighthouse, Lake Superior (right) & Spectacle Reef, Lake Michigan-Huron (left)**
(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 WG 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 and Gronewold, 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. 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 are illustrated in Figures 6 and 7 as the water level responses to the cumulative effect of NBS over time.

![Figure 6 - Cumulative NBS for Lake Superior](image)

MCON_S plotted against the coordinated and provisional residual NBS, and the GLERL NBS
Figure 7 - Cumulative NBS for Lake Michigan-Huron
(including Georgian Bay)
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 resulted in two existing time series of component NBS. The GLERL component NBS dataset for 1948-2008 was re-analyzed and updated in light of the observations and investigations. 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 confidence 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 and Gronewold, 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 (Figures 6 and 7).
It was not possible within the timeframe of the investigation 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. 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 WG 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 8). These MBP data were used to show the improvement in water balance closure shown in Lake Superior and Lake Michigan-Huron.

Using this back-projected information, a time-series of precipitation, evaporation and runoff for each of the upper lakes was generated. Table 1 highlights these components for the 1948-2008 periods. 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 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
One of the goals was to reconcile the differences in results when using the component and residual 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 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.

## 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 WG 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.)

### 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).

### Overlake Precipitation

<table>
<thead>
<tr>
<th>Lake</th>
<th>Method</th>
<th>Overlake Precipitation mm/year</th>
<th>Evaporation mm/year</th>
<th>Runoff mm/year</th>
<th>NBS mm/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superior</td>
<td>Component (GLERL)</td>
<td>789.2</td>
<td>605.6</td>
<td>616.4</td>
<td>799.2</td>
</tr>
<tr>
<td></td>
<td>Component (MBP)</td>
<td>859.3</td>
<td>531.1</td>
<td>468.5</td>
<td>796.7</td>
</tr>
<tr>
<td></td>
<td>Residual</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>774.9</td>
</tr>
<tr>
<td>Michigan-Huron</td>
<td>Component (GLERL)</td>
<td>840.8</td>
<td>655.1</td>
<td>721.1</td>
<td>906.8</td>
</tr>
<tr>
<td></td>
<td>Component (MBP)</td>
<td>895.4</td>
<td>661.5</td>
<td>648.7</td>
<td>882.6</td>
</tr>
<tr>
<td></td>
<td>Residual</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>860.0</td>
</tr>
<tr>
<td>Erie</td>
<td>Component (GLERL)</td>
<td>924.2</td>
<td>925.5</td>
<td>813.9</td>
<td>812.6</td>
</tr>
<tr>
<td></td>
<td>Component (MBP)</td>
<td>973.1</td>
<td>933.8</td>
<td>770.1</td>
<td>809.4</td>
</tr>
<tr>
<td></td>
<td>Residual</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>765.4</td>
</tr>
</tbody>
</table>
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 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 precipitation estimates succeeded in replicating the MESH results and that the bias was eliminated (IUGLS, 2012).

**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 2). This further exacerbates the uncertainty in overall estimates of runoff from the Great Lakes basin.

<table>
<thead>
<tr>
<th>Year</th>
<th>Lake Superior</th>
<th>Lake Michigan</th>
<th>Lake Huron</th>
<th>Lake Erie</th>
</tr>
</thead>
<tbody>
<tr>
<td>1992</td>
<td>34 %</td>
<td>24%</td>
<td>34 %</td>
<td>25%</td>
</tr>
<tr>
<td>2008</td>
<td>40%</td>
<td>25%</td>
<td>38 %</td>
<td>42%</td>
</tr>
</tbody>
</table>

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

Three types of errors associated with estimating basin runoff in the GLERL approach (DeMarchi et al., 2009) were evaluated:

- 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.

### 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 WG 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 Grorued 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 9 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 9. 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 overall Study. In general, there is an increasing evaporation in all of the lakes since 1948. However, it was 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 9 - Annual Mean Net Overlake Precipitation, Runoff, and Component NBS (1948 to 2008) Note: derived from and Fortin and Gronewold, 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). Investigations 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 WG 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 WG concluded that evaporation has increased in all of the lakes since 1948. However, 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.
3.0 Assessing the Reliability of Historical Recorded and Estimated Data

In the second theme of the hydroclimatic analysis, the representativeness of historical variations and estimated data was assessed 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.

3.1 Paleo-analyses

The Hydroclimatic WG 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).

Initial investigations looked at recorded water level data prior to 1860. Early lake levels prior to 1860 were recorded at a number of sites. Early lake levels, prior to 1860, were recorded at Copper Harbor, Eagle River, Sault St. Marie and Superior for Lake Superior, Milwaukee for Lake Michigan-Huron, and Cleveland, Buffalo, and Black Rock for Lake Erie. A summary of the findings are given in the Table 3 and 4 below. The data for Lake Michigan-Huron have been corrected for glacial isostatic adjustment (GIA) relative to the outlet while the Lake Erie data are unadjusted. There are no comparable older recorded levels for Lake Superior.

<table>
<thead>
<tr>
<th>Year</th>
<th>High or Low Level</th>
<th>Elevation (IGLD55) meters</th>
<th>Elevation (IGLD85) meters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1819</td>
<td>Low</td>
<td>175.8</td>
<td>176.0</td>
</tr>
<tr>
<td>1838</td>
<td>High</td>
<td>177.8</td>
<td>178.0</td>
</tr>
<tr>
<td>1858</td>
<td>High</td>
<td>177.5</td>
<td>177.7</td>
</tr>
<tr>
<td>1876</td>
<td>High</td>
<td></td>
<td>177.57</td>
</tr>
<tr>
<td>1886</td>
<td>High</td>
<td></td>
<td>177.59</td>
</tr>
<tr>
<td>1934</td>
<td>Low</td>
<td></td>
<td>175.67</td>
</tr>
</tbody>
</table>

Table 3  
Significant maximum monthly high and minimum monthly low lake levels for Lake Michigan-Huron at Harbor Beach  
Modern period highs and lows are provided for comparison. Levels are not corrected for changes in the St. Clair River hydraulic regime.

---

7 Isostatic - Equilibrium in the earth's crust such that the forces tending to elevate landmasses balance the forces tending to depress landmasses.
Table 4
Significant maximum monthly high and minimum monthly low lake levels for Lake Erie at Cleveland
Modern period highs and lows for comparison.

<table>
<thead>
<tr>
<th>Year</th>
<th>High or Low Level</th>
<th>Elevation (IGLD55) Meters</th>
<th>Elevation (IGLD85) Meters</th>
<th>Outlet level at Buffalo (IGLD85) Meters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1819</td>
<td>Low</td>
<td>172.97</td>
<td>173.15</td>
<td>173.29</td>
</tr>
<tr>
<td>1838</td>
<td>High</td>
<td>174.72</td>
<td>174.90</td>
<td>175.02</td>
</tr>
<tr>
<td>1876</td>
<td>High</td>
<td>174.70</td>
<td>174.80</td>
<td></td>
</tr>
<tr>
<td>1936</td>
<td>Low</td>
<td>173.15</td>
<td>173.21</td>
<td></td>
</tr>
<tr>
<td>1952</td>
<td>High</td>
<td>174.76</td>
<td>174.75</td>
<td></td>
</tr>
<tr>
<td>1964</td>
<td>Low</td>
<td>173.38</td>
<td>173.46</td>
<td></td>
</tr>
<tr>
<td>1986</td>
<td>High</td>
<td>175.05</td>
<td>175.03</td>
<td></td>
</tr>
<tr>
<td>1997</td>
<td>High</td>
<td>175.00</td>
<td>174.97</td>
<td></td>
</tr>
</tbody>
</table>

Further investigations looked at reconstructing lake levels for Lake Michigan based upon beach ridges at several sites (Baedke and Thompson, 2000; Wilcox, D.A, Thompson, T.A., Booth, R.K., and Nicholas, J.R., 2007). Figure 10 shows lake level reconstruction for the past 5000 years. An examination of the figure over the past 1000 years shows extremely low lake levels 600 years ago (~1300 AD) and about 1000 years ago (~1000 AD). Extreme high levels occurred about 900 years ago (~1100 AD). The low about 900 AD is lower than the record lows in the 1930s and 1960s. These peaks are similar in magnitude to the measured data over the past 200 years. It is highly likely that individual year residual levels may have exceeded the smoothed peaks (Baedke and Thompson, 2000).
Two studies on Lake Superior were conducted by Johnson et al (2000) and by Larsen (1999). Johnson vibrocored Lake Superior beach ridges at Grand Traverse Bay Michigan. His analysis showed that Lake Superior varied between about 182 m and 184.5 m over the period 600-1400 years BC on IGLD 1985 datum.

In addition to the methodologies discussed above, the use of tree ring derived data which has been used for analyzing Great Plains drought (Woodhouse and Brown, 2001) and Great Lakes water levels (Quinn and Sellinger, 2006; Wiles et al, 2009) were also investigated. For the analyses discussed herein gridded tree ring derived Palmer Drought Severity Index (PDSI) annual values have been used as surrogates for the net basin water supply (NBS). The PDSI values for each individual lake have been calculated using an average of the grid points and smoothed using a five weight binomial filter. The results are given in Figures 11-13. The figures all indicate both wetter and dryer episodes in the past 700 years than we have recorded in our historical records.

---

8 **Vibrocored** - A sampling technique which utilizes a concrete vibrator to create high-frequency low-amplitude vibrations that are transferred down a series of aluminum tubes. Vibrations liquefy a 1 to 2mm layer of sediment in contract with both the inside and outside of the core tube wall, thus allowing penetration through soft sediment.
Figure 11 - Weighted PDSI values and corresponding annual water levels at Point Iroquois

Figure 12 - A comparison of PDSI for Lake Erie with water levels at Buffalo
Through the analyses presented above it is possible to extrapolate pre-historic Great Lakes water levels over the past 1000 years. Figures 14-16, illustrates the wide range of possible lake levels.
Figure 15 - Lake Michigan-Huron maximum and minimum water levels.

In addition to the paleo investigations discussed above, paleo-modelling (Brown, 2011) using a stochastic simulation framework (Prairie et al., 2008) was also employed to generate NBS sequences which would represent what may have occurred in the past and which could occur in the future. 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\(^9\) (k-NN) to resample observational NBS magnitudes conditioned on the hydrological states.

For the purposes of this investigation 500 sequences of 100 annual net basin supply time series were generated using the methodology described above. The sequences generally captured the mean, standard deviation, coefficient of skew, maximum, minimum, serial-correlation and cross correlation of the observed net basin supply within the inter-quartile range.

It is important to note that the PDSI reconstructed data used here was vital in generating realistic variety of net basin supplies. The reconstructed data were obtained from the National Climatic Data Center for Paleoclimatology. In general, it was found that the Pearson’s coefficients between 5-year running means of PDSI reconstructions and NBS series for Lakes Superior, Michigan-Huron, St. Clair, and Erie predictors range between 0.5-0.6. This level of correlation is considered to be, in general, strong.

Figure 17 illustrate the normalizing PDSI and NBS values for the four lakes. Of particular interest is to look at the correspondence of high and low state conditions between the PDSI reconstructions and NBS series.

\(^9\)The k-nearest neighbor algorithm (k-NN) is a method for classifying objects based on closest training examples in the feature space.
For some years the PDSI reconstructions failed to match the extremes in the NBS series. A possible reason for this could be the quality of the observed NBS used in this study. As is noted by Neff and Nicholas (2005) the NBS series are not observed, rather computed by the component and/or residual method. Both methods show greater level of uncertainty and the difference between the two estimates is significant. However, in spite of these discrepancies, the PDSI wet and dry years tend to agree with the trend of high and low NBS periods, with respective hit rates of 78, 73, 68 and 62 percent for Lake Superior, Michigan-Huron, Erie and Lake Saint Clair.

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 18 illustrates the relative frequencies of uninterrupted dry and wet years for each lake 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 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 since 1860 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 18 - Relative Frequencies of Uninterrupted Dry and Wet Years, by Lake
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, investigations 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.

CARMA Model

An initial stochastic model of was developed updating the approach of Fagherazzi et al. 2005, with a new and longer record (1900-2008) of the contemporary water supplies (Fagherazzi 2011). This modeling scheme includes the use of a 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.

The 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. Figure 19 illustrates the revised Great Lakes Residual NBS data base (1900-2008) of Lake Superior (SUP), Lake Michigan-Huron with Georgian Bay (MHG), Lake Erie (ERI), Lake St-Clair (STC) and Lake Ontario (ON) utilized in this stochastic analysis.

![Figure 19 – Great Lakes Residual NBS Data Base](image-url)
The generated set of 55,590 monthly NBS series for Lakes Superior, Michigan Huron, St Clair and Erie were routed with the Coordinated Great Lakes Rouging Model to produce annual average statistics. These statistics are shown in the Table 5. The stochastically generated NBS series entering the Great Lakes system was derived to be statistically equivalent to the historical one. Therefore, when simulating a longer series, the effect of changes in storage is very small and the simulated annual average outflow of Lake Erie corresponds exactly to the sum of generated Upper Lakes NBS.

### Table 5

**Upper Lakes annual average statistics of generated NBS and corresponding simulated outflows using the Coordinated Great Lakes Regulation and Routing Model**

<table>
<thead>
<tr>
<th></th>
<th>Average NBS (m$^3$/s)</th>
<th>Diversion (m$^3$/s)</th>
<th>Change in Storage over 55590 years (m$^3$/s)</th>
<th>NBS+Diversion+Change in storage (m$^3$/s)</th>
<th>Routed outflows (with coordinated model) (m$^3$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Superior</td>
<td>2014</td>
<td>141</td>
<td>-0.01</td>
<td>2154.99</td>
<td>2160</td>
</tr>
<tr>
<td>Lake Michigan-Huron</td>
<td>3197</td>
<td>-91</td>
<td>-0.03</td>
<td>5260.96</td>
<td>5262</td>
</tr>
<tr>
<td>St Clair River</td>
<td>133</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Detroit River</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lake Erie</td>
<td>625</td>
<td>50</td>
<td>-0.01</td>
<td>6018.95</td>
<td>6017</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>5969</strong></td>
<td><strong>50</strong></td>
<td><strong>-0.05</strong></td>
<td><strong>6018.95</strong></td>
<td><strong>6017</strong></td>
</tr>
</tbody>
</table>

The implementation of exceptional criteria on water resources management plans is strongly related to the severity of a period of water supplies surplus or deficits that could arrive to the system. Even more, in the context of multi-objective, multi-users water resource system, the consequences of extended dry or wet periods could vary according to the characteristics of the user’s need. For this investigation, a surplus or deficits analysis, or Runs Analysis, was performed to identify “extreme level subsamples”. This analysis was helpful in assessing the long term global performance of the system.

Figures 20 and 21 below illustrate Box-plots of the simulated monthly levels prepared with the stochastic NBS, with superposed 4 consecutive years (Lake Superior) to 6 consecutive years (Lake Erie) of high and low generated levels. The figures show that the monthly level distributions are symmetric, and how a sample of many consecutive months of high or low levels compare to the overall statistics of the series.
Figures 20-25 illustrate the sequences of maximum drought and surplus for Lake Erie levels, Lakes Superior and Michigan-Huron. It can be seen that Lake Erie, being the last (and smaller) lake of the Upper Lakes system, is strongly influenced by the hydrological characteristics of the lakes located upstream, as well as the local NBS characteristics. It is expected that a long surplus or deficit level sequence for Lake Erie is accompanied by similar sequences of levels in Lake Michigan-Huron and even Lake Superior.
Figure 22 – Simulated Levels Dry Sequence 1

Figure 23 – Simulated Levels Dry Sequence 2
The next stochastic methodology investigated used two approaches combined contemporary climate data with longer-term inter-annual and decadal climate oscillations, such as the El Niño 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.

The first approach linked annual NBS components to the El Niño–Southern Oscillation (ENSO) indices using a non-linear autoregressive model with exogenous inputs (NL-ARX). 50000 synthetic yearly ENSO values were afterward generated using a combination of the empirical mode decomposition (EMD) and non-stationary oscillation resampling (NSOR). The synthetic yearly ENSO values were used with the NL-ARX model to generate the mean values of the NBS time series. Finally, noise was generated and added to the mean using a stochastic process whose parameters were optimized to reproduce the key statistical characteristics (temporal and spatial variability, cross correlations and temporal correlation) of historical annual NBS time series. The generated annual NBS time series were disaggregated into the monthly data employing a parametric disaggregation model by Lee et al. (2011). The monthly values were further disaggregated to the quarter-monthly time-scale using a non-parametric disaggregation approach based on Genetic Algorithms (Lee et al., 2010). The resulting NBS sequences were routed with the Coordinated Great Lakes Regulation and Routing Model and resulting lakes levels obtained.

The general methodology used for generation of synthetic sequences of contemporary Net Basin Supplies, for the two alternative stochastic models, utilized historical NBS sequences to reproduce the required statistical properties. The basic statistical properties (mean, standard deviation, temporal correlation and variance-covariance matrix) of the monthly residual 1900-2009 NBS supplies series are presented in Tables 6 and 7.

| Table 6 | Basic statistical characteristics of historical residual NBS supplies |
|----------------------------------|-----------------|-----------------|-----------------|---------------|---------------|
| | Lake Superior | Lake St-Clair | Lake Michigan-Huron with Georgian Bay | Lake Erie | Lake Ontario |
| Mean (1900-2008) | 2.0082e+003 | 272.2272 | 3.1026e+003 | 742.0932 | 1.0784e+003 |
| Standard deviation (1900-2008) | 446.7279 | 60.9862 | 685.1876 | 269.4839 | 218.6631 |
| Temporal correlation (annual, 1900-2008) | 0.1460 | 0.5272 | 0.1117 | 0.2905 | 0.2052 |
For each of the five lakes, the statistical properties of the historical NBS sequences were reproduced through a generation procedure at the yearly and monthly scales. The statistical properties included: the historical mean (1900-2008 period); standard deviation (1900-2008 period); and lag one autocorrelation (1900-2008 period). The variance-covariance matrix of the system was reproduced as well.

These statistical properties were then applied to a general model used for generating synthetic annual NBS. The deterministic component for each lake’s NBS was eventually linked to a set of climate related predictors.

The initial model developed, within this portion of the investigation, reproduced contemporary residual supplies using global climate indices to calibrate candidate NL-ARX models for each of the five Lakes.

Six time series of climate indices were considered, because of the availability of 50000 synthetic values of these climates indices from Lee and Ouarda (2010). The historical observations of these indices were used to calibrate candidate NL-ARX models for each of the five Lakes. The length of the historical observations of these climate indices are presented in Table 8.

The best NL-ARX model was selected for each of the five lakes (Superior, St. Clair, Michigan-Huron, Erie, and Ontario). The characteristics of the selected NL-ARX model for each of the five Lakes are presented in Table 9.

### Table 7
Variance-Covariance matrix of observed annual NBS series

<table>
<thead>
<tr>
<th></th>
<th>SUP</th>
<th>MHG</th>
<th>ERI</th>
<th>ONT</th>
<th>STC</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUP</td>
<td>2.3434e+005</td>
<td>1.8904e+005</td>
<td>3.1880e+004</td>
<td>2.0616e+004</td>
<td>5.1991e+003</td>
</tr>
<tr>
<td>MHG</td>
<td>1.8904e+005</td>
<td>5.5080e+005</td>
<td>1.0881e+005</td>
<td>1.0668e+005</td>
<td>2.1628e+004</td>
</tr>
<tr>
<td>ERI</td>
<td>3.1880e+004</td>
<td>1.0881e+005</td>
<td>8.4465e+004</td>
<td>4.3046e+004</td>
<td>1.1699e+004</td>
</tr>
<tr>
<td>ONT</td>
<td>2.0616e+004</td>
<td>1.0668e+005</td>
<td>4.3046e+004</td>
<td>5.5889e+004</td>
<td>8.1608e+003</td>
</tr>
</tbody>
</table>

### Table 8
Available climate indices

<table>
<thead>
<tr>
<th>CLIMATE INDICE</th>
<th>AVAILABILITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENSO winter</td>
<td>1900-2009</td>
</tr>
<tr>
<td>ENSO annual</td>
<td>1900-2009</td>
</tr>
<tr>
<td>PDO winter</td>
<td>1900-2009</td>
</tr>
<tr>
<td>PDO annual</td>
<td>1900-2009</td>
</tr>
<tr>
<td>NAO winter</td>
<td>1900-2009</td>
</tr>
<tr>
<td>NAO annual</td>
<td>1900-2009</td>
</tr>
</tbody>
</table>

### Table 9
Selected NL-ARX model per lake
Figures 26-30 below compares observed annual NBS for all five lakes with the values simulated with their respective NL-ARX models. For all the lakes the fit is generally good, with a validation Nash coefficient ranging from 0.2233 (Lake St-Clair) to 0.4075 (Lake Superior).
Figure 27 - Best NL-ARX fit, Lake Michigan-Huron with Georgian Bay

Figure 28 - Best NL-ARX fit, Lake St. Clair
The final NL-ARX models for each lake were utilized to generate the 50000 values of mean NBS values using the synthetic climate indices generated by Lee and Ouarda (2010). Table 10 presents the statistical properties of the residual time series obtained by subtracting the outputs of the NL-ARX models from observed annual NBS series.
The next approach developed a set of models which linked annual NBS to climate variables obtained from both GCM runs and NCEP reanalysis. The only differences between the models presented here and prior models was that the climate indices were replaced by time series of NCEP variables averaged over the Great Lakes’ watersheds and a stepwise regression replaced the NL-ARX models.

Initially, monthly values of 25 climate variables covering the 1948-2009 period were extracted and/or calculated from the NOAA Earth System Research Laboratory website. The variables spatially interpolated and averaged over the water-sheds of each lake, and then standardized using the mean and the standard variation of the 1961-2009.

For each of the five lakes, predictors and annual NBS for a period of 53 years (1957-2009) were utilized. The 53 years were divided into a 60% calibration period (1957-1988) and a 40% validation period (1989-2009). Stepwise regression was applied to select the best explanatory variables for each lake’s NBS. The resulting stepwise regression analyses are illustrated in Figures 31-34 for each lake.

### Table 10

Mean and autocorrelation of the residuals

<table>
<thead>
<tr>
<th>Lake</th>
<th>SUP</th>
<th>MHG</th>
<th>ERI</th>
<th>ONT</th>
<th>STC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (cms)</td>
<td>-19.2851</td>
<td>5.9824</td>
<td>-21.1081</td>
<td>-5.5898</td>
<td>26.0280</td>
</tr>
<tr>
<td>Lag 1 autocorrelation</td>
<td>-0.1484</td>
<td>0.4643</td>
<td>-0.1653</td>
<td>0.0753</td>
<td>0.3522</td>
</tr>
</tbody>
</table>
Figure 32 - Best Multiple Regression fit, Lake Michigan-Huron

Figure 33 - Best Multiple Regression fit, Lake Erie
The resulting synthetic NBS generation, using NCEP variables, followed the same procedure as was used with climate indices.

**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), for two climate scenarios (A1B and A2 à) representing moderate and high emissions of greenhouse gases, were used to calculate future values of the predictors.

The model used has a spatial resolution of roughly 2.8 degrees latitude/longitude. Figure 35 illustrates the Great Lakes watersheds and corresponding CGCM3 grid cells. While developed in Canada it has been used in many climate change studies and remains a popular GCM worldwide (IPCC 2007).
Outputs from the third generation of the Canadian Circulation Model (CGCM3) were obtained from the Data Access Integration (DAI) website which is maintained by Environment Canada and the Global Environmental and Climate Change Centre (GEC3) out of Quebec, Canada. CGCM3 predictor data for the SRES A2 and SRES A1B climate change scenario were obtained for the years of 1961-2000 and from 2001 – 2100. The predictors were averaged over the Lakes watersheds (assuming the predictors values are constant on each grid-cell), and finally were standardized using the mean and the standard variation of the 1961-1990 period.

The length of the generated sequences can only be as long as the length of the predictors. Therefore, instead of one continuous sequence of 50000 values, 500 sequences of 100 years (corresponding to years 2001-2100) were generated for each of the A1B and A2 scenarios. These sequences were routed using the coordinated Great Lakes Routing Model. The climate change induced variations of both annual NBS and lake levels were evaluated for periods 2001-2025, 2026-2050, 2051-2075 and 2076-2100.

The results illustrated below (Figures 36-43) shows a continuous decrease of the NBS and levels of both Lake Superior and Lake Michigan-Huron under both scenarios. Lake Erie NBS supplies will be almost stable under scenario A1B and increasing under scenario A2. Its levels will decrease from above the 1900-2008 historical mean in 2000-20025 to below the same mean in 2076-2100 for both scenarios. The decrease is more pronounced for scenario A2. Lake St-Clair NBS supplies will be significantly above the 1900-2008 historical mean in 2001-2025 and 2076-2100 periods for both climate change scenarios. The St. Clair NBS supplies will be above but close to the 1900-2008 historical mean for the periods 2026-2050, and 2051-2100. However, the levels will be decreasing for both scenarios, driven by the level decreases in Lakes Superior and Michigan-Huron.
Figure 36 - Superior NBS variations under climate change

Figure 37 - Superior levels variations under climate change
Figure 38 - Michigan-Huron NBS variations under climate change

Figure 39 - Michigan-Huron levels variations under climate change
Figure 40 - Erie NBS variations under climate change

Figure 41 - Erie levels variations under climate change
Figure 42 - St-Clair NBS variations under climate change

Figure 43 - St-Clair levels variations under climate change
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.

4.0 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 4.4 illustrates the Study’s climate change modelling framework. As illustrated, 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 44
Climate Change Modelling Framework

Revised Climate Change Strategy

565 Sequences from Angel & Kunkel’s 23 GCMs

Screening of Scenarios

160 Statistically downscaled runs

Environment Canada’s Regional Climate Modelling

Canadian, German & French GCMs as Boundary

Eight dynamically downscaled runs

GLERL’s Regional Climate Modelling

US GCM as Boundary

One dynamically downscaled

Compare RCM results with higher resolution GCM & historic NBS

Check plausibility of occurrence

Test Robustness of the Candidate Regulation Plans

A – External process to Climate Change

B – External process to Climate Change

Stochastic scenarios from random and tele-connection runs
4.1 GCM Climate Modelling

To fully encompass estimates of the future climate of the Great Lakes, output of 565 model runs from 23 GCMs compiled by Angel and Kunkel (2010) were evaluated. 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). Both the validity of the model runs and the applicability of utilizing the entire data set or a subset of the runs were considered.

The analysis used the GLERL model to calculate NBS and lake levels for the current climate (covering the period 1970 to 1999), 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 11 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 11. 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 11 are indicative rather than predictive.

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

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, 2010).

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

CRCM - Runs

To evaluate the 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.

The atmospheric lateral boundary conditions were provided from a variant of the Canadian Regional Climate Model (CRCM) CGCM3.1v2 (Scinocca et al., 2008) running at T47 resolution (= about 3.75O X 3.75O). The “observed 20th century” emission scenario for the current climate period (nominally 1961-2000), and the SRES A2 emission scenario for 2001-2100 was used. Data from this run were downcaled using the Ouranos Climate Simulation Team10 (Montreal) version of the Canadian Regional Climate Model (CRCM4.2.3) over a North American grid (known as “AMNO”) of about 45 km horizontal resolution. The grid used (Figure 45) was 100 x 90 cells (polar – stereographic) at about 22.5 km horizontal resolution (exact at 60 ,N), oriented in such a way that each grid cell on the AMNO grid is made up of exactly 4 grid cells of the GLCRCM grid.

The Ouranos Climate Team operationally produces CRCM simulations on the North American grid based on a number of driving GCM simulations, and archive monthly results for general use. This investigation used precipitation, evaporation, and runoff data from eight of these simulations and derived estimates of NBS were inputted directly into the CGLRRM.

---

10 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.
This version of the CRCM did not include streamflow routing, but did have a simple lake model, which the driving GCM did not. 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.

The data from the eight simulations runs were driven by three different Global Climate Models and thus comprise a multi-model, multi-member ensemble. One of these simulations was further downscaled using a variant of the CRCM known locally as the Great Lakes Regional Climate Model (GLRCM), developed for the IUGLS. This system is made up of the dynamical core of the CRCM, the physical parameterization package of the Canadian GCM (internal version gcm13d) along with an updated version of the Canadian Land Surface Scheme (CLASS v3.3), a high resolution land surface database, a simple routing scheme, and a link to the Coordinated Great Lakes Regulation and Routing Model (CGLRRM). The operational runs of the CRCM are on a medium resolution polar stereographic grid of 45 km horizontal resolution, while the GLRCM uses a higher resolution grid of 22.5 km horizontal resolution.

An analysis of the NBS mean seasonal cycle (illustrated Figure 46) reveals that changes are not uniform throughout the year, with declines in NBS largely concentrated during late summer - early fall (i.e. the annual minimum period) with no change or increases (especially Lake Superior) during winter and spring. The simulation suggests an amplified NBS seasonal cycle in the future climate period.
Lake levels response to mean NBS values and the actual simulated monthly sequence were modest but all negative. Table 12 shows that the simulated changes in levels were: -3 cm for Lake Superior, -5 cm for Lake Michigan – Huron, and -6 cm for Lake Erie. These results were primarily a function of both the simulated changes in NBS for each lake as well as the current regulation plan.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Superior</td>
<td>183.46 (0.174)</td>
<td>183.46 (0.181)</td>
<td>183.43 (0.170)</td>
<td>-0.03</td>
</tr>
<tr>
<td>Michigan – Huron</td>
<td>176.63 (0.407)</td>
<td>176.65 (0.285)</td>
<td>176.60 (0.274)</td>
<td>-0.05</td>
</tr>
<tr>
<td>Erie</td>
<td>174.34 (0.352)</td>
<td>174.41 (0.218)</td>
<td>174.35 (0.204)</td>
<td>-0.06</td>
</tr>
</tbody>
</table>
Examination of the mean seasonal cycle in simulated lake levels (Figure 47) demonstrates that Lake Superior levels have an amplified seasonal cycle in the future climate period compared to the present. The largest declines take place during winter and slight increases during summer. The decline in levels for Michigan–Huron and Erie are more consistent throughout the year.

![Graph showing lake levels]

All three lakes show a reduction in mean level, ranging from 3 cm for Lake Superior to 8 cm for Lake Erie, in the future climate. Interestingly, Lake Superior shows a drop in level even though the change in NBS is slightly positive, and Lake Michigan–Huron shows a significant drop in level even though the change in NBS is only weakly negative. This suggests that changes in the upper Great Lakes system may be largely controlled by changes over Lake Erie and its watershed (for which we found a significant decrease in NBS under future climate conditions) – at least under the current regulation plan as encoded in the CGLRRM.

It is generally 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).

In order to make use of a larger ensemble size, an identical analysis was performed on eight simulations of the CRCM on its coarser grid directly, that is without downscaling through the GLRCM. One of these runs provided the boundary conditions for high resolution simulation, allowing evaluation of the impact of the downscaling exercise on NBS and lake levels. Apart from bias, all of the simulations reproduced the gross features of the mean annual cycle in most NBS components, as well as NBS itself.

The NBS components for the current climate period (1961 – 1990) from all eight simulations are summarized in Table 13 along with observed estimates from GLERL.

Table 13
Summary of observed (GLERL) and simulated (CRCM) average annual NBS components for 1961–1990.

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

Monthly average components for the current climate period are plotted in Figures 48 -50. The annual pattern is similar for over lake and over land precipitation with higher values during the summer than the winter for both the GLERL data and the CRCM data. The exception was lake evaporation, where the model simulated peak evaporation 2 – 3 months early, evidently a deficiency in the lake scheme used here. This resulted in an NBS cycle that was generally too low during late summer – early fall and generally too high during winter, even when bias corrected. Nevertheless, when input to the CGLRRM, the adjusted NBS sequences yielded reasonable current climate lake levels both in terms of annual mean and seasonal cycle.
Figure 48 - Mean seasonal cycle for current climate (1961-1990) precipitation and evaporation components for Lake Superior.

Figure 49 - Mean seasonal cycle for current climate (1961-1990) precipitation and evaporation components for Lake Michigan – Huron.
Future climate NBS sequences were computed based on the same factors. The future period was defined as 2041 – 2070, as this is the time slice simulated by the Ouranos simulation group operationally. All of the simulations indicated more precipitation during the future period compared to the present, but also large increases in lake evaporation. Land evaporation also increased somewhat resulting in a general increase in runoff. The net resulting change in NBS for the future 2041-2070, shown in Table 14, is in general negative but small.

**Table 14**

Summary of simulated (CRCM) average annual NBS change (2041-2070 period minus 1961-1990 period). Units are mm over lake.

<table>
<thead>
<tr>
<th>Component</th>
<th>Lake</th>
<th>CGCM</th>
<th>ECHAM5</th>
<th>ARPEGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>adjusted NBS</td>
<td>Superior</td>
<td>-40.8</td>
<td>45.1</td>
<td>-135.4</td>
</tr>
<tr>
<td>(mm over lake)</td>
<td>Michigan/Huron</td>
<td>-9.4</td>
<td>-30.3</td>
<td>-48.7</td>
</tr>
<tr>
<td></td>
<td>Erie</td>
<td>-20.6</td>
<td>-59.9</td>
<td>-18.4</td>
</tr>
</tbody>
</table>

Although the annual changes were modest, examining the monthly distribution of the changes in NBS reveals a consistent seasonal pattern (illustrated in Figure 51) with increases in NBS generally occurring during winter and spring, and decreases seen in the late summer and early fall.
Finally, the results for lake level changes are summarized in Table 15 and Figure 52. Median results suggest no change, and our GLRCM results are well within the range of the CRCM ensemble. Once again an amplified seasonal cycle in Lake Superior levels is indicated.

Table 15
Summary of simulated (CRCM) average annual lake level change 2041-2070 period minus 1961-1990 period.

<table>
<thead>
<tr>
<th></th>
<th>Superior</th>
<th>Michigan-Huron</th>
<th>Erie</th>
</tr>
</thead>
<tbody>
<tr>
<td>CGCM #1</td>
<td>0.08</td>
<td>0.15</td>
<td>0.12</td>
</tr>
<tr>
<td>CGCM #2</td>
<td>0.03</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>CGCM #3</td>
<td>-0.08</td>
<td>-0.07</td>
<td>-0.03</td>
</tr>
<tr>
<td>CGCM #4</td>
<td>-0.02</td>
<td>-0.04</td>
<td>-0.02</td>
</tr>
<tr>
<td>GLRCM</td>
<td>-0.03</td>
<td>-0.05</td>
<td>-0.06</td>
</tr>
<tr>
<td>CGCM #5</td>
<td>-0.13</td>
<td>-0.11</td>
<td>-0.02</td>
</tr>
<tr>
<td>ECHAM5 #1</td>
<td>0.02</td>
<td>0.08</td>
<td>0.07</td>
</tr>
<tr>
<td>ECHAM5 #2</td>
<td>0.14</td>
<td>0.13</td>
<td>0.07</td>
</tr>
<tr>
<td>ARPEGE #1</td>
<td>-0.22</td>
<td>-0.39</td>
<td>-0.22</td>
</tr>
<tr>
<td>MEDIAN</td>
<td>0.00</td>
<td>-0.01</td>
<td>-0.005</td>
</tr>
<tr>
<td>RANGE</td>
<td>[-0.22, 0.14]</td>
<td>[-0.39, 0.15]</td>
<td>[-0.22, 0.12]</td>
</tr>
</tbody>
</table>
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: \( P_{\text{current}} \) and \( P_{\text{future}} \) may be poorly simulated but \( \Delta P = P_{\text{future}} - P_{\text{current}} \) 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.

For this investigation a 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 16. These differences appear to be within the range of differences of historical estimates between the GLERL and EC models (1948-2008) differences

<table>
<thead>
<tr>
<th></th>
<th>Superior</th>
<th>Michigan – Huron</th>
<th>Erie – St. Clair</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overlake Precipitation</td>
<td>5 %</td>
<td>2 %</td>
<td>10 %</td>
</tr>
<tr>
<td>Lake Evaporation</td>
<td>-9 %</td>
<td>-1 %</td>
<td>-9 %</td>
</tr>
<tr>
<td>Runoff</td>
<td>-9 %</td>
<td>7 %</td>
<td>-2 %</td>
</tr>
<tr>
<td>NBS</td>
<td>8 %</td>
<td>9 %</td>
<td>21 %</td>
</tr>
</tbody>
</table>

To compare projected future NBS results with the present, monthly means and standard deviations for the current (1962-1990) and future (2021-2050) climate periods were summarized (Table 17). On average, 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.

<table>
<thead>
<tr>
<th></th>
<th>Superior</th>
<th>Michigan – Huron</th>
<th>Erie</th>
</tr>
</thead>
<tbody>
<tr>
<td>NBS</td>
<td>Observed = GLRCM 1962-1990</td>
<td>GLRCM 2021-2050</td>
<td>Change</td>
</tr>
<tr>
<td>Superior</td>
<td>67.9 (70.5)</td>
<td>68.3 (86.3)</td>
<td>0.4 (15.8)</td>
</tr>
<tr>
<td>Michigan – Huron</td>
<td>74.8 (69.7)</td>
<td>73.2 (79.2)</td>
<td>-1.6 (9.5)</td>
</tr>
<tr>
<td>Erie</td>
<td>82.7 (106.6)</td>
<td>74.9 (113.8)</td>
<td>-7.8 (7.2)</td>
</tr>
</tbody>
</table>

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 18 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 the design period of 2040. The annual pattern is similar for overlake and overlend 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 18
Summary of Observed (GLRL) and Simulated Average Annual NBS Components for 1961-1990**

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

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.
**Coupled Hydrosphere Atmospheric Research Model – CHARM**

To assess future climate variability investigations were conducted utilizing 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.

The model includes both lateral boundary nudging near the edges of the model domain and spectral nudging in the interior of the domain, based on GCM data. Output on the native grid of CHARM includes surface runoff and sub-surface percolation, which can be transformed into an estimate of river runoff based on tributary sub-basins. CHARM also has output of a full range of atmospheric and hydrologic variables, notably including surface-atmosphere energy fluxes (sensible heat, latent heat, and long-wave and short-wave radiation) that can aid in interpreting the reasons behind changes in hydrologic phenomena. The version of CHARM used for this analysis was also updated to include a newer version of the Regional Atmospheric Modeling System (RAMS) and the substitution of the formulation of Hostetler and Bartlein (1990) for vertical diffusion of heat within the lakes' water column on a spatially distributed basis in place of a parameterization of the lake thermodynamics that treats each lake as a single spatially lumped column.

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.

The CHARM model simulation of over-land air temperature is illustrated in Figure 53, for all lakes. The over-land air temperature was shown to be biased toward being too warm during the winter and too cold during the summer. The bias of the largest magnitude occurs during January, with the largest magnitude being in the Lake Superior basin, where there is a positive bias of about 7 degrees.
Figure 53 - Climatological air temperature (C°) at 2m above the surface observations and from the 1982 time slice for the land portion of each Lake’s drainage basin.

The effects of additional anthropogenic greenhouse gases on near-surface air temperatures over land are highly uniform among the lake basins and across the seasonal cycle. Figure 54 illustrated this variation. Air temperatures for all basins and all months are increased by between 2 and 3 degrees in the 2055 time slice relative to the 1982 time slice.
During the summer months, CHARM-simulated temperatures in the 1982 time slice have a strong cool signature from the lakes overlaid on the general north-south temperature gradient. The future case with increased greenhouse gases has a general increase in air temperature during the summer, but the magnitude of the air temperature increase is smaller directly over the lakes than elsewhere in the domain, with temperature increases of less than 2 degrees over central Lake Huron and most of Lake Superior.

During the winter, warmer air is present over the lakes than in the surrounding areas. The warming trend between the two time slices lacks the lake signature that was present during the summer, but displays a slight meridional gradient in its magnitude, with higher values toward the north.

The precipitation simulated over the land portion of the basins shows different biases among the basins and in different seasons. Figure 55 shows all of the basins tend to have positive precipitation biases.
during the summer months, especially June and July, but the magnitude and duration of this positive bias is greater in the Georgian Bay, Lake St. Clair, and Lake Ontario basins than the others. There are more negative biases during the winter, especially in the Lake Superior and Lake Erie basins.

Changes in overland precipitation in the basins due to enhanced greenhouse gases are somewhat mixed and of rather small magnitude as illustrated in Figure 56. Small increases generally prevail except in the Lake St. Clair and Lake Ontario basins. Increases also prevail more during winter, spring, and summer, but not during fall. Lake St. Clair may be influenced by increases in precipitation associated with the larger lakes moving the focus of precipitation and drawing atmospheric moisture from the Lake St. Clair basin. For Lake Ontario, it is possible that the precipitation center in the northeastern corner of the model domain, an artifact of the model setup, is drawing precipitation from the Lake Ontario basin.

The climatological precipitation in the 1982 time slice during June, July, and August shows a strong gradient of precipitation increasing from west to east. The change in summer precipitation with
increasing greenhouse gases in the future is a general increase, with the strongest increases on the downwind sides of the lakes, where air can be highly unstable and prone to convective precipitation. Additional moisture received via the atmosphere both from within and outside the model domain via the boundary conditions can be fed into convective complexes that tend to occur most frequently in these locations.

Simulated precipitation during the winter in the 1982 time slice shows less of an east-west gradient. It has localized concentrations of precipitation over the lakes and immediately adjacent to them. With increasing greenhouse gases, winter precipitation is increased generally, but most intensely directly over the lakes. In both winter and summer, the largest increases in precipitation are focused on the locations with the greatest atmospheric static instability—land adjacent to the lakes during the summer and the lakes themselves during the winter.

![Climatological precipitation rate (mm/day) from observations and from the 1982 time slice of CHARM for the land portion of each lake’s drainage basin.](image)

*Figure 56 - Climatological precipitation rate (mm/day) from observations and from the 1982 time slice of CHARM for the land portion of each lake’s drainage basin.*
The precipitation that occurs directly over the lake, illustrated in Figure 57, does not have any readily available validation data. Quite consistently over all lakes, the future time slice has an increase in precipitation over the past time slice during the months of June, July, December, and January. Especially during the winter, this can be attributed to reduced static stability over the lakes, although such an effect on static stability also occurs during the spring, with much less influence on precipitation.

![Figure 57 - Climatological precipitation rate (mm/day) comparing the 1982 and 2055 time slices of CHARM for each lake.](image)

The lake-averaged surface water temperatures simulated by CHARM in the 1982 time slice are compared to lake-averaged surface temperatures based on satellite data processed in the Coast Watch project (Leshkevich et al. 1993, Schwab et al. 1999) in Figure 58. The deeper lakes are characterized by a smaller annual temperature range than observed, especially Lake Superior. That is, although the annual mean temperatures are not strongly biased, the water is unrealistically warm during the winter and cool during the summer.
The shallower waters of Georgian Bay and Lake Erie matched the observations much more closely. In contrast to the deeper lakes, the epilimnion (surface mixed layer) tends to extend near the bottom of these lakes or all the way to it. This means that wind has little influence on the depth of the epilimnion, the effective heat capacity of the lake, and the magnitude of the annual cycle of lake surface temperature. In the cases of Georgian Bay and Lakes St Clair and Erie, it should be noted that the CoastWatch data detects ice surface temperatures, i.e. some surface temperatures can be below the freezing temperature. However, the CHARM-simulated lake surface temperatures here are strictly liquid water temperatures, and cannot dip below 0° C, helping to explain the discrepancies during the winter. The shallow lake that does not match as well to observations is Lake St. Clair, with a sizable positive temperature bias during the summer and a negative bias during November and December, i.e. its problem in magnitude of the annual cycle is opposite to that of Lakes Superior, Michigan, and Huron. Also, despite its greater depth, Lake Ontario's surface temperatures match very well with observations.
Lake surface temperatures increase throughout the year, as seen in Figure 59, but with the greatest magnitude during the summer. On the shallow lakes, the ones that form ice more readily, Lake Surface temperatures approach or reach the freezing point in both time slices and the surface temperature difference is near zero. On the deeper lakes, the winter temperature difference is closer to one degree. During the summer, however, lake surface temperature increases are closer to 2 degrees on all lakes.

The evaporation occurring directly from the lakes shows slight increases in Figure 60. Increases are most consistent among the basins during the fall and early winter months. However, there are few months in which the lake evaporation increases by more than 10%.
Lake evaporation, similar to the land evapotranspiration is not simply driven by temperature. Although it would be closer to the truth to say that it is driven by temperature gradient between the water and the overlying air, the bigger picture is that lake evaporation is contingent on sufficient input of energy from the sun and the atmosphere. Despite lake surface temperature being one factor in evaporation, other factors can compensate in order to maintain a balance among the energy terms in the lake, notably moistening of the overlying atmosphere that accompanies the mutual warming of lake and atmosphere. However, one likely source of bias is the bias in seasonal lake surface temperature and ice cover. Because of the strong mixing and small magnitude of the seasonal variation of lake surface temperature, little ice forms on the deep lakes, and this removes the potential for lake evaporation to be enhanced by the reduction in ice cover under an enhanced greenhouse gas scenario.

All of the lake basins have deficient net basin supply (NBS) simulated by CHARM and shown in Figure 61. The annual mean and the peak time is out of phase with residual calculations NBS. The overall
The deficit is less severe in Lakes St. Clair and Erie than in the lakes farther to the northwest. The warm winter temperature biases are one reason for the lack of the distinct peak around March and April that is in the residual numbers, due to lack of winter snow accumulation and the temporally concentrated snowmelt season.

As illustrated in Figure 62, the 2055 time slice has small increases in net basin supply in most months relative to the 1982 time slice. The most notable increases are in December and January for the basins other than Lake Superior. These increases are mainly attributable to increased precipitation directly over the lakes.
Adjusting the projected net basin supply so that its mean and standard deviation during the 1982 time slice match those parameters for the residual NBS was investigated. For each month of the year, a mean value was calculated for the residual NBS and the CHARM-projected NBS. Also, a standard deviation was calculated for each month and each of the datasets. Then, for the monthly value for each month of the time series in the 1982 CHARM time slice, the deviation of the value from the mean NBS if the 1982 CHARM time slice is divided by the standard deviation within the 1982 time slice, then multiplied by the standard deviation in the residual NBS. The result was then added to the mean of the residual NBS to get the adjusted value. For the 2055 time slice, the same procedure was used, using the departure of individual monthly values from the 2055 time slice from the mean of the 1982 time slice, dividing this deviation by the standard deviation from the 1982 time slice, multiplying by the standard deviation from the residual NBS data, then adding the mean values from the residual NBS. The results are shown in Figure 63. This process helps to accentuate the 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.
When using a regional climate model that is driven by the results of a larger-scale model, the effects of climate change due to increased greenhouse gases show various effects. The air temperatures over the land portions of the basin are increased in a highly consistent way throughout the years and in all basins. The changes in precipitation are generally increases, but are variable by month and basin. One of the consistent changes is that increases in precipitation occur more strongly over 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. Lake surface temperatures during the 1982 time slice generally show too small of a seasonal cycle. 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 net basin supply due to increased greenhouse gases are generally small increases.

The NBS simulation results, shown in Figure 63 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.

4.2 Integration of Results

The 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 64 illustrates the integration of the hydroclimatic analysis.

The figure 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, 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 64 - 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.

Investigations 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. Hydroclimatic investigation addressed this bias by making adjustments on NBS itself rather than on individual components.

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, was assessed. 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. Investigations revealed that the 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.
5.0 Application of the Findings

5.1 Knowledge and Products Gained

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, hydroclimatic efforts 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. 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. A variety of approaches were used 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 19 summarizes the hydrological time series developed by the WG for the hydroclimatic analysis. The different approaches used 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 19
Summary of the Hydrological Time Series

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Product</th>
<th>Product Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analysis of Observations</td>
<td>Historical Residual NBS Sequences¹¹ 1860-1899</td>
<td>1860-1899</td>
</tr>
<tr>
<td></td>
<td>Historical Residual NBS Sequences 1900-2008</td>
<td>1900-2008</td>
</tr>
<tr>
<td></td>
<td>Historical Component NBS Sequences 1948-2006</td>
<td>1948-2006</td>
</tr>
<tr>
<td>Derived sequences from residual NBS</td>
<td>Stochastic Sequence of Contemporary Residual Supplies</td>
<td>55,000 years</td>
</tr>
<tr>
<td></td>
<td>Stochastic Sequence of Contemporary Residual Supplies using ENSO indicator</td>
<td>50,000 years</td>
</tr>
<tr>
<td></td>
<td>Stochastic Sequence of Contemporary Residual Supplies using NCEP 500 mb anomalies indicator</td>
<td>50,000 years</td>
</tr>
<tr>
<td></td>
<td>Paleo-Sequence</td>
<td>1000 years</td>
</tr>
<tr>
<td></td>
<td>Stochastic Sequence with Climate Change emission scenario A2</td>
<td>500 sequences of 100 years of monthly NBS</td>
</tr>
<tr>
<td></td>
<td>Stochastic Sequence with Climate Change emission scenario A1b</td>
<td>500 sequences of 100 years of monthly NBS</td>
</tr>
<tr>
<td>RCM Sequence</td>
<td>8 Ouranos 45 km runs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 RCM 22.5 km runs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 Charm 40 km runs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>~500 Angel and Kunkel time slices (A2, A1B, B1 emission scenarios)</td>
<td></td>
</tr>
</tbody>
</table>

¹¹ 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.
6.0 **Key Points**

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

- The first major task of the Hydroclimatic WG 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 the 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 WG 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 WG 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 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 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.
7.0 Recommendations

Based on the findings presented in this chapter, the HC-WG 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 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 WG 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.

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 WG 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 WG 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.
References


Kieffer and Assoc. (1976). *Preliminary Design Report for the Calumet System of the Tunnel*


