Hydroclimatic Technical Work Group

HYDROLOGY AND CLIMATE MODELLING STRATEGY

Stannard Rock Lighthouse with inset of eddy covariance instrumentation tower
Photos courtesy of Chris Spence and Newell Hedstrom

June 2008
# Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Introduction</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>Primary Science Issues</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>Science Questions Framework</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>Project Matrix and Timeframe</td>
<td>18</td>
</tr>
<tr>
<td>5</td>
<td>Hydrology and Climate Modeling Strategy</td>
<td>18</td>
</tr>
<tr>
<td>6</td>
<td>Evaluation of Uncertainty</td>
<td>25</td>
</tr>
<tr>
<td>7</td>
<td>Assessment and Integration of Results</td>
<td>29</td>
</tr>
<tr>
<td>8</td>
<td>References</td>
<td>31</td>
</tr>
</tbody>
</table>

## Figures
- Figure 1. Hydrologic components of the Great Lakes water balance
- Figure 2. Uncertainty in net basin supply
- Figure 3. Lake water balance components
- Figure 4. Comparative analysis of NBS and component time series
- Figure 5. Comparative analysis work flow
- Figure 6. Statistical Analysis and Teleconnections work flow
- Figure 7. Climate change sequences work flow
- Figure 8. Residual vs. component estimates of NBS to Lake Superior
- Figure 9. Overall error and bias between the component and residual methods
- Figure 10. Results integration, analysis, visualization and interpretation

## Tables
- Table 1a St. Clair River Science Questions
- Table 1b Lake Superior Science Questions
- Table 2a St. Clair River Tasks, Key Milestones, Products and Outcomes
- Table 2b Lake Superior Tasks, Key Milestones, Products and Outcomes
- Table 3a Critical path analysis – St. Clair River tasks
- Table 3b Critical path analysis – Lake Superior tasks
- Table 4 Correlation and coefficient estimates for Lake Superior NBS
- Table 5 Correlation and coefficient estimates for Lake Michigan-Huron NBS

## Annexes
- Annex A Comparative Analysis Of Net Basin Supply Computations
- Annex B Comparative Analysis of Net Basin Supply Components and Climate Change Impact on the Upper Great Lakes
- Annex C Closing The Water Balance Of The Upper Laurentian Great Lakes: A Coupled Land, Lake, And Atmosphere Modeling Approach
- Annex D Analysis Of Changes In Net Basin Supply Components
- Annex E Direct Observations of Lake Superior Evaporation
- Annex F Linking Climate Scenarios and Teleconnections to Great Lakes Ice, Precipitation, and Water Levels
### Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AHPS</td>
<td>Advanced Hydrologic Prediction System</td>
</tr>
<tr>
<td>CDAS</td>
<td>NCEP Reanalysis Project</td>
</tr>
<tr>
<td>CHARM</td>
<td>Coupled Hydrologic Atmospheric Research Model</td>
</tr>
<tr>
<td>CRCM</td>
<td>Canadian Regional Climate Model</td>
</tr>
<tr>
<td>ECNWDAS</td>
<td>Environment Canada Numerical Weather and Data Assimilation System</td>
</tr>
<tr>
<td>GCM</td>
<td>Global Climate Model</td>
</tr>
<tr>
<td>GLERL</td>
<td>Great Lakes Environmental Research Laboratory</td>
</tr>
<tr>
<td>HC TWG</td>
<td>Hydroclimatic Technical Working Group</td>
</tr>
<tr>
<td>IJC</td>
<td>International Joint Commission</td>
</tr>
<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
</tr>
<tr>
<td>IUIGLS</td>
<td>International Upper Great Lakes Study</td>
</tr>
<tr>
<td>INRS-ETE</td>
<td>Institut National de la Recherche Scientifique - Eau, Terre et Environnement</td>
</tr>
<tr>
<td>LBRM</td>
<td>Large Basin Runoff Model</td>
</tr>
<tr>
<td>LLTM</td>
<td>Large Lake Thermal Model</td>
</tr>
<tr>
<td>MPE</td>
<td>Multi-sensor Precipitation Estimate</td>
</tr>
<tr>
<td>NBS</td>
<td>Net Basin Supply</td>
</tr>
<tr>
<td>NCEP</td>
<td>National Center for Environmental Prediction</td>
</tr>
<tr>
<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
</tr>
<tr>
<td>NWS</td>
<td>National Weather Service</td>
</tr>
<tr>
<td>PCMDI</td>
<td>Program for Climate Model Data and Intercomparison</td>
</tr>
<tr>
<td>PEG</td>
<td>Plan Evaluation Group</td>
</tr>
<tr>
<td>PI</td>
<td>Principal Investigator</td>
</tr>
<tr>
<td>RCM</td>
<td>Regional Climate Model</td>
</tr>
<tr>
<td>TWG</td>
<td>Technical Working Group</td>
</tr>
</tbody>
</table>
1. **Introduction**

The Hydrology and Climate Modeling Strategy proposed herein, is being undertaken as part of the International Joint Commission’s International Upper Great Lakes Study (IJC-IUGLS). The IJC, created by the Boundary Waters Treaty of 1909, has the responsibility to manage the shared waters between Canada and the United States. The IJC established the 5-year binational Study in February 2007 in response to concerns regarding declining lake levels. The Study was officially launched in March 2007, with the formation of the Study Board. The study area includes lakes Superior, Michigan, Huron and Erie, and their interconnecting channels (St. Mary's River, St. Clair River, Lake St. Clair, Detroit River and Niagara River), up to Niagara Falls. More details on the mandate, study organization, Plan of Study, etc. are available at www.iugls.org.

The Study’s mandate is two fold: 1) to investigate physical changes in the St. Clair River as one factor that might be affecting water levels and flows; and 2) to examine whether the regulation of Lake Superior outflows can be improved to address the evolving needs of the upper Great Lakes. To address these mandates respectively, the Board established the St. Clair Task Team and the Lake Superior Task Team. Technical Working Groups (TWGs) were established in support of the Task Teams.

The Hydroclimatic Technical Work Group (HC TWG) was formed as one of the few TWGs to serve both Task Teams. Accordingly, the objectives of the HC TWG are two-fold. The first is to assess changes to the contemporary hydrology affecting the levels of the lakes. The second is to examine future climate variability and change and any future challenges in lake regulation that may be expected as a result of a changing climate regime. The first objective primarily relates to addressing the St. Clair River issue; how much of the change in Lake Huron levels can be attributed to channel conveyance and how much to water supplies? The second objective primarily relates to Upper Lakes regulation; can we anticipate and adapt lake regulation to a changing climate? However, in designing a modeling strategy to answer each question separately, we found many interdependencies between the two efforts. The modeling strategy reflects these interdependencies and we attempt to leverage work between the two objectives.

In order to address these questions, one needs to have a thorough understanding of the water balance of the Great Lakes. A water balance (Figure 1) is an accounting of all water entering and leaving a given body of water, for a given period of time. This can be easily expressed as “inflow equals outflow plus change in storage”. A water balance is quantified through the evaluation and accounting of these three major components.

The Great Lakes are an immense hydrologic system whose volume could cover the continents of North America, South America, and Africa to a depth of more than 30 cm (Neff and Nicholas, 2005). The surface of the Great Lakes spans over 800 km from the northern to southern tip while spanning a length of over 1200 km from east to west. The unique cascade of Lake Superior to Lakes Michigan-Huron to Lake Erie is a significant factor in both their water balances and connecting channel hydraulics. For example, the dominant component of water
supply to Lake Superior is precipitation; while for Lake Erie it is inflow from Lakes Michigan-Huron. Yet Lakes Michigan-Huron outflow to Lake Erie is in part affected by the lower lake’s water level through a backwater effect via the St. Clair and Detroit Rivers. Researchers have quantified Great Lakes water balances for many decades, and hundreds of water-balance studies have been done. However, uncertainties in estimates of the various components of the water balance in such a large system can vary dramatically, leading to uncertainty in the overall water balance. These uncertainties can mask or confound our understanding and the attribution of changes in various water balance components should they be occurring. Thus addressing this uncertainty becomes a key underlying aspect of the HC TWG modeling strategy.

Figure 1. Hydrologic components of the Great Lakes water balance. Based on 1950-1960 data; adapted from “Regulation of Great Lakes Water Levels”, International Great Lakes Level Board, December 1973. (not available in metric units)

2. Primary Science Issues

The two primary science questions for the HC TWG modeling strategy have been posed as follows:

- What are the historic estimates of the net basin supply 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?
To address these questions from both contemporary and future perspectives, it is essential to quantify the water-balance. With the Hydraulics TWG focusing on the connecting channel hydraulics and flows, the HC TWG will focus on quantifying net basin supply (NBS) – the net amount of water entering each Great Lake, not counting the supply of water from upstream Great Lakes. One feature of NBS is that it can be computed two ways, by the component method or the residual method (Croley and others, 2001; Lee, 1992). The methods differ in the water-balance terms used to determine NBS. The **component** method determines NBS directly from overlake precipitation, lake evaporation and basin runoff. The **residual** method determines NBS indirectly as the difference of the connecting channel inflow and/or outflow and the change in storage as determined by change in lake level. Each method allows the researcher some freedom to evaluate select hydrologic parameters to derive NBS, an important feature for quantifying uncertainty, yet each have their own inherent problems. Each approach is better suited for certain applications than the other. Traditionally, the residual approach has been used by the operational agencies for lake regulation and water balance accounting. More recently, developments in climate and hydrologic modeling and remote sensing have enabled the use of the component method. Mathematical expressions of the complete accounting of NBS for each method are given by Lee (1992) and adapted by Neff and Nicholas (2005) as:

**Component NBS calculation**

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

Where:

- \( P \) is over-lake precipitation,
- \( R \) is basin runoff to a Great Lake,
- \( E \) is evaporation from the lake surface, and
- \( G \) is ground-water flux into a Great Lake (net).

It is common to assume the groundwater flux is negligible yielding:

\[
NBS = P + R - E \quad \text{(Equation 2)}
\]

**Residual NBS calculation**

\[
NBS = O - I + \Delta S - \Delta S_T + D_o - D_i + C_{use} \quad \text{(Equation 3)}
\]

Where:

- \( O \) is outflow from a given Great Lake,
- \( I \) is inflow from an upstream Great Lake,
- \( \Delta S \) is change in water storage of a Great Lake,
- \( \Delta S_T \) is change in water storage caused by thermal expansion or contraction of the water body,
- \( D_o \) is diversion of water out of a basin, and \( D_i \) is diversion in,
- \( C_{use} \) is consumptive use of Great Lakes water.
Because it is very difficult to determine the thermal expansion/contraction term, and consumptive use is considered small relative to the other terms, Equation 3 is commonly simplified to

\[ \text{NBS} = O - I + A S + D_o - D_i \]  
(Equation 4)

Ideally, determination of NBS using either method should yield the same values. However, as noted by Neff and Nicholas (2005) and illustrated in Figure 2, given the imperfections and uncertainties in estimating any of the terms, the difference between the two estimates of NBS is not negligible.

![Figure 2](image)

**Figure 2.** Uncertainty in net basin supply using component and residual methods. Uncertainty is expressed in equivalent flow in cubic feet per second. (Neff and Nicholas, 2005) (not available in metric)

Figure 2 highlights the estimated uncertainty in both the component and residual NBS methods. It is interesting to note that the component method shows greater uncertainty for the most upstream lakes (Superior, Michigan-Huron) while the residual method shows greater or equal uncertainty for the downstream lakes (Erie, Ontario). Regardless, both methods show large levels of uncertainty. Inherent to the HC TWG modeling strategy will be examining both methods and understanding how this uncertainty relates to the confidence of our findings.

Figure 3 shows the main water balance terms from Equations 2 and 4 for each of the lakes. Clearly lake precipitation and basin runoff (noted in Figure 3 as streamflow) dominate the inflow to Lake Superior and Lakes Michigan-Huron, while upstream connecting channel inflow dominates the inflow to Lakes Erie and Ontario. This is one reason Lake Superior and Lakes Michigan-Huron are more sensitive and reactive to prolonged precipitation deficits. Likewise, lake evaporation and connecting channel outflow dominate the outflows of Lake Superior and Lakes Michigan-Huron, while lake evaporation plays a much smaller role in the water balances for Lake Erie and Lake Ontario. The significance of lake evaporation for the two upper lakes is
a critical factor in assessing their vulnerability under a changing climate with increasing air and water temperatures. The importance of connecting channel flow to all of the lakes’ water balances makes estimating this term accurately of high importance.

**Figure 3.** Lake water balance components expressed as equivalent flow in cubic feet per second. (Neff and Nichols, 2005) (not available in metric)

3. **Science Questions Framework**

To address the primary science questions and better understand cause and effects, various hypotheses or secondary science questions need to be addressed. Tables 1a (St. Clair) and 1b (Lake Superior) contain the science questions framework and identify which question(s) each task is addressing. More details on how exactly each task plans to address the question(s) are available in the project descriptions that can be found in the respective Annexes.

In preparation for addressing both the St. Clair and Lake Superior issues, Task 1 will make modifications to the existing regulation and routing model that serves as the accepted standard between the United States and Canada. This task is primarily a functional one that will provide improvements to the tool required for the hydraulic and hydrologic assessments. [Each of the tasks introduced here are more fully described in Section 5 – Hydrology and Climate Modelling Strategy.]

**Science Question 1.** In order to address the St. Clair issue, an assessment of contemporary estimates of the water balance, their uncertainty and methodological approaches will be undertaken. Once the assessment is completed and the best estimates of the water balance are established, attribution of changes in water supplies to lake levels can be conducted with quantification of the uncertainty. First (Task 2) is an overall understanding and updating of existing residual and component NBS estimates used in the current management strategies by both the US and Canada. This includes re-examining updated NBS estimates using the
accepted standards for residual method calculations. This work is being done in partnership with the Data TWG and will provide an important benchmark for comparison to other NBS methods. Task 2 also includes a comparative analysis of the residual and Great Lakes Environmental Research Laboratory (GLERL) component NBS will be undertaken to better understand where differences in the data occur and their causative factors. It includes updated GLERL model outputs through calendar year 2006 and making these component NBS estimates available to all investigators.

Second (Task 3), a systematic assessment of the various terms of the NBS will be undertaken. This will include comparison of over lake precipitation (P), runoff into the lakes (R), and overlake evaporation (E) using separate methodologies. The specific terms (P, R, E) will be derived in part from existing numerical weather and climate models that use data assimilation techniques to derive the components of the water balance. A series of independent models that compliment the existing quasi-operational modeling system developed by GLERL will be used to assess and pinpoint potential deficiencies in modeling approaches and further refine the water balance estimates. These models are primarily the National Center for Environmental Prediction CDAS reanalysis (NCEP CDAS) and Environment Canada’s Numerical Weather and Data Assimilation System (ECNWDAS). In addition, observations using new technology will be employed such as radar precipitation and two eddy covariance towers set-up within Lake Superior and Lake Huron to establish direct estimates of lake evaporation. Moreover, any systematic biases between various methods will be addressed. Figure 4 illustrates the comparative analysis time series and Figure 5 illustrates the comparative analysis workflow.

Third (Tasks 4.1-4.2), Bayesian change point and trend analyses and teleconnection studies will be performed to assist in identifying the causative factors related to any changes in the Upper Lakes water supplies. Figure 6 illustrates the statistical analysis and teleconnections work flow. And lastly, Task 5 will integrate the work done in Tasks 1-4 to 1) rank and describe the uncertainty of the water balance components relative to one another and assess the impact of uncertainty on the attribution of water supply changes to lake levels and 2) determine the affect of net basin supply on the change in lake level relationship.

**Science Question 2.** The second question of climate variation and the influence this may have on future Lake Superior regulation will also be examined (Tasks 4 and 6). Although many Global Circulation Models (GCMs) have been well-established and run over the Great Lakes region, the spatial scale of these models is not entirely appropriate for the required assessments. Typical GCM resolution is on the order of 200 to 300 km, which implies that the variation in precipitation and temperature across the upper lakes region is represented by only 4 to 6 grid points. Traditional downscaling techniques established in the Lake Ontario study will be applied to this study. However two regional climate models will also be established for the Great Lakes to derive downscaled climate scenarios (the US Coupled Hydrologic Atmospheric Research Model – CHARM and the Canadian Regional Climate Model – RCRM) by using GCM boundary conditions to force the regional models. In this way, the models act as interpolators of the climate scenarios using atmospheric physics as opposed to statistical methods to derive important climate forcing that will impact the water cycle. An ensemble of possible future states of the climate system will be derived using these methods or a
combination of them. These will then be used to derive NBS scenarios to evaluate climate impacts.

**Figure 4.** Comparative analysis of NBS and component time series. Note that the St. Clair report will be due after the initial assessment through year 2006; the assessment will continue through the Study duration and be reported in the Final Study report.

Although the functional procedures for downscaling have been somewhat defined at this point in time (illustrated in Figure 7), there is still considerable discussion as to how to select the climate scenario(s) and apply them to Lake Superior plan formulation and evaluation. A Hydrology and Climate Workshop was held June 9-10th on this topic that was attended by 29 invited experts including representatives from the Midwest Climate Center, Lawrence Livermore Laboratory, Columbia University, Bureau of Reclamation, the US Geological Survey and Environment Canada. The following summarizes the meeting’s discussions.

Anthropogenic forcing of the climate system due to increasing concentrations of carbon dioxide and other radiatively-active gases will likely 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). Assessment of such probabilities is best determined using global (GCM) and regional (RCM) climate models as they are based on the
Figure 5. Comparative analysis workflow.
Figure 6. Statistical analysis and teleconnections work flow.
Figure 7. Climate change sequences work flow.
fundamental laws of physics. That being said, the complexity of the physics of the climate system is formidable and many compromises are made in the representation of the physics in these models. A large number of future climate simulations were conducted for analyses underlying the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2007). As has been the case with previous IPCC assessments, these simulations show a large range of future outcomes. Some of this range is due to different assumptions about the path of atmospheric concentrations of greenhouse gas concentrations. However, a sizeable portion of the range is due to different choices among modeling groups about how climate system physics processes are represented.

Conceptually, there is no reason to believe that all GCMs are of equal quality although there is high level of cross-fertilization of ideas and commonality of model parameterizations among modeling groups. Much work (see Randall, et al., 2007) has been done to evaluate the quality of models in a number of model intercomparison studies and other independent work, comparing model simulations of the historical climate with observations. There are several motivations for intercomparison studies. The goal in some studies is to identify model deficiencies and thus accelerate model improvements. A typical goal in application studies is to reduce the uncertainty of future projections by culling inferior models. However, as noted below, this is not necessarily achieved because future projections have not been shown to be closely related to estimates of model quality.

Typically, intercomparison studies have examined global metrics of model performance, although regional metrics have also been used in a few studies (Brekke et al. 2008). There are distinct differences among models in the fidelity of their simulations compared to observations. However, estimates of model skill depend on the chosen metrics and even the worst (best) models do very well (poorly) for some metrics (e.g., Gleckler et al., 2008). Further, we would not have high confidence in a model which poorly simulates the historical climate, but that does not mean that the ability of a model to simulate the historical climate well is necessarily an indication that the model will perform better under future climate scenarios. For a specific application, a subset of metrics may be viewed as most important and may result in a different set of optimal models.

The bulk of model evaluation studies have utilized global metrics. For regional applications, such as IUGLS, it could be argued that regional metrics are more applicable. But, the regional climate is driven by both global and regional processes and highest confidence should probably be placed in models that produce good simulations of both important regional processes and relevant global ones. There have been relatively few regional assessments of models for the Great Lakes or adjoining regions (e.g. Kunkel et al. 2006).

An upcoming report of the US Climate Change Science Program (“Climate Models: An Assessment of Strengths and Limitations”) addresses the question of how well the current generation of models simulates current climate conditions. Based on the draft released for public comments, the seasonal cycle and large-scale geographical variations of near-surface temperature are well simulated on a global scale. Climate model simulation of precipitation has improved over time but is still problematic. There is a basic similarity of precipitation...
magnitudes and patterns in most regions of the globe, with the most striking disagreements occurring in the tropics. Simulation of storms and jet streams in middle latitudes is one of the strengths of atmospheric models and there is relatively high confidence in the models’ ability to simulate changes in these as the climate changes. Models forced by the observed well-mixed greenhouse gas concentrations, volcanic aerosols, estimates of variations in solar energy incidence, and anthropogenic aerosol concentrations are able to simulate the recorded 20th Century global mean temperature in a plausible way (Hegerl et al., 2007). However, on a regional scale the relative lack of warming in the central U.S. is not captured very well by models (Kunkel et al. 2006).

The assessments that have been performed, particularly those by the Program for Climate Model Data and Intercomparison (PCMDI), provide an adequate basis for the evaluation of climate models in the IUGLS. Given the lack of a universally-recognized set of criteria/metrics to use for model assessments for regional applications, there is no strong justification for undertaking an independent assessment for this study. The results of the previous assessments are adequate to inform this study. The study is attempting to determine the potential impact of climate change over the next 30 years. Within that time frame, the agreement among projections doesn't depend significantly on the greenhouse gas emissions scenario represented in the projection, and therefore emissions scenario is not viewed to be a significant factor for climate scenario selection in this study. Also in this time frame, there is reasonable agreement among the models’ projections regarding potential changes in the parameters that are of most interest to this study: temperature and precipitation.

The specific process for selection of future climate scenarios can take several paths. A critical first step is to clearly define the question(s) to be addressed by the scenarios. The decision-makers should be engaged from the very beginning. Once this has been established, the actual climate information needs can be determined and used as the basis for choosing model scenarios. Since the ranking of models can change substantially depending on the choice of metrics, one option is to use all model simulations as equally-probable outcomes of the future. Alternatively, a set of metrics most appropriate to this application can probably be identified and a subset of models chosen with superior performance for those metrics. In practice, this may not produce a very different outcome (in terms of the range of possible future climates) as long as the number of models is relatively not too small (say, more than about ten; see Waugh and Eyring, 2008). Work at the Hadley Centre has shown that models with similar simulations of the present climate can produce quite different outcomes for the future. Since there is not a small subset of models that are universally recognized as superior, the most important factor to include a sizeable number of models to represent the range. This can also be accomplished by choosing a small number of models that represent the tails (e.g. 10th and 90th percentile) of the distributions. Assessment of the spread of projections over the Great Lakes region can be conveniently done using the “Statistically Downscaled WCRP CMIP3 Climate Projections” web-archive, which serves 112 monthly T and P projections over the contiguous U.S. (encapsulating upper GL basin). This site supports custom data requests using a web-form (http://gdo-dcp.ucnl(ln.org/downscaled_cmip3_projections/). Although these data do not substitute for statistically downscaled projections to force impacts analyses, it can be used to select the framing GCM projections. These statistically downscaled datasets have served

hydrologic impacts assessments in much of the western U.S. (e.g., DOE Accelerated Climate Prediction Initiative studies; Maurer 2007).

Regional climate models are believed to provide more realistic climate simulations at the regional scale because of the higher spatial resolution and better representation of regional processes. It is important to note that RCMs are nested within GCMs, which provide the lateral boundary conditions and thus constrain the RCM solutions; as such, they do not provide completely independent projections of the future. However, the RCM projections are not simply higher resolution versions of the GCMs’ regional climates because processes internal to the RCM domain may be better represented in an RCM compared to a GCM. For example, topographic variability is more realistic and higher resolution and more complete physics representation can result in superior simulations of precipitation climatology (e.g. Liang et al. 2004, 2007). Of particular application to the IUGLS, a major advantage of RCMs is the better representation of the Great Lakes and their interactions with the atmosphere. However, the number of RCM simulations that are available is limited and probably do not represent the full magnitude of the uncertainty about the future. Their main application to the IUGLS is to more fully understand the dynamics of the interactions of the lakes with the atmosphere and how that affects the climate of the region.

Despite the physical basis of GCMs and RCMs, their simulations typically contain biases and lack necessary detail for hydrologic models. Therefore, statistical downscaling is still needed to provide suitable input to hydrologic models. Also, as noted above, simulation of precipitation remains problematic, even in many RCMs (Jiao and Caya 2006). Statistical downscaling of model data can provide more reliable scenarios by utilizing relationships between precipitation and variables for which the model simulations are more robust (e.g. Cheng et al. 2007). Representation of future variability is a major challenge. A key question here is the possible future change in the frequency and intensity of extreme wet/cool and dry/warm extremes. It is a misconception that unforced variability is generally too weak in models (AchutaRao et al., 2007; Domingues et al., 2008). Nevertheless, it would not be prudent to rely solely on models nor to assume the possible range of conditions can be gauged from the instrumental record. A broader perspective may be found in paleoclimatic data, keeping in mind the following caveat. Paleo climates are limited in that they do not represent conditions under the current and future enhanced anthropogenic forcing. Statistical methods can provide scenarios, but such methods do not have any physical input to guide future changes. While the physical basis for our understanding of possible future changes in extremes has largely been derived from analysis of climate model simulations, paleoclimatic data can alert us to any inconsistencies between model projections and the climates of the past.

Observed climate trends in the Upper Great Lakes basin may be due to a combination of natural, unforced variability and anthropogenic forcing. Model simulations include best guesses of anthropogenic forcing that produce trends that on a global scale are similar to observed. Models also produce sufficient natural, unforced variability that regional “trends” on a multi-decadal timescale can emerge (Kunkel et al. 2006). Given the uncertainties about the causes of observed trends on the regional scale, it is probably sufficient to use the simulations as they are and allow their range of outcomes to represent trends.
Finally, how should these scenarios and their uncertainties be applied to lake plan formulation and evaluation? The hydrologic inputs to the evaluation model will at least be used to recommend options for regulating Lake Superior, but by virtue of the reputation of the IJC, will also stand as the reference expert opinion on the future water levels of the lake. Especially because the regulation of Lake Superior has so little impact on other lakes, if this study reports, for example that in one study scenario Lake Huron levels were a meter lower than its twentieth century low, politicians, experts and citizens around the lake will ask how likely we think it is that those low levels will happen, and how soon. It’s our feeling that no matter how clever we are we can’t confidently estimate those chances, but that makes it even more important for us to develop methods to identify trends as soon as we can and develop general measures now for adapting to changing hydrology.

The consensus of the Workshop participants is that it would be hard to defend estimated probabilities of future lake level trends. Past studies that estimated the probabilities of wet or dry periods based on statistical extrapolation of the historic record overlooked climate variability and human induced climate change and there is ample evidence that those forecasts were often significantly misleading. But the new evidence we have of climate variability and change doesn’t improve our confidence in forecasting the future – it makes us more respectful of the chance that we will be wrong about the future. It’s important to admit that the actual future may be significantly different from any of the traces we generate. (The probability that the future will be contained with four differing informed guesses is not one).

So the Workshop participants suggest the development of test data for developing new regulation plans that recognize the hubris of assigning probabilities and that the test data be iteratively developed based on a dialogue between hydrologists, plan formulators and evaluators (including subject matter experts from all the TWGs). The iterative process would allow experts to discover the hydrologic situations that would be most difficult to manage, then hydrologists could try to describe the forcing factors what would make those conditions more likely. It would be important for the two groups to work together to design an adaptive approach. For example, it might be possible for hydrologists and mathematicians to develop indicators that would tell regulators it was time to switch to a more conservative release pattern.

It’s less important to know the future when designing a regulation plan, which can be changed, than committing funds to a new reservoir, which is not easily reversed and whose costs are mostly paid in expectation of future benefits.

This is a different approach than has been used in the past, but not as risky as its newness might suggest. The stochastic and climate change hydrology from the Lake Ontario study established this precedent and is available for use in this study. In addition, the new philosophy acknowledges that we cannot find the correct dataset through careful selection of the right GCMs and the successful application of RCMs, so it reduces the concern that a misstep early in the study in the choice of model ensembles will undermine the eventual decisions.

The next step is to lay out the iterative steps in a practical way that can be realized with scopes of work that provide levels of certainty and flexibility acceptable to both the Study Board and the experts.
4. **Project Matrix and Timeframe**

The project matrix (Tables 1a and 1b) illustrates respectively the relevancy, redundancy and interdependency of the projects for the St. Clair River and Lake Superior science questions. Similarly, Tables 2a and 2b show the key tasks, milestones and outputs. The critical path analysis (Tables 3a and 3b) describe what is required in delivering the results within the proposed timeframe. It is important to note that the hydrology and climate projects depend on tasks from the Hydraulics and Data TWGs. Also of note is that many of the projects related to the St. Clair science questions will continue past the St. Clair River report due date. These projects will report preliminary findings that will be revisited for the final Study report. Given the linkages and dependencies of all the projects, on-going communications and analysis will be critical to the success of the project. The HC TWG meets on a regular monthly basis via teleconference and periodically face-to-face as the need arises. The members and associated Principal Investigators are listed below.

**Members**
- Ms. Deborah H. Lee
- Dr. Al Pietroniro
- Mr. John Kangas
- Mr. Rob Caldwell

**Principal Investigators**
- Dr. Carlo DiMarchi
- Dr. Murray MacKay
- Dr. Brent Lofgren
- Dr. Taha Ouarda
- Mr. Matt McPherson
- Dr. Vincent Fortin
- Dr. Peter Blanken
- Dr. Chris Spence
- Dr. Frank Quinn
- Ms. Laura Fagherazzi
- Ms. Erika Klyszejko

5. **Hydrology and Climate Modeling Strategy**

The Hydrology and Climate Modeling Strategy consists of a series of inter-related tasks that address the St. Clair and Lake Superior science questions. These tasks are:

**Task 1 - Improvements to the Coordinated Regulation and Routing Model**

**Task 1.1 Programming improvements**

**Lead PI: Matt McPherson**

This task will program various improvements to the Coordinated Regulation and Routing Model to support lake level evaluation, plan formulation, and climate change assessment. Parameter inputs will be added for increased flexibility in plan formulation, US and Canadian staff will be trained in operation of the model, and the model will be adapted for routing of the stochastic NBS series.
Task 1.2 Visual interface and linkages
Lead PI: to be identified

A visual interface to the Coordinated Regulation and Routing Model will be constructed and linkages (data exchange) to the socio-economic and environmental models will be established for plan evaluation. This task will be defined and performed in conjunction with the Plan Evaluation Group.

Task 2 - Comparative Analysis of Net Basin Supply

Task 2.1 Analysis of GLERL net basin supply component uncertainty and its impact on net basin supply
Lead PI: Carlo De Marchi

The principal investigator (PI) will produce error estimates for each term of the 1948-2006 GLERL NBS (P, R, E) based on existing literature and analysis and its effect on the NBS of each lake. Further, assuming independence among the component errors, the investigator will estimate the overall GLERL NBS uncertainty and confidence interval using a Monte Carlo analysis.

Task 2.2 Comparative Analysis of Current Net Basin Supply Computations
Lead PI: Frank Quinn

The purpose of this investigation is to perform an analysis of the 1900-2006 residual NBS to quantify the uncertainties in the NBS and its respective terms. A second purpose is to statistically compare the residual and component (Task 2.1) NBS. Corrections to the data will be identified and recommended to the Data TWG. The outcome should be the identification of those terms that are most uncertain with recommendations on how to reduce the uncertainties. Finally, a water balance of the Upper Lakes using both the residual and component NBS to identify any problems with conservation of mass will be performed.

Task 3- Experimental Focus on Areas with Greatest Uncertainty

Task 3.1 Overlake Precipitation
Task 3.1.1 Computation of ECNWDAS overlake/overland precipitation for 2004-2009
Lead PI: Murray Mackay and Vincent Fortin

A five-year hindcast of overlake/overland precipitation will be produced using Environment Canada’s operational numerical weather and data assimilation system (ECNWDAS) for comparison in Task 3.1.2. The analysis system uses numerical weather model output, observations, and ground based radar imagery within a Kalman filter system to establish over-lake precipitation estimates.

Task 3.1.2 Comparison of GLERL overlake/land precipitation for 1948 – 2006
Lead PI: Carlo De Marchi

The PI will assemble 1) GLERL Thiessen weighted monthly overlake/overland precipitation for 1948-2006, 2) National Center for Environmental Prediction Multi-sensor Precipitation Estimates (NCEP MPE) data for 2002-2006, and 3) NCEP CDAS data for the period 1948-2006 for the Great Lakes region and transform them into monthly overlake/overland precipitation. Precipitation data from these sources and the ECNWDAS (Task 3.1.1) will be compared and analyzed.

Task 3.2 Lake Evaporation

Task 3.2.1 Computation of ECNWDAS lake evaporation 2004-2006

Lead PI: Murray Mackay and Vincent Fortin

A five-year hindcast of lake evaporation will be produced using Environment Canada’s operational numerical weather and data assimilation system (ECNWDAS) for comparison in Task 3.2.2. Lake evaporation is modeled via an aerodynamic roughness formulation (based on satellite observed lake surface temperature/lake ice conditions.

Task 3.2.2 Comparison of GLERL Large Lake Thermal Model (LLTM) lake evaporation estimates with ECNWDAS lake evaporation estimates and NCEP CDAS estimates

Lead PI: Carlo De Marchi

The calibration of the GLERL LLTM will be extended to the period 1989-2001 using water surface temperature and ice cover available from conventional and remote sensing sources. Recalibrated LLTM will be used to simulate the 1948-2006 lake evaporation with observed meteorology. GLERL will assemble the required NCEP CDAS data for the period 1948-2006 for the Great Lakes region, estimate evaporation, and subdivide it between lake and land evaporation. LLTM, NCEP CDAS, and ECNWDAS (Task 3.2.1) evaporation estimates will be compared.

Task 3.2.3 Measurements of lake evaporation using Eddy Covariance System

Lead PI: Chris Spence and Peter Blanken

Lake evaporation is usually estimated as a residual of the long-term water budget or from buoy-based meteorological data. The former approach suffers from the daunting and uncertain task of determining lake-wide precipitation, run-off, and run-in estimates; the latter approach suffers from the need to first parameterize the equations which requires independent evaporation measurements to begin with, and the failure to resolve high-frequency turbulent events which can be responsible for up to 65% of the total evaporation.

Due to importance of making accurate measurements of lake evaporation, and the uncertainties described above for the traditional methods, the PIs propose to directly measure evaporation using the eddy covariance method. This method, based on solid and tested theory, is essentially based on the degree of covariance between high-frequency (e.g. 10 Hz) measurements of vertical wind and water vapor density. Blanken and Spence were the first to successfully measure lake evaporation from Great Slave Lake, which is similar in size and volume to Lake Superior.
Eddy covariance and associated instrumentation will be installed on Stannard Rock Light (47.1834 N; 87.225 W), located 24 miles southeast of Manitou Island; 45 miles north of Marquette, and owned by the US Coast Guard. Stannard Rock is located far from the shore and is 35-m tall, providing excellent fetch and security (see cover photo). In addition, Stannard Rock is National Data Buoy Center Site (Station STDM4) providing current and historic (since 1984) meteorological data. The PIs will use these data, along with data provided from the NOAA buoy network (4 sites), to extrapolate evaporation measurements in space and time using parameters developed through simultaneous meteorological and evaporation measurements. A second site will be identified and established in Lake Huron. Estimates of lake evaporation will be compared with those in Tasks 3.2.1 and 3.2.2.

**Task 3.2.4 Changes in ice regime and surface water temperature on evaporative flux**

**Lead PI: Jia Wang (funding under consideration)**

The PI will use conventional statistical methods to analyze the NCEP reanalysis (1948-present) and climate GCM products (IPCC AR4), along with historical sea ice observations including recent satellite measurements and gage runoff to examine the statistical relationship between lake ice cover, water level and climate patterns in both spatial and temporal spaces. First, the empirical orthogonal function (EOF) analysis will be applied to sea-level pressure (SLP), surface air temperature (SAT), surface precipitation, and 700 hPa geopotential height fields to reveal the Arctic Oscillation/North Atlantic Oscillation (AO/NAO; first mode) and Pacific-North America (PNA; second mode) pattern. The time series of these two modes can be used to conduct linear regression of sea ice cover and water level. The composite analyses of lake ice and water level will be conducted based on the indices. Then the difference between the +AO/NAO and -AO/NAO phases will be tested using a Student t-test. A similar ice composite analysis will be applied to the +PNA and -PNA phases. Furthermore, a linear regression of lake ice and water level will be applied to SLP, SAT, precipitation, and 700 hPa height fields to map the spatial correlation. Generalized relationships between lake ice cover, water level and atmospheric circulation patterns will be revealed.

**Task 3.3 Basin Runoff**

**Task 3.3.1 Computation of ECNWDAS basin runoff 2004-2009**

**Lead PI: Murray Mackay and Vincent Fortin Canada**

A five-year hindcast of basin runoff will be produced using ECNWDAS for comparison in Task 3.3.2.

**Task 3.3.2 Improve proration of gauged area streamflow to ungauged areas through correlation of spatial land characteristics**

**Lead PI: to be identified**

This task will develop spatial statistical methodologies for prorating gauged area streamflow to ungauged areas for 1948-2006 data. Approaches developed by INRS-ETE and the US Geological Survey will be considered.
Task 3.3.3 Comparison of GLERL runoff estimates with INRS-ETE/USGS geo-statistical approach and ECNWDS reanalysis
Lead PI: Carlo De Marchi

The GLERL Large Basin Runoff Model (LBRM) was developed in the 1980s for estimating rainfall/runoff relationships on the 121 large watersheds surrounding the Laurentian Great Lakes. The PI will compute runoff for 1948-2006 for each of the 106 watersheds covering the Upper Great Lakes basin. For each lake, the PI will aggregate runoff of all watersheds in total basin runoff and in ways compatible with the INRS-ETE/USGS geo-statistical approach and with the ECNWDS model.

Task 3.4 Connecting Channel Flow and Retardation Factors
Task 3.4.1 Development of Connecting Channel apparent ice and weed retardation values, assessment of trends and significance to lake levels
Lead PI: Rob Caldwell and Taha Ouarda

Winter ice formation and summer weed growth has a transient effect on seasonal connecting channel flows. To account for this effect, flow retardation factors are computed on a monthly basis by the operational agencies with responsibility for Great Lakes management. Evidence of trends in the data will be investigated as well as correlations with potential causative factors. An analysis will be performed to determine the significance of any potential climate induced changes to ice and weed retardation values on lake levels. This task is dependent upon Task P2 from the Hydraulics TWG which will provide a review of the St. Clair and Detroit River stage-discharge equations.

Task 3.5 Lake Levels and Change in Storage
Task 3.5.1 Assessment of uncertainty in change in storage
Lead PI: Frank Quinn

An assessment of the uncertainty of beginning of month water levels will be undertaken with extension to the uncertainty of change in storage computations. The impact on residual NBS computations will be estimated.

Task 4 Trend Analysis, Teleconnections and Stochastic Analysis

Task 4.1 Trend Analysis
Lead PI: Taha Ouarda

The objective of this task is to statistically analyze changes in net basin supply components and explanatory variables (evaporation, runoff, inflow, temperature, precipitations, etc.). Specific objectives are:

1) Analyze and assess previous NBS stochastic modeling efforts. This includes the recent efforts that dealt with the use of the shifting level model in the IJC Lake Ontario-St. Lawrence River Study to confirm or revise information concerning detected shifts.
Collaboration will be established with Laura Fagherazzi (Hydro-Québec) who was a principal investigator in the prior study.

2) In addition to the shifting level model, use of traditional trend and shift detection tests of hypothesis such as Spearmann’s Rho test, Mann-Kendall test, modified Mann-Kendall test for seasonal data and a segmentation procedure will be used to analyze changes in the NBS components. All components of the Great Lakes system will be considered, including Lake Ontario supplies.

3) Use recent developments in Bayesian changepoint detection to analyze past modifications and attribute them to the known causal factors. This work will be based on corrected data sets, and involves the application of Bayesian procedures to investigate modifications in the parameters of the relationships between key variables, and the attribution of the changes to plausible causal factors (such as dredging or deforestation). The last step involves the estimation of future conditions if they are different from present ones.

Task 4.2 Teleconnections
Lead PI: Taha Ourada

The second component of Task 4 deals with the analysis of atmospheric teleconnections. Climate oscillations such as ENSO are shown to affect rainfall and runoff in Canada and the US in several papers. There is clearly room to develop more complex dependence models between climate indices and hydrological variables in the study area and develop non-stationary frequency analysis tools for the region of study. All observed data sets, as well as derived data sets (precipitations, temperature, evaporation, channel flows, etc.) will be analyzed. Ice cover information will also be analyzed (input from Task 3.2.4). Analysis of atmospheric teleconnections will lead to better explanation of the fluctuations of precipitation, inflows and lakes levels, and help predict these variables in the future. This activity involves a) identifying the climatic indices that have impacts on key elements of the net basin supply, b) develop a statistical model of the variable of interest conditioned by the climate index c) quantify the benefits of using this dynamical modeling versus a static approach. Several linear and non-linear approaches will be considered including the use of wavelet analysis and neural network models.

Task 4.3 Stochastic Analysis
Lead PI: Taha Ouarda and Laura Fagherazzi

This task will review the validity of the stochastic analysis completed for the IJC Lake Ontario-St. Lawrence River Study in light of new findings from the statistical and trend analyses. If required, the stochastic analysis will be reformulated and a new series of stochastic water supplies and other hydraulic variables generated.
Task 5 Integration of Tasks 1-4: Affect of NBS on the change in Lakes Michigan-Huron and Lake Erie level relationship

Task 5.1 Rank and describe the uncertainty of the water balance components and assess the impact on the attribution of water supply changes to lake levels
Lead PI: All

This task will integrate all contributing work for the St. Clair issue (Tasks 1-4). Based on the findings of the tasks, causative factors relating to the change in Upper Lakes water supplies will be identified. The assessment of uncertainty will be used to determine the level of confidence in the attribution of the causative factors. Recommendations on new observations and modeled data for computation, monitoring, and forecasting of Upper Lakes water supplies are expected.

Task 5.2 Determine the affect of NBS on the change in lake level relationship
Lead PI: All

Considering Task 5.1, this task will identify the causative factors related to the change in lake levels between Lakes Michigan-Huron and Lake Erie. A water balance approach will be used as well as traditional routing of water supplies through the Coordinated Great Lakes Regulation and Routing Model with residual supplies.

Task 6 Climate Change Sequences

Task 6.1 Prepare base simulation for comparison with scenarios
Lead PI: Rob Caldwell

Using the corrected/adjusted hydrologic data and revised connecting channel stage-discharge relationships from prior tasks, compute lake levels and flows with the Coordinated Regulation and Routing Model that represent current conditions, or the ‘base case’. The series of levels and flows will serve as the benchmark for all other simulations used in lake regulation plan formulation and evaluation.

Task 6.2 Regional downscaling using Canadian RCM
Lead PI: Murray Mackay

In this task a regional climate model is developed and used to analyze the water balance of the Great Lakes system, both over the past 30 years and into the next 3 decades. This model is based on the very well established Canadian Regional Climate Model coupled with the latest version of the Canadian Land Surface Scheme (CLASS). Amongst the numerous improvements this latest version entails, CLASS can now better represent hydrological controls on soil moisture with the addition of surface runoff, subsurface flow, and groundwater recharge parameterizations. Furthermore, CLASS will be coupled to the WATROUTE model to simulate baseflow and allow for channel and lake routing. Lake evaporation is modeled via an aerodynamic roughness formulation (based on satellite observed lake surface temperature/lake
ice conditions), or modeled explicitly within 1-D thermal lake modules. This Great Lakes Regional Climate Modeling System will be used in GCM downscaling experiments of both present and future climate in order to develop some understanding of current Great Lakes water availability and plausible future projections out to about 2040.

**Task 6.3 Conventional downscaling of IPCC IV GCM for hydrological simulation with GLERL’s Advanced Hydrologic Prediction System (AHPS)**

*Lead PI: Carlo DeMarchi*

Given the coarse spatial and temporal resolutions of the earlier generations of GCMs, the impact of climate change on the hydrology of a region was often evaluated by driving the hydrologic models with inputs based on observed meteorological time series with offsets taken from general circulation model (GCM) monthly mean results—offsetting the temperature by the difference in temperature between a recent past time period and a future time period, as simulated by the GCM, and precipitation offset using the ratio between recent past and future simulations. This method has the merit of generating spatially and temporally consistent meteorological fields, but it is able to account only for changes in monthly mean climate. That is, no change in the frequency of intense storms or droughts can be simulated.

Based on an agreed-upon choice of GCM scenarios of present and future climate, use GLERL’s LBRM and LLTM to compare the net basin supplies of the Great Lakes basin using established conventional downscaling techniques.

**Task 6.4 Regional Downscaling using GLERL’s CHARM**

*Lead PI: Brent Lofgren*

This task, similar to Task 6.2, will use the CHARM regional climate/hydrologic model for GCM downscaling. GLERL will prepare data for overlake precipitation, overlake evaporation, and runoff from the drainage basin as predicted using CHARM, driven by boundary conditions from selected GCM scenarios. The output will be compared to the results from Tasks 6.2 and 6.3 for selection of the downscaling technique.

**Task 6.5 Interaction between HC TWG and the Plan Evaluation Group (PEG) for the joint development of climate scenarios**

*Lead PI: All*

This task will integrate Tasks 6.1-6.4 by comparing downscaling techniques and develop metrics for the selection of the best technique. Through interaction with PEG, the appropriate climate scenarios will be selected among the suite available from the IPCC IV simulations.

6. **Evaluation of Uncertainty**

Water resources management systems use hydrologic and hydraulic models with relatively simple mathematical equations to conceptualize and aggregate complex, spatially distributed, temporally integrated and highly interrelated water mass, energy, and momentum processes. In consequence of this aggregation, model parameters are frequently not directly measurable and

must therefore be estimated. During the model calibration stage, parameters are adjusted so that the model replicates as precisely and consistently as possible the observed response of the hydraulic and hydrologic system over a defined historical period of time. Nonetheless, uncertainties associated with the observations used to delimit boundary conditions, and to calibrate and validate the models, as well as with the model parameters derived through the calibration, and in the model structure itself lead to uncertainties in the model predictions. The current study recognizes the importance of attempting to quantify these uncertainties. However, given the difficulty in space-time estimates of the various NBS components, it is not possible to qualitatively assess uncertainty in each of the various model components. As a result, this study addresses the uncertainty issue by using a combination of accepted techniques to assess the major water balance components in the individual lakes, and makes qualitative (and to a lesser degree) quantitative attempts to understand the attribution of uncertainty and biases in the NBS. The most comprehensive study to date on uncertainty analysis for the Great Lakes basin was produced by the USGS in 2005 (Neff and Nicholas, 2005), and forms the basis for the discussion outlined below.

In the case of this study, uncertainty is almost exclusively related to the uncertainty attributable to either residual or component NBS estimates. As discussed above, the Great Lakes water balance is a compilation of thousands of daily measurements of many hydrologic and atmospheric parameters. Numerous approaches to assess each component are available, and each approach introduces a different amount of potential uncertainty to the water balance. These uncertainties include measurement uncertainties and model uncertainties, as well as monitoring gaps.

As noted by Neff and Nicholas (2005), the uncertainty of most water-balance components is difficult to assess quantitatively. However, it is possible to examine a simple model error structure to determine which terms in the NBS may provide greater uncertainty. A simple analysis can be formulated and provides some insights into the relative magnitude of uncertainty. In an ideal situation, the difference of the component methods and residual methods for estimating monthly NBS would be 0. Simply, if we estimated over-lake precipitation (P), lake evaporation (E) and total runoff into the lake (R) (including diversions as an abstraction), the NBS should appear something like this:

\[ P + R - E - \text{NBS}_{\text{comp}} = 0 \]  

(Equation 5)

Since there are biases and differences between the 2 completely independent methods, then one could formulate an error model as follows:

\[ a(P) + b(R) + c(E) + \text{error} = \text{NBS} \]  

(Equation 6)

This simple model is expressed as a linear regression where the regression coefficient represents a percent bias in the monthly estimates and the error term is simply the intercept of the NBS. A plot of component and residual NBS for Lake Superior shows good agreement in July but poor agreement in January as shown below.
A linear regression for each month (using Equation 6) on Lake Superior and Lake Huron-Michigan was completed and yielded the following results. For Lake Superior the intercept (interpreted here as the error between the 2 methods) indicates a value of about 26 mm for the month. Correlation coefficients for each of the 3 components (a, b, c) are estimated as 0.70, 0.75 and -0.48 respectively. Based on this regression, there seems to be a larger uncertainty in the lake evaporation than the other 2 components of NBS (the closer each coefficient is to 1, the more reliable the component estimate). Table 4 highlights the regression correlation coefficients and the estimated coefficients for each month for Lake Superior. These values are plotted in Figure 2 and illustrate, qualitatively, the seasonal differences in NSB estimates using both the component and residual methods.

Table 4 – Correlation and coefficient estimates for residual and component NBS according to Equation 6 for Lake Superior

<table>
<thead>
<tr>
<th></th>
<th>January</th>
<th>February</th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>October</th>
<th>November</th>
<th>December</th>
</tr>
</thead>
<tbody>
<tr>
<td>R Square</td>
<td>0.53</td>
<td>0.65</td>
<td>0.85</td>
<td>0.85</td>
<td>0.90</td>
<td>0.91</td>
<td>0.91</td>
<td>0.88</td>
<td>0.89</td>
<td>0.86</td>
<td>0.79</td>
<td>0.49</td>
</tr>
<tr>
<td>Pre_coef</td>
<td>0.70</td>
<td>1.15</td>
<td>1.05</td>
<td>1.19</td>
<td>1.17</td>
<td>1.22</td>
<td>1.03</td>
<td>1.02</td>
<td>0.94</td>
<td>1.03</td>
<td>1.30</td>
<td>0.72</td>
</tr>
<tr>
<td>Run_coef</td>
<td>0.75</td>
<td>0.72</td>
<td>0.59</td>
<td>0.99</td>
<td>0.94</td>
<td>0.94</td>
<td>1.04</td>
<td>1.34</td>
<td>1.44</td>
<td>1.15</td>
<td>0.92</td>
<td>1.05</td>
</tr>
<tr>
<td>Evap_coef</td>
<td>-0.48</td>
<td>-0.80</td>
<td>-0.97</td>
<td>-0.98</td>
<td>-0.29</td>
<td>-1.10</td>
<td>-1.06</td>
<td>-0.97</td>
<td>-1.27</td>
<td>-1.21</td>
<td>-0.75</td>
<td>-0.60</td>
</tr>
</tbody>
</table>

It is important to note that the intercept in Figure 8 represents the overall error between the 2 methods, while the correlation coefficient approximates the bias estimate for any systematic monthly error in each of the component terms. In the case of January, only 53% of the variance between the component and residual methods can be explained by the linear error model. However, this increases to 91% in July. Similarly, the correlation coefficients are closer to 1.0 (i.e. no bias) in the summer for all 3 components than in the late fall and winter.
Figure 9. Overall error and bias between the component and residual methods.

Similar methods for Lake Huron-Michigan were derived. Table 5 below shows the range of coefficients for each month. As with Lake Superior, evaporation shows the highest potential for error, particularly in the shoulder seasons and in the winter.

Table 5 – Correlation and coefficient estimates for residual and component NBS for Lake Michigan-Huron

<table>
<thead>
<tr>
<th></th>
<th>January</th>
<th>February</th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>October</th>
<th>November</th>
<th>December</th>
</tr>
</thead>
<tbody>
<tr>
<td>R Square</td>
<td>0.76</td>
<td>0.87</td>
<td>0.94</td>
<td>0.93</td>
<td>0.96</td>
<td>0.95</td>
<td>0.89</td>
<td>0.86</td>
<td>0.95</td>
<td>0.88</td>
<td>0.88</td>
<td>0.86</td>
</tr>
<tr>
<td>Intercept</td>
<td>-2.83</td>
<td>8.45</td>
<td>0.16</td>
<td>-2.52</td>
<td>-6.75</td>
<td>-5.65</td>
<td>-35.94</td>
<td>-4.04</td>
<td>-11.33</td>
<td>-17.04</td>
<td>-55.70</td>
<td>-14.33</td>
</tr>
<tr>
<td>Pre_coef</td>
<td>1.00</td>
<td>1.17</td>
<td>1.28</td>
<td>0.83</td>
<td>1.09</td>
<td>1.12</td>
<td>1.04</td>
<td>0.96</td>
<td>0.94</td>
<td>0.88</td>
<td>1.02</td>
<td>1.18</td>
</tr>
<tr>
<td>Run_coef</td>
<td>0.98</td>
<td>0.95</td>
<td>0.97</td>
<td>1.18</td>
<td>0.92</td>
<td>0.86</td>
<td>1.30</td>
<td>0.83</td>
<td>1.03</td>
<td>1.17</td>
<td>1.03</td>
<td>1.01</td>
</tr>
<tr>
<td>Evap_coef</td>
<td>-0.80</td>
<td>-1.06</td>
<td>-1.14</td>
<td>-0.88</td>
<td>-0.95</td>
<td>-0.53</td>
<td>-0.68</td>
<td>-1.19</td>
<td>-1.15</td>
<td>-1.11</td>
<td>-0.48</td>
<td>-0.87</td>
</tr>
</tbody>
</table>

Using the above analysis and the quantitative approaches described by Neff and Nicholas (2005) it is possible to summarize the NBS errors as follows. In each case, for Tasks 3.1-3.3, the tasks attempt to provide, at a minimum, an independent method of assessing the variable of interest, and to compare these independent methods to the standard methods currently developed.

All three terms (P, R, E) of the Great Lake NBS are highly uncertain and there are no consistent or accepted methods of accurately assessing these uncertainties. In an attempt to estimate the various water balance components, the regression model above illustrates some seasonal differences and challenges. Using independent and differing scientific approaches to assess the three major water balance components provides the Study Board with a comparison of methods that represent a broad range of physical modeling approaches from which to approach the challenge as outlined. Model inter-comparison is the realistic means for arriving at a best estimate of the various balance components, and providing a range of possible model outcomes. The proposed ensemble of models will provide the best and only means of assessing uncertainty as well as attributing any defects to the models themselves.
7. **Assessment and Integration of Results**

As the study is employing a multi-pronged approach, it is difficult to precisely anticipate how the results will be integrated, particularly in the context of the climate change assessment. As was proposed, interaction with the St. Clair and Lake Superior task teams will require us to adapt the plan of study depending on outcomes. Figure 10 illustrates the work flow for result integration, analysis, visualization and interpretation.

The very simplified uncertainty analysis presented indicates that evaporation is likely a very important term to rectify, particularly in late fall and winter seasons. Similarly over-lake precipitation is likely very important during summer periods and the influence of the lakes on localized precipitation is not readily understood. Runoff from ungauged regions, particularly in the peak season of spring can also have impacts on NBS. Using independent modeling and observation approaches for each of these components provide independent estimates of these components.

In the context of climate change sequences, there are three downscaling approaches that are proposed to be carried out in the context of this study. Our focus with respect to climate change will rely on traditional methods for statistical downscaling, as well as the use of RCMs. The choice of scenarios and the focus for deriving these scenarios need to be established in the framework of the overall program objectives. Our efforts in the context of the future climate projections will be largely driven by the results of Task 6.4 and the results of interaction with the Lake Superior and St. Clair tasks teams.

A clear structure that covers all anticipated outcomes has been articulated. There may be a requirement for some minor adjustment and perhaps focus on particular scientific and engineering aspects during the project implementation. Once such example could be to focus our attention on observed and anticipated changes in ice-extent on the lakes and the influence this has on the evaporation regime. This is a far different problem than focusing our attention on over-lake precipitation. Carrying this over to a climate change context, the focus may be quite different in how we develop future scenarios. We feel that the approaches outlined above, with further refinement as the project moves on will cover all possible reasonable eventualities.
Figure 10. Results integration, analysis, visualization and interpretation.
8. References:


<table>
<thead>
<tr>
<th>No.</th>
<th>Project</th>
<th>SD1</th>
<th>SD2</th>
<th>SD3</th>
<th>SD4</th>
<th>What are the historic estimates of the net basin supply in the upper lakes and how have any potential changes to the NBS and its components affected the level of the lakes?</th>
<th>What potential impact could variations in the climate system have on future regulations of the Upper Great Lakes?</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>Improvements to the Coordinated Regulation and Routing Model</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1.1</td>
<td>Miscellaneous programming improvements to support lake level evaluation, plan formulation, and climate change assessment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2</td>
<td>Comparative Analysis of Net Basin Supply</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2.1</td>
<td>Analysis of GLERL NBS Component Uncertainty and its Impact on NBS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2.2</td>
<td>Comparative Analysis of current Net Basin Supply Computations</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3</td>
<td>Experimental focus on components with greatest uncertainty</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3.1</td>
<td>Overlake Precipitation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3.1.1</td>
<td>Computation of ECNMDAS overlake precipitation 2004-2006</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3.1.2</td>
<td>Computation of GLERL overlake precipitation with ECNMDAS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3.2</td>
<td>Lake Evapotranspiration</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3.2.1</td>
<td>Computation of ECNMDAS lake evaporation 2004-2006</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3.2.2</td>
<td>Computation of GLERL LLTM lake evapotranspiration with ECNMDAS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3.2.3</td>
<td>Measurements of Lake Evaporation Using Eddy Covariance System</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3.2.4</td>
<td>Changes in ice regime and surface water temperatures on evapotranspiration</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3.3</td>
<td>Basin Runoff</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3.3.1</td>
<td>Computation of ECNMDAS basin runoff 2004-2009</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
# Table 1a - St. Clair Tasks Result Integration - Hydrology and Climate Technical Group

<table>
<thead>
<tr>
<th>No.</th>
<th>Project</th>
<th>Science Questions Framework</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>What are the historic estimates of the net basin supply in the upper lakes and how have any potential changes to the NBS and its components affected the level of the lakes?</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>St. Clair Task Team</th>
<th>Superior Task Team</th>
</tr>
</thead>
<tbody>
<tr>
<td>T3.7.2</td>
<td>Yes</td>
</tr>
<tr>
<td>T3.8.3</td>
<td>Yes</td>
</tr>
<tr>
<td>T3.4</td>
<td>No</td>
</tr>
<tr>
<td>T3.5</td>
<td>Yes</td>
</tr>
<tr>
<td>T3.6.1</td>
<td>Yes</td>
</tr>
<tr>
<td>T4.1</td>
<td>Yes</td>
</tr>
<tr>
<td>T4.2</td>
<td>Yes</td>
</tr>
<tr>
<td>T4.3</td>
<td>Yes</td>
</tr>
<tr>
<td>T5.1</td>
<td>Yes</td>
</tr>
<tr>
<td>T5.2</td>
<td>Yes</td>
</tr>
<tr>
<td>T6.1</td>
<td>No</td>
</tr>
<tr>
<td>T6.2</td>
<td>No</td>
</tr>
</tbody>
</table>

- T3.7.2: Improve prediction of ungauged areas shown in Figure 4 through correlation of spatial and surface characteristics.
- T3.8.3: Comparison of GLEAMS model estimates with NBS-Data/NOAA-EPA modeled data and NBS-Data/NOAA-EPA data.
- T3.4: Connecting Channel Flow and Residence Time.
- T3.5: Lake Levels and Change in Stroma.
- T3.6.1: Assessment of uncertainty in change in Stroma.
- T4.1: Trend Analysis.
- T4.2: Teleconnections.
- T4.3: Stochastic Analysis.
- T5.1: Estimate bias introduced in the Stroma model due to the mean bias.
- T5.2: Identify and describe the uncertainty of the net basin components relative to each other and assess the impact of uncertainty on the net basin of water supply changes to lake levels.
- T6.1: Prepare base simulation for comparison with new models.
### Table 1a - St. Clair Tasks Result Integration - Hydrology and Climate Technical Group

<table>
<thead>
<tr>
<th>No.</th>
<th>Project</th>
<th>Science Questions Framework</th>
<th>St. Clair Task Team</th>
<th>Superior Task Team</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>What are the historic estimates of the net basin supply in the upper lakes and how have any potential changes to the NBS and its components affected the level of the lakes?</td>
<td>SQ1</td>
<td>SQ2</td>
</tr>
<tr>
<td>58.2</td>
<td>Regional downscaling using Canadian RCM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>58.3</td>
<td>Conventional downscaling using GLELR's AMPBS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>58.4</td>
<td>Regional downscaling using GLELR's CHARM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>58.5</td>
<td>Interaction between HIC TWG and PEG for joint development of climate scenarios</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Integration of Tasks 4-6, Climate change assessment by year 2040</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.1</td>
<td>Climate change assessment by year 2040</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Legend:**
- **Primary Focus**
- **Secondary Focus**
- **Contributing Task to Superior Task Team**
- **Dependent Task from Superior Task Team**
- **Dependent Task from St. Clair Task Team**
## Table 1b - Superior Task Team Results Integration - Hydrology and Climate Technical Group

<table>
<thead>
<tr>
<th>No.</th>
<th>Project</th>
<th>St. Clair Task Team</th>
<th>Superior Task Team</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Improvements to the Coordinated Regulation and Routing Model</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1</td>
<td>Miscellaneous programming improvements to support lake-level evaluation, plant/irrigation, and climate change assessment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Comparative Analysis of Net Basin Supply</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td>Analysis of GLERL NBS Component Uncertainty and its Impact on NBS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.2</td>
<td>Comparative Analysis of current Net Basin Supply Computation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Experiments focus on components with greatest uncertainty</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.1</td>
<td>Overtakes Precipitation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.1.1</td>
<td>Computation of ECOWADAS overestimated precipitation (2004-2005)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.1.2</td>
<td>Comparison of GLERL overestimated precipitation with ECOWADAS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.2</td>
<td>Lake Evaporation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.2.1</td>
<td>Computation of ECOWADAS lake evaporation (2003-2005)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.2.2</td>
<td>Comparison of GLERL lake evaporation estimates with ECOWADAS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.2.3</td>
<td>Measurements of Lake Evaporation Using Eddy Covariance System</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.2.4</td>
<td>Changes in ice regime and surface water temperature on evaporation flux</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.3</td>
<td>Basin Runoff</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.3.1</td>
<td>Computation of ECOWADAS basin runoff (2004-2005)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Notes
- symbol indicates the project's status in addressing the science questions framework.
<table>
<thead>
<tr>
<th>No.</th>
<th>Project</th>
<th>St. Clair Task Team</th>
<th>Superior Task Team</th>
<th>St. Clair Task Team</th>
<th>Superior Task Team</th>
</tr>
</thead>
<tbody>
<tr>
<td>TGR</td>
<td>Assessment of climate change scenarios</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TGR1</td>
<td>Does the project help establish the suite of suitable climate change scenarios?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TGR2</td>
<td>Does the project identify and apply downscaling methodologies for regional assessments?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TGR3</td>
<td>Does the project consider future climate variability and change and its application to lake plan formulation and evaluation?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TGR4</td>
<td>What are the historic estimates of the net basin supply in the upper lakes and how has any potential change to these numbers and the components of these numbers been considered?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TGR5</td>
<td>How do the project results fit into the superior task team developments and the superior team developments?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Table 1b - Superior Task Team Results Integration - Hydrology and Climate Technical Group</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------------------------------------------------------------------------------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Science Questions Framework</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>What are the historic estimates of the net basin supply in the upper lakes and how have any potential changes to the NBS and its components affected the level of the lakes?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>What potential impact could variations in the climate system have on future regulations of the Upper Great Lakes?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>St. Clair Task Team</strong></td>
<td><strong>Superior Task Team</strong></td>
<td><strong>SCE</strong></td>
<td><strong>SCE</strong></td>
<td><strong>SCE</strong></td>
<td></td>
</tr>
<tr>
<td>No.</td>
<td>Project</td>
<td>Does the project help establish the suite of suitable climate change scenarios?</td>
<td>Does the project identify and employ downscaling methodologies for regional assessment?</td>
<td>Does the project consider future climates variability and impacts in formal climate planning and evaluation?</td>
<td></td>
</tr>
<tr>
<td>T6.2</td>
<td>Regional downscaling using Canadian RCM</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T6.3</td>
<td>Conventional downscaling using GLERL's AHPS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T6.4</td>
<td>Regional downscaling using GLERL's CHARM</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T6.5</td>
<td>Interaction between HEC-RTK and TED for joint development of climate scenarios</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S5</td>
<td>Integration of Tasks 4-6: Climate change assessment to year 2040</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S4</td>
<td>Climate change assessment to year 2040</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Legend**
- **Primary Focus**
- **Secondary Focus**
- Contributing Task to Superior Task Team
- Dependent Task from St. Clair Task Team

---

### Table 2a – St. Clair Key Tasks, Milestones and Output

<table>
<thead>
<tr>
<th>No.</th>
<th>Tasks</th>
<th>Milestones</th>
<th>Key Output &amp; Products</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>T1</strong></td>
<td>Improvements to the Coordinated Regulation and Routing Model</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| T1.1 | Miscellaneous programming improvements to support lake level evaluation, plan formulation, and climate change assessment | • Parameter inputs added for increased flexibility in plan formulation by Mar 2008  
• Training of new staff on model operation by Mar 2008  
• Apply model in Task T5 by Nov 2008  
• Modification of model completed to run stochastic series by Jan 2009 | • US and Canadian coordinated regulation and routing program flexible for plan formulation and stochastic analysis |
| T1.2 | See Table 2b                                                          |                                                                          |                                                                                        |
| **T2** | Comparative Analysis of Net Basin Supply                             |                                                                          |                                                                                        |
| T2.1 | Analysis of GLERL NBS Component Uncertainty and Its Impact on NBS    | • Perform Monte Carlo analysis Oct 2008  
• Complete analysis and provide results to Task T2.2 by Nov 2008 | • 1948-2006 component GLERL NBS  
• Error estimates for each component of GLERL NBS  
• Overall GLERL NBS uncertainty and confidence interval |
| T2.2 | Comparative Analysis of current Net Basin Supply Computations (NBS)   | • Initial analysis of historic time series data (channel flows, change in storage, and residual NBS) 1900-2006 for uncertainties in computing NBS  
• Statistical comparison of 1948-2006 residual and component NBS  
• Provide guidance to Data TWG on data corrections for Task D1 by Mar 2008  
• Receive corrected historic data from Data TWG by Sep 2008  
• Provide corrected data to Task T4 by Sep 2008  
• Complete analysis and provide results to Task | • Identification of supply components with the most uncertainty and recommendations on how to reduce those uncertainties  
• Comparison of residual and component NBS to explore differences and identify causative factors  
• Analysis of Connecting Channel flows as they pertain to computing NBS specifically addressing water balance issues for the Upper Lakes  
• From a water balance perspective, address how any potential changes to the NBS and its components have affected Upper Lakes levels |
<table>
<thead>
<tr>
<th>No.</th>
<th>Tasks</th>
<th>Milestones</th>
<th>Key Output &amp; Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>T3</td>
<td>Experimental focus on components with greatest uncertainty</td>
<td>T5 by Dec 2008</td>
<td></td>
</tr>
<tr>
<td>T3.1</td>
<td>Overlake Precipitation</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
• Provide first results to Task T3.1.2 by Nov 2008  
• Prepare 2007-2009 ECNWDAS hindcast of overlake/overland precipitation  
• Provide final results to Task T3.1.2 by Nov 2010 | • ECNWDAS estimate of monthly overland/overlake precipitation for 2004-2009 |
| T3.1.2 | Comparison of GLERL overlake/land precipitation with ECNWDAS reanalysis/NCEP reanalysis/NOAA MPE gridded radar rainfall | • Prepare 1948-2006 Thiessen interpolated precipitation  
• Receive ECNWDAS data for 2004-2006 from Task T3.1.2  
• Obtain NOAA MPE data for 2002-2006  
• Obtain NCEP reanalysis data for 1950-2006  
• Compare 4 estimates of overland/overlake monthly precipitation  
• Provide first results to Task T5.1 by Dec 2008  
• Prepare or obtain 2007-2009 Thiessen interpolated, MPE, and NCEP estimates and receive ECNWDAS estimates  
• Provide final results to Task T5.1 by Dec 2010 | • 3 estimates of monthly overland/overlake precipitation (Thiessen interpolation, MPE, NCEP)  
• Uncertainty assessment of overlake and overland precipitation estimates  
• New methods for estimating overland/overlake precipitation |
| T3.2 | Lake Evaporation |  |  |
| T3.2.1 | Computation of ECNWDAS lake evaporation 2004 - 2009 | • Prepare 2004-2006 ECNWDAS hindcast of lake evaporation  
• Provide first results to Task T3.2.2 by Nov | • ECNWDAS estimate of monthly lake evaporation for 2004-2009 |
<table>
<thead>
<tr>
<th>No.</th>
<th>Tasks</th>
<th>Milestones</th>
<th>Key Output &amp; Products</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2008</td>
<td></td>
</tr>
</tbody>
</table>
|     |       | • Prepare 2007-2009 ECNWDAS hindcast of lake evaporation  
|     |       | • Provide final results to Task T3.2.2 by Nov 2010 |                       |
| T3.2.2 | Comparison of GLERL LLTM lake evaporation estimates with ECNWDS reanalysis/NCEP reanalysis | • Re-calibrate the GLERL LLTM for 1980-2001  
| | | • Simulate the 1948-2006 lake evaporation with LLTM  
| | | • Obtain NCEP reanalysis data for 1950-2006  
| | | • Receive ECNWDS data for 2004-2006 from Task T3.2.1  
| | | • Compare 3 estimates of monthly lake evaporation  
| | | • Provide first results to Task T5.1 by Dec 2008  
| | | • Continue data development and comparisons for 2007-2009  
| | | • Provide final results to Task T5.1 by Dec 2010 | • 2 estimates of monthly lake evaporation for 1950-2006 (LLTM, NCEP)  
| | | | • Comparison of 3 estimates of monthly lake evaporation (LLTM, NCEP, ECNWDS for 2004-2009; LLTM, NCEP for 1950-2009)  
| | | | • Uncertainty assessment of lake evaporation estimates  
| | | | • New methods for estimating lake evaporation |
| T3.2.3 | Measurements of lake evaporation using eddy covariance system | • Install eddy covariance and other met instrumentation on Lake Superior at Stannard Rock Lighthouse by May 2008  
| | | • Conduct site reconnaissance for Lake Michigan-Huron site and install May 2009  
| | | • Collect data for 2008-2009  
| | | • Develop methodology for extrapolating across the lake and estimate overlake evaporation by Dec 2009  
| | | • Compare 4 estimates of lake evaporation by Jan 2010  
| | | • Report findings and | • Direct observations of Lake Superior and Lake Michigan-Huron lake evaporation  
| | | | • New method for observing and estimating lake evaporation  
<p>| | | | • Comparison of 4 estimates of monthly lake evaporation for 2008-2009 (LLTM, NCEP, ECNWDS and direct observations) |</p>
<table>
<thead>
<tr>
<th>No.</th>
<th>Tasks</th>
<th>Milestones</th>
<th>Key Output &amp; Products</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td><strong>conclusions for final Study Report by Jun 2011</strong></td>
<td></td>
</tr>
</tbody>
</table>
|     |       | **T3.2.4** Changes in ice regime and surface water temperatures on evaporative flux | • Perform a statistical spatial and temporal analysis of best estimate of evaporative flux with historical ice observations, surface water temperatures, and AO/NAO/PNA teleconnections for 1970-2006  
  • Provide first results to Task T5.1 by Nov 2008  
  • Continue data development and comparisons for 2007-2009  
  • Provide final results to Task T5.1 by Nov 2010  
  • Identification of causative factors in changes to ice regime and evaporative fluxes  
  • Reduces uncertainties of the NBS and its components through new observations (winter ice extent and thickness) and statistically modeled data (ice characteristics, atmospheric teleconnections, and water temperatures) |
| T3.3 | Basin Runoff | **T3.3.1** Computation of ECNWDAS basin runoff 2004-2009 | • Prepare 2004-2006 ECNWDAS hindcast of basin runoff  
  • Provide first results to Task T3.3.3 by Nov 2008  
  • Prepare 2007-2009 ECNWDAS hindcast of basin runoff  
  • Provide final results to Task T3.3.3 by Nov 2010  
  • ECNWDAS estimate of monthly basin runoff for 2004-2009 |
|     |       | **T3.3.2** Improve proration of gauged area streamflow to ungauged areas through correlation of spatial land surface characteristics | • Develop spatial statistical methodologies for prorating gauged area streamflow to ungauged areas for 1948-2006 data  
  • Provide first results to Task T3.3.3 by Nov 2008  
  • Extend analysis to 2007-2009 data  
  • Provide final results to Task T3.3.3 by Nov 2010  
  • Prorated estimate of monthly basin runoff for 1948-2009  
  • Improved method for estimating basin runoff |
| T3.3 | Comparison of | **T3.3.3** | • Prepare GLERL runoff  
  • 3 estimates of monthly basin runoff for |

<table>
<thead>
<tr>
<th>No.</th>
<th>Tasks</th>
<th>Milestones</th>
<th>Key Output &amp; Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>T3.4</td>
<td>Connecting Channel Flow and Retardation Factors</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Development of Connecting Channel apparent ice and weed retardation values, assessment of trends and significance to lake levels</td>
<td>Prepare monthly ice and weed retardation values for 1900-2006 based on coordinated residual NBS and connecting channel flows by Jun 2008 • Receive results of Task P2 by Aug 2008; revise retardation values if required • Provide retardation values to Task T4.1 for trend analysis by Sep 2008 • Provide results to Task T5.2 by Dec 2008</td>
<td>Ice and weed retardation values for 1900-2006 • Assessment of trend in ice and weed retardation values and their impact on lake levels</td>
</tr>
<tr>
<td>T3.5</td>
<td>Lake Levels and Change in Storage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P22</td>
<td>Lake Levels and Change in Storage</td>
<td>Provide assessment of isostatic rebound on</td>
<td>Identification of causative factors related to the change in storage computations</td>
</tr>
<tr>
<td>No.</td>
<td>Tasks</td>
<td>Milestones</td>
<td>Key Output &amp; Products</td>
</tr>
<tr>
<td>-----</td>
<td>-------</td>
<td>------------</td>
<td>----------------------</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>lake levels, channel rating equations and change in storage</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Provide results of Task P22 to Task T3.5.1 by Aug 2008</td>
</tr>
<tr>
<td>T3.5.1</td>
<td>Assessment of uncertainty in change in storage</td>
<td>• Perform uncertainty assessment of beginning of month water levels</td>
<td>• Uncertainty assessment of lake change in storage estimates and impact on residual NBS computations</td>
</tr>
<tr>
<td>D1</td>
<td>Correct/Adjust 1900-2006 water balance data based on findings from Tasks 2 and 3</td>
<td>• Receive input from Tasks T2 and T3 on corrections and best methodologies for computing NBS</td>
<td>• New observations and modeled data for estimates of NBS</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Provide improved data to Tasks T5 and T6 by Nov 2008</td>
</tr>
<tr>
<td>T4</td>
<td>Statistical Analyses, Teleconnections and Stochastic Analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T4.1</td>
<td>Trend Analysis</td>
<td>• Receive corrected data sets from Task T2.2 by Sep 2008</td>
<td>• Identification of causative factors related to the change in Upper Lakes water supplies</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Perform Bayesian change point analysis on water balance data</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Perform trend analysis</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Report findings by Nov 2008</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Provide results to Task T4.3 by Nov 2008</td>
</tr>
<tr>
<td>T4.2</td>
<td>Teleconnections</td>
<td>• Determine correlations between climate signals and water balance data</td>
<td>• Identification of causative factors related to the change in Upper Lakes water supplies</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Integrate results from Task T3.2.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Report findings by Nov 2008</td>
</tr>
<tr>
<td>T4.3</td>
<td>See Table 2b</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T5</td>
<td>Integration of Tasks 1-4: Affect of net basin supply on the change in Lakes Michigan-Huron</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No.</td>
<td>Tasks</td>
<td>Milestones</td>
<td>Key Output &amp; Products</td>
</tr>
<tr>
<td>-----</td>
<td>-------</td>
<td>------------</td>
<td>-----------------------</td>
</tr>
</tbody>
</table>
|     | and Lake Erie lake level relationship | • All contributing work for St. Clair report completed by Nov 2008  
• Final St. Clair report completed Feb 2009  
• Final analysis and reports completed by Dec 2010  
• Final H&C TWG Study Report completed Jun 2011 | • Identification of causative factors related to the change in Upper Lakes water supplies  
• Assessment of uncertainty in the confidence of the attribution of causative factors  
• Recommendations on new observations and modeled data for computation, monitoring and forecasting of Upper Lakes water supplies |
| T5.1 | Rank and describe the uncertainty of the water balance components relative to one another and assess the impact of uncertainty on the attribution of water supply changes to lake levels | • All contributing work for St. Clair report completed by Nov 2008  
• Final St. Clair report completed Feb 2009  
• Final analysis and reports completed by Dec 2010  
• Final H&C TWG Study Report completed Jun 2011 | • Identification of causative factors related to the change in Upper Lakes water supplies  
• Assessment of uncertainty in the confidence of the attribution of causative factors  
• Recommendations on new observations and modeled data for computation, monitoring and forecasting of Upper Lakes water supplies |
| T5.2 | Determine the affect of net basin supply on the change in lake level relationship | • All contributing work for St. Clair report completed by Nov 2008  
• Final St. Clair report completed Feb 2009  
• Final analysis and reports completed by Dec 2010  
• Final H&C TWG Study Report completed Jun 2011 | • Identification of causative factors related to the change in lake levels between Lakes Michigan-Huron and Lake Erie  
• Assessment of uncertainty in the confidence of the attribution of causative factors  
• Recommendations on new observations and modeled data for computation, monitoring and forecasting of Upper Lakes water levels |
### Table 2b – Lake Superior Key Tasks, Milestones and Outputs

<table>
<thead>
<tr>
<th>No.</th>
<th>Tasks</th>
<th>Milestones</th>
<th>Key Output &amp; Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>Improvements to the Coordinated Regulation and Routing Model</td>
<td></td>
<td>US and Canadian coordinated regulation and routing program flexible for plan formulation and stochastic analysis</td>
</tr>
<tr>
<td>T1.1</td>
<td>See Table 2a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1.2</td>
<td>Develop visual interface and linkages to socio-economic and environmental models for plan evaluation</td>
<td>• Define visual interface requirements</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Define linkages to plan evaluation models</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Complete model improvements by Jan 2010</td>
<td></td>
</tr>
<tr>
<td>T4</td>
<td>Statistical Analyses, Teleconnections and Stochastic Analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T4.1</td>
<td>See Table 2a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T4.2</td>
<td>See Table 2a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T4.3</td>
<td>Stochastic Analysis</td>
<td>• Receive results of Task T4.1 by Nov 2008</td>
<td>Stochastic time series of present climate for plan formulation and evaluation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Determine if new stochastic analysis is required by Feb 2009</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Perform stochastic analysis if required by Jan 2010</td>
<td></td>
</tr>
<tr>
<td>T6</td>
<td>Climate Change Sequences</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T6.1</td>
<td>Prepare base simulation for comparison with scenarios</td>
<td>• Receive corrected historical water supply scenarios 1900-2006 from Task D1 by Nov 2008</td>
<td>The hydraulic, hydrologic, socio-economic and environmental conditions that represent the base conditions for the Study</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Develop and coordinate current hydraulic conditions by Jun 2009</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Route water supply scenario by Jul 2009</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Quantify uncertainty of base case by Dec 2009</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Input levels and flows to socioeconomic and environmental models by Jan 2010</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Import results into Decision Integration Framework by Jan 2010</td>
<td></td>
</tr>
<tr>
<td>No.</td>
<td>Tasks</td>
<td>Milestones</td>
<td>Key Output &amp; Products</td>
</tr>
<tr>
<td>-----</td>
<td>-------</td>
<td>------------</td>
<td>----------------------</td>
</tr>
</tbody>
</table>
| **T6.2** | Regional downscaling using Canadian RCM | - Set model up for simulations by Dec 2008  
- Perform simulations by Dec 2009  
- Provide results to Task T6.5 for comparison with CHARM results | - RCM downscaled GCM scenarios for hydrologic simulation with MESH model for plan formulation and evaluation |
| **T6.3** | Conventional downscaling using GLERL’s AHPS | - Receive Canadian RCM boundary forcing data by Jun 2008  
- Set model up for simulations by Dec 2008  
- Perform simulations by Dec 2009  
- Provide results to Task T6.5 for comparison with CHARM results | - Conventionally downscaled GCM scenarios for hydrologic simulation with GLERL AHPS models for plan formulation and evaluation |
| **T6.4** | Regional downscaling using GLERL’s CHARM | - Receive Canadian RCM boundary forcing data by Jun 2008  
- Set model up for simulations by Dec 2008  
- Perform simulations by Dec 2009  
- Provide results to Task T6.5 for comparison with conventional downscaling technique | - CHARM downscaled GCM scenarios for plan formulation and evaluation |
| **T6.5** | Interaction between HC TWG and PEG for joint development of climate scenarios | - H&C TWG Climate Workshop to identify IPCC IV climate scenarios; performance metrics for selecting downscaling method (conventional, CHARM, Canadian RCM); by Jan 2010  
- Generate climate change water supply scenarios by Jun 2010 | - Comparison of downscaling techniques  
- Assessment of importance of downscaling technique and selection of technique  
- Downscaled GCM scenarios for plan formulation and evaluation |

<table>
<thead>
<tr>
<th>S</th>
<th>Integration of Tasks 4-6: Climate change assessment to year 2040</th>
</tr>
</thead>
</table>
| S1 | Climate change assessment to year 2040 | - Receive climate change water supply scenarios from Task T6.5 by Jun 2010 | - Report on climate change impact assessments  
- Proposed lake regulation plan and adaptive management strategy |
<table>
<thead>
<tr>
<th>No.</th>
<th>Tasks</th>
<th>Milestones</th>
<th>Key Output &amp; Products</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>• Perform plan formulation and evaluation from Jun 2010 to Jun 2011</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Assess impacts and provide final report and analysis by Mar 2012</td>
<td></td>
</tr>
<tr>
<td>No.</td>
<td>Tasks</td>
<td>2007</td>
<td>2008</td>
</tr>
<tr>
<td>-----</td>
<td>-----------------------------------------------------------------------</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>11</td>
<td>Improvements to the Coordinated Regulation and Routing Model</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.1</td>
<td>Miscellaneous programming improvements to support lake level evaluation, plan formation, and climate change</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Comparative Analysis of Net Basin Supply</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.1</td>
<td>Analysis of GLERL NBS Component Uncertainty and Its Impact on NBS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.2</td>
<td>Comparative Analysis of current Net Basin Supply Computations (NBS)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Experimental focus on components with greatest uncertainty</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.1</td>
<td>Overland Precipitation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.1.2</td>
<td>Comparison of GLERL overland precipitation with ECNWEDAS analysis/RCEP analysis/MDA/MDAP gridded data rainfall</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.2</td>
<td>Lake Evaporation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.2.1</td>
<td>Computation of ECNWEDAS lake evaporation 2004-2009</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.2.2</td>
<td>Comparison of GLERL lake evaporation estimates with ECNWEDAS analysis/RCEP analysis/MDA/MDAP analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.2.3</td>
<td>Measurements of lake evaporation using eddy covariance system</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.2.4</td>
<td>Changes in ice regime and surface water temperatures on evaporative flux</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.3</td>
<td>Basin Runoff</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.3.1</td>
<td>Computation of ECNWEDAS basin runoff 2004-2007</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.3.2</td>
<td>Improve protection of gauged area streamflow to ungaged areas through correlation of spatial land surface characteristics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.3.3</td>
<td>Comparison of GLERL runoff estimates with ECNWEDAS analysis/RCEP analysis/MDA/MDAP analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14.4</td>
<td>Connecting Channel Flow and Retention Factors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14.4.1</td>
<td>Review of St. Clair &amp; Detroit River Rating Curves and Develop Hydraulic Performance Graphs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14.5</td>
<td>Lake Levels and Change in Storage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14.5.1</td>
<td>Assessment of uncertainty in change in storage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Correct/Adjust 1900-2005 water balance data based on findings from Tasks 2 and 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Statistical Analysis, Teleconnections and Stochastic Analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16.1</td>
<td>Trend Analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16.2</td>
<td>Teleconnections</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Integration of Tasks 1-4: Effect of net basin supply on the change in Lakes Michigan-Huron and Lake Erie lake levels</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17.1</td>
<td>Rank and describe the uncertainty of the water balance components relative to one another and assess the impact of uncertainty on the attribution of water supply changes to lake levels</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17.2</td>
<td>Determine the impact of net basin supply on the change in lake level relationship</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Final Reports for St. Clair River Tasks completed by**

**All Projects for St. Clair River Tasks due November 30,**
### Table 3b – Lake Superior Regulation Key Tasks and Milestones

<table>
<thead>
<tr>
<th>No.</th>
<th>Tasks</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>Improvements to the Coordinated Regulation and Routing Model</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1.2</td>
<td>Develop visual interface and linkages to socio-economic and environmental models for plan evaluation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T4</td>
<td>Statistical Analyses, Teleconnections and Stochastic Analysis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T4.3</td>
<td>Stochastic Analysis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T6</td>
<td>Climate Change Sequences</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T6.1</td>
<td>Prepare base simulation for comparison with scenarios</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T6.2</td>
<td>Regional downscaling using Canadian RCM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T6.3</td>
<td>Conventional downscaling using GLERL’s AHPS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T6.4</td>
<td>Regional downscaling using GLERL’s CHARM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T6.5</td>
<td>Interaction between HSC TWG and PEG for joint development of climate scenarios</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Integration of Tasks 4-6: Climate change assessment to year 2040</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Climate change assessment to year 2040</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

M - Project Milestones
Annex A

BASIN HYDROLOGY NBS/CLIMATE CHANGE TECHNICAL WORKING GROUP

SCOPE OF WORK
TASKS 1a and 1b: COMPARATIVE ANALYSIS OF NET BASIN SUPPLY COMPUTATIONS

GENERAL GUIDELINES AND INFORMATION

Objective

The purpose of this investigation is to specify all uncertainties that go into the computation of net basin supplies (NBS) and to perform sensitivity analyses to understand the effects of these uncertainties on estimates of NBS. Investigative methods to be used include literature review, data analysis, and sensitivity analysis through computational experiments.

Computation of Net Basin Supply

There are two approaches commonly used to estimate NBS. The first approach, which is called the component method, derives NBS using a water balance of the components of the hydrological cycle. The second method, called the residual method, is more indirect and is based on change in storage of the lake and knowledge of the connecting channel flows.

With the component method, NBS is computed as the precipitation occurring over the lake plus runoff to the lake from the surrounding basin, plus groundwater, plus condensation on the lake surface minus evaporation from the lake surface. Runoff to the lake by the surrounding watershed is a composite of flow from measured tributaries and estimated ungauged tributaries. It is important to note that the runoff when measured by conventional stream gauges would reflect all upstream impacts on the available water supply including any upstream diversions, consumptive use or changes due to land use. Estimation of contribution of water from ungauged tributaries within the local basin should also take into account upstream diversions and consumptive use. The groundwater component is not quantitatively included in most analyses of balance within the Great Lakes basin. Computing NBS by the component method requires an estimation of overlake precipitation, evaporation and condensation, which are not directly measured but can be derived using various models. For example, precipitation over the Great Lakes is typically estimated based on interpolated point measurement data from inland stations. The uncertainty associated with the estimation of overlake precipitation and evaporation has been estimated to range from 15 to 60%.

An alternative approach for estimating NBS is through the residual method. This method is a mass balance of streamflow entering and leaving the system plus or minus any changes in storage on the local lake. Recorded amounts of the diversions into and out of the lake, and estimates of consumptive use, and lake thermal expansion can be factored in when calculating the net basin supply. For example,
Lakes Michigan-Huron NBS is computed as the change in volume of water in storage on Lakes Michigan-Huron plus the outflow through the St. Clair River, plus out-going diversions and consumptive use, minus the outflow from Lake Superior. Outflow from Lakes Michigan-Huron is derived using hydraulic ratings which correlate water levels and river flow. The inflow from Lake Superior, through the St. Marys River is determined as the summation of recorded flows through each of the different structures at Sault Ste Marie. Ideally, the change in water storage in a lake is determined by knowing the surface area at various elevations; however in the case of Lakes Michigan-Huron a constant lake surface area is used. Rating equations are subject to error usually less than 5% of the flow value, while the stage or elevation of the lake is an average reading of a number of representative water level gauges within the combined lake system. Determining the lake-wide average level is subject to measurement error, and readings over a period of two days from a network of gauges are used to determine lake-wide end-of-month levels.

SPECIFIC INFORMATION AND TASKS

The following tasks are to be performed where applicable for Lake Superior, Lakes Michigan-Huron, Lake St. Clair and Lake Erie. The tasks are also to be performed for the St. Mary’s, Detroit, St. Clair and Niagara Rivers as pertinent.

Specific Tasks

1) A sensitivity analysis to see what percentage changes in the various components for both the residual and component methods would have on the NBS computations. The outcome should be the identification of those components that are most uncertain with recommendations on how to reduce the uncertainties. This task should specifically address:
   a. Connecting Channel flows
   b. Change in storage (lake-wide levels)
   c. Thermal expansion
   d. Diversions
   e. Groundwater
   f. Consumptive Use
   g. Overlake precipitation
   h. Overland runoff
   i. Lake evaporation

2) A comparison of annual NBS for both the residual and component methods. The comparison should include, but not be limited to, an assessment of time-series trends, bias, correlation, frequency analysis and distributions, and exploration of any significant deviations.

3) A comparison of monthly NBS for both the residual and component methods. The comparison should include, but not be limited to, exploration of seasonal differences and correlation with other variables to identify causative factors.

4) An analysis of special concerns related to Connecting Channel flows, specifically addressing:
   a. The effect of potential changes to the Ashland Avenue rating on the Lake Erie NBS
b. The impact of potential changes to the St. Clair River flows on the Michigan-Huron NBS

c. A focused look at the Lake St. Clair water balance to explore problems between the St. Clair and Detroit River flows

d. The impact of errors in ratings of the St. Marys outlet works on St. Marys flows and Lake Superior and Lakes Michigan-Huron NBS

5) A water balance of the Upper Lakes using both the residual and component NBS to identify any problems with conservation of mass

Data to be Provided

The following data will be provided by the Data Verification and Monitoring TWG:

Residual NBS (1900-2006)
Change in storage (1900-2006)
Coordinated Connecting Channel flows (1900-2006)
Connecting Channel ice and weed retardation (1900-2006)
Lake Superior control work outflows (compensating works, power houses, leakage (1900-2006)
Long Lac-Ogoki Diversion (Period of Record)
Chicago Diversion (Period of Record)
Component NBS (1948-2006)
GLERL estimates of overlake precipitation (1948-2006)
GLERL estimates of overland runoff (1948-2006)
GLERL estimates of lake evaporation (1948-2006)
Connecting Channel flow measurements (upon request)
Stage-Discharge relationships (upon request)

References to be Provided


Linkage with other TWGs

This work should be performed in coordination and consultation with the Data Verification and Monitoring TWG.
DELMIVERABLES

A detailed scientific report with appropriate appendices showing calculations and data should be submitted in electronic format, both Microsoft Word and Adobe PDF. Metadata for the report is required, with final payment provided upon receipt of the metadata.

TIMELINE

The work detailed by this scope is to commence upon approval of the scope and selected contractor by the Study Program Manager, and is to be completed in full within 3 months from the start date.

COSTS

$30,000 US is allocated for this study to include: the contractor’s compensation, travel, software and report production costs. The contractor will provide all computer hardware. The contractor is not responsible for costs incurred by the Study for French translation.
Annex B

Comparative Analysis of Net Basin Supply Components and Climate Change Impact on the Upper Great lakes - Submitted by Brent Lofgren, NOAA/GLERL, and Carlo DeMarchi, UM/CILER

Comparative Analysis of Net Basin Supply Components and Climate Change Impact on the Upper Great lakes

Statement of work for contributions by the NOAA Great Lakes Environmental Research Laboratory and the University of Michigan’s Cooperative Institute for Limnology and Ecosystems Research to the Hydrological Modeling component of the International Joints Commission’s International Upper Great Lakes Study.

Submitted by Brent Lofgren, NOAA/GLERL, and Carlo DeMarchi, UM/CILER
Proposal title

Comparative Analysis of Net Basin Supply Components and Climate Change Impact on the Upper Great lakes

Principal Investigators

Brent Lofgren, NOAA Great Lakes Environmental Research Laboratory
Carlo DeMarchi, Cooperative Institute for Limnology and Ecosystem Research, University of Michigan

Table of Content

TWG-1b .........................................................................................................................3
TWG-1c-i ....................................................................................................................... 5
TWG-1c-ii ......................................................................................................................7
TWG-1c-iii ....................................................................................................................8
TWG-1c, comparison of CHARM output with CRCM and other data .....................8
TWG-3a .........................................................................................................................9
TWG-3b .........................................................................................................................9
Budget justification .....................................................................................................10
Proposal timeline .......................................................................................................11
Quantification of 1948-2006 Net Basin Supply Components and Analysis of Uncertainty Impact on NBS (Hydrology TWG Plan of Study, Article 1b)

Lead PI: Carlo DeMarchi

Background
Generally speaking, the Net Basin Supply (NBS) of a waterbody is the net amount of water entering the waterbody. In the component method the NBS is defined as:

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

Where:
P = direct precipitation over the waterbody
R = River watershed runoff to the waterbody
E = evaporation from the waterbody surface
G = Groundwater influx into the waterbody minus seepage

NOAA GLERL maintains a database of the monthly NBS components for the period 1948 to present (Croley and Hunter, 1993), in which the components are computed according to different methods.

Direct precipitation over the Lakes surface (over-lake precipitation)
GLERL subdivides each lake basin into a regular grid of 1 km x 1 km cells. Precipitation is computed for each pixel using Thiessen interpolation of all available daily data from stations in the basin or within approximately 0 - 30 km from the basin, depending upon station density near the edge of the basin. Over-land precipitation is computed considering only precipitation falling over land pixels, including islands and smaller inner lakes. Over-lake precipitation is computed considering only open-water pixels. Finally, over-basin precipitation is computed considering all pixels.

Station data for the U. S. are obtained from the National Climatic Data Center, and station data for Canada are obtained from the Atmospheric Environment Service.
Because of the small number of off-shore gages, over-lake precipitation is dominated by the few gages along lakeshores, which are probably not representative of the over-lake precipitation (e.g., lake-snow effect). Over-land precipitation, on the other hand, is the result of the contributions of many more stations, thus probably better reflecting the climatological precipitation. Consequently, GLERL estimates the direct precipitation component of the NBS estimates by multiplying the average over-land precipitation times the lake area.

River Watershed Runoff
GLERL estimates watershed runoff by using streamflow records from major rivers, available from the U.S. Geological Survey for U.S. streams and the Inland Waters Directorate of Environment Canada for Canadian streams. Daily runoff values provided by these agencies were summed for each watershed within a lake basin. The runoff is extrapolated over ungaged areas (between 22% and 43% of the Great Lakes basin remains ungaged; Lee, 1992). Weights are assigned to each non-overlapping stream-flow gage by dividing its drainage area by the watershed area. Daily
watershed runoff estimates were computed by summing all daily station values in the watershed and then dividing by the sum of their weights, to extrapolate for ungaged areas. Finally, daily lake basin runoff estimates are computed in a similar manner by summing the watershed estimates, for which there are data available, and then dividing by the ratio of the area of those watersheds to the total basin area. Monthly basin runoff is computed by simply summing the daily basin runoff estimates for all days in each month.

Lake Evaporation
GLERL estimates lake evaporation for the five Great Lakes, Lake St. Clair, and Georgian Bay, by using Large Lake Thermodynamics Model (LLTM). This a lumped-parameter model of evaporation and thermodynamic fluxes for the Great Lakes based on an energy balance at the lake's surface (Croley 1989a,b) and on one-dimensional (vertical) lake heat storage (Croley 1992a). Ice formation and loss is coupled also to lake thermodynamics and heat storage (Croley and Assel 1994). Model inputs are areal-average daily air temperature, windspeed, humidity, precipitation, and cloudcover. LLTM has been calibrated for the period 1948-1988 against ice cover and surface temperature observations.

Groundwater influx into the waterbody minus seepage
Up to now there was no comprehensive analysis of the net groundwater influx into the Great Lakes, and it is regarded as a minor portion of the total water budget. Thus, this component is not considered in the GLERL’s NBS components.

Direct measurements of overlake precipitation are few and spatially inhomogeneous due to the limited number of islands in the lakes. For this reason, estimates of the overlake precipitation uncertainty are very approximate. Similar problems also affect evaporation estimates.

Quantification of 1948-2006 Net Basin Supply Components
Proposed work
GLERL will make available the 1948-2006 NBS components as text files for use by the Hydrology TWG and its partners.

Personnel time: 0-month FTE (Data are already available)

Analysis of NBS Component Uncertainty and Its Impact on NBS
Proposed work
GLERL will produce error estimates for each component of the NBS based on existing literature and analysis and its effect on the NBS of each lake. Further, assuming independence among the component errors, GLERL will estimate the overall NBS uncertainty and confidence interval using a Monte Carlo analysis.

Personnel time: 1-month FTE PI; ½-month FTE Computer specialist.
Timeline: Starting date+ 1 month.

Lead PI: Carlo De Marchi

Background
Different methods are used for estimating over-lake and over-land precipitation for different periods.

GLERL’s Thiessen Interpolation
The methodology used by GLERL to compute overlake precipitation was illustrated earlier. Data are already available for the 1948-2005 period and complete data for 2006 should be available by spring 2008.

National Center for Environmental Prediction Multi-sensor Precipitation Estimate Stage IV.
MPE products are obtained by merging radar-derived hourly precipitation estimates with gage-measured hourly precipitation data from a relatively sparse network of rain gages. Radar-derived precipitation is first debiased using a procedure developed by Smith and Krajewski (1991). Gage data and bias-corrected radar-derived precipitation are merged together using optimal estimation techniques developed by Seo (1998). The schemes optimally estimate rainfall fields using raingage and radar data under partial data coverage conditions. Data from single radar are visually inspected and then mosaicked into a national product. MPE’s temporal resolution is hourly, while spatial resolution is 4 km. Stage IV data are available for the period 2002-2006, while earlier, less reliable, versions are available for 1996-2001.

National Center for Environmental Prediction Reanalysis Project (CDAS)
The CDAS reanalysis system includes the NCEP global spectral model operational in 1995, with 28 "sigma" vertical levels and a horizontal triangular truncation of 62 waves, equivalent to about 2.5 degrees. The analysis scheme is a 3-dimensional variational (3D-Var) scheme cast in spectral space denoted Spectral Statistical Interpolation (Parrish and Derber, 1992). The assimilated observations are (Kistler et al., 2001)

- upper air rawinsonde observations of temperature, horizontal wind and specific humidity;
- operational TOVS vertical temperature soundings from NOAA polar orbiters over ocean, with microwave retrievals excluded between 20°N and 20°S due to rain contamination;
• temperature soundings over land only above 100 hPa
• cloud tracked winds from geostationary satellites;
• aircraft observations of wind and temperature;
• land surface reports of surface pressure, and
• oceanic reports of surface pressure, temperature, horizontal wind and specific humidity.

CDAS produces several gridded databases of atmospheric variables, including convective and total precipitation. Data are made available at a spatial resolution of 2.5 degrees and temporal resolution of 6 hours and cover the 1950-2007 period.

Proposed work
First, GLERL will assemble the NCEP-MPE data for the period 2002-2006 for the Great Lakes region, transform them into monthly precipitation, and develop a set of rain gages with consistent data coverage.

Rain gage data will be compared with coincident MPE estimates and the maximum correlation between MPE data and rain gage data will be mapped (Figure 1) to determine the areas where MPE data are reliable.

![Figure 1: Maximum correlation in monthly precipitation between MPE and gage for Lake Erie, April – September 2002-2005.](image)

Earlier work by GLERL in the Lake Erie area and by Watkins et al. (2007) showed that MPE data over land present a good correlation with rain gages, but underestimate precipitation by around 10%. This bias is probably a result of the low spatial density and inherent bias of the hourly rain gage data used in the MPE. Thus, MPE data will be regionally debiased using a simple ratio of average gage precipitation and average MPE data over the pixels containing gages.

GLERL will assemble NCEP CDAS data for the period 1948-2006 for the Great Lakes region. To facilitate a comparison of the different precipitation estimation methods, GLERL will produce the following additional datasets of monthly precipitation for the 2001-2006 period:
• Average areal precipitation over the NCEP CDAS grid using Thiessen polygons;
• Average areal precipitation over the NCEP CDAS grid using MPE data;
• Over-lake and over-land average precipitation using a weighted average of the NCEP CDAS data;
• Over-lake and over-land average precipitation using MPE data.
• Average areal precipitation over the Environment Canada numerical weather prediction and data assimilation system (ECNWDAS) grid using Thiessen polygons;
• Average areal precipitation over the ECNWDAS grid using MPE data;
• Average areal precipitation over the ECNWDAS grid using a weighted average of the NCEP CDAS data;

Precipitation data from these sources and the ECNWDAS will be compared and analyzed.

Personnel time: 2-month FTE PI; 3-month FTE GRA; 1/2-month Computer specialist
Timeline: Thiessen-interpolation data sets: Start date + 2 months;
MPE data sets: Start date + 4 months;
NCEP data sets: Start + 4 months;
Complete analysis: Start + 6 months;

Comparison of ECNWDAS lake evaporation estimates with NCEP estimates and GLERL's lake thermodynamic model recalibrated for the period 1980-2001 (Hydrology TWG Plan of Study, Article 1c-ii)

Lead PI: Carlo De Marchi

Background

GLERL’s lake evaporation estimates
The methodology used by GLERL to estimate lake evaporation was illustrated earlier in the proposal. Evapotranspiration in river watersheds is estimated by the Large Basin Runoff Model.

National Center for Environmental Prediction Reanalysis Project (CDAS)
The CDAS reanalysis system was described earlier in the proposal. GLERL will use temperature, SST, 2m humidity, and latent/sensible heat flux, outputs for estimating evaporation in lake and land CDAS pixels.

Proposed work
The calibration of the LLTM will be extended to the period 1989-2001 using water surface temperature (WST) and ice cover available from conventional and remote sensing sources.
Recalibrated LLTM will be used to simulate the 1948-2006 lake evaporation with observed meteorology and produce output in text-file format:
GLERL will assemble the required NCEP CDAS data for the period 1948-2006 for the Great Lakes region, estimate evaporation, and subdivide it between lake and land evaporation. Evaporation over mixed pixels will be apportioned between lake and land according to their land and water portions.
LLTM, NCEP CDAS, and ECNWDAS evaporation estimation will be compared.

Personnel time: 3-month FTE PI; 1-month FTE Computer specialist; 2-month FTE GRA
Timeline: NCEP data sets: Start + 4 months;
LLTM recalibration completed: Start date + 10 months;
Complete analysis: Start date + 12 months;

Comparison of GLERL runoff approach with INRS-ETE geo-statistical approach for 1948-2006 (Hydrology TWG Plan of Study, Article 1c-iii)

Lead PI: Carlo De Marchi

Background

GLERL’s Large Basin Runoff Model
The LBRM was developed in the 1980s for estimating rainfall/runoff relationships on the 121 large watersheds surrounding the Laurentian Great Lakes. The LBRM model is a lumped-parameter model that serves the needs of the long-range forecaster in water resource supply considerations. The model was calibrated for 1965-1982 and is currently used at the daily time interval at GLERL for a variety of studies, including hydrological forecasting in GLERL’s AHPS.

Proposed work
GLERL will compute runoff for the 1948-2006 period for each of the 106 watersheds covering the Upper Great Lakes basin. For each lake, GLERL will aggregate runoff of all watersheds in total basin runoff and in ways compatible with the INRS-ETE geo-statistical approach, and with the MESH model.

Personnel time: 1-month FTE PI; 1-month FTE Computer specialist
Timeline: LBRM data sets: Start date + 6 months (depending on when definitive precipitation data are available for Canada);
Complete analysis: Start date + 12 months;

Comparison of GLERL’s CHARM Model Data to Canadian RCM Data (Hydrology TWG Plan of Study, Article 1c)
Lead PI: Brent Lofgren
This activity is aimed at fulfilling item 1c from the TWG Plan of Study, from the standpoint of the CHARM regional climate/hydrologic model. We will prepare data for overlake precipitation, overlake evaporation, and runoff from the drainage basin as predicted using CHARM, driven by boundary conditions from the North American Regional Reanalysis (NARR) dataset. Because of limitation of computing resources, CHARM output will be restricted to a period of 10-20 years. Each of these sets of output can be compared to similar data from “observed” sources such as CAPA Reanalysis, NCEP reanalysis, and MPE radar rainfall product, and also to predictions by the Canadian Regional Climate Model and the INRS-ETE geostatistical approach. The extraction of data from observational datasets was discussed in the previous section and will need to be divided with other study participants.

**Action items:** Derive overlake precipitation and evaporation, as well as land-originated runoff from CHARM. Compare precipitation to reanalysis and radar-based datasets and CRCM. Compare evaporation results to Canadian operational weather model and CRCM. Compare runoff to output from INRS-ETE geostatistical method and CRCM.

**Personnel time:** 2 months PI + 1 month computer specialist  
**Timeline:** Starting date + 18 months

### Climate Change Impact Assessment

The potential impact of future climate change on Great Lakes net basin supplies and lake levels is something that needs consideration in planning for the future needs of the Upper Great Lakes and their management. This action is important for evaluating the resilience of different management schemes to possible changes in climate. We plan to approach this using two different basic methods.

#### Conventional downscaling of IPCC IV GCM for hydrological simulation with GLERL’s AHPS (Hydrology TWG Plan of Study, Article 3a)

**Lead PI:** Carlo DeMarchi

**Background**

Given the coarse spatial and temporal resolutions of the earlier generations of GCMs, the impact of climate change on the hydrology of a region was often evaluated by driving the hydrologic models with inputs based on observed meteorological time series with offsets taken from general circulation model (GCM) monthly mean results—offsetting the temperature by the difference in temperature between a recent past time period and a future time period, as simulated by the GCM, and precipitation offset using the ratio between recent past and future simulations. This method has the merit of generating a spatially and temporally consistent meteorological fields, but it is able to account only for changes in monthly mean climate. That is, no change in the frequency of intense storms or droughts can be simulated.

In 2003, Croley used this methodology to analyze the impact of climate change on the Great Lakes: two GCMs were used to project the 2040-2069 climate resulting from two emission scenarios. The resulting four climate projections were used to perturb the observed 1961—1990 climate series and drive the AHPS to assess their impact on the basin hydrology.
Proposed work
Based on an agreed-upon choice of GCM scenarios of present and future climate, use AHPS to compare the net basin supplies of the Great Lakes basin using unaltered historical observations as input vs. those altered by changes in meteorological variables predicted by GCM simulations. The GCM scenarios will be chosen from those that participated in the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4), dated 2007.

Personnel time: 3-month FTE PI + 2-month FTE computer specialist
Timeline: Starting date + 18 months

Comparative analysis of regional models with lake feedback and without (Hydrology TWG Plan of Study, Article 3b)
Lead PI: Brent Lofgren

Second will be the use of the Coupled Hydrosphere-Atmosphere Research Model (CHARM), a regional climate model that simulates both the atmosphere and the land and lake surfaces in the Great Lakes basin. This model includes full interaction between the surface and the atmosphere and calculates runoff on its native 40 km square grid. It 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 similar to that used in Action item 6. Output on the native grid of CHARM includes surface runoff and sub-surface percolation, which can be transformed offline 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 longwave and shortwave radiation) that can aid in interpreting the reasons behind changes in hydrologic phenomena. The computational requirements for CHARM are extensive. Even with computer time provided on the “jet” group of computing clusters at NOAA Earth System Research Laboratory, a reasonable amount of time to simulate using CHARM is about 20 years for recent past and future scenarios.
Action items: Execute CHARM for the time period 1980-1999 and for a 20-year period in the future appropriate for comparison with AHPS and CRCM runs. Boundary conditions will be derived from one of the GCMs used to drive AHPS in Action item 6.

Personnel time: 3 months PI + 2 months computer specialist
Timeline: Starting date + 18 months

Budget and justification
Carlo DeMarchi (10 months)—will have primary responsibility for preparing, running, and analyzing simulations involving the AHPS suite of models for both the historical record and the future. Will participate in activities comparing among output from AHPS, CHARM, CRCM, and observational and reanalysis-based data.
Brent Lofgren (5 months)—will have primary responsibility for preparing, running, and analyzing simulations using the CHARM model for both the historical record and the future. Will participate in activities comparing among output from AHPS, CHARM, CRCM, and observational and reanalysis-based data.
Computer specialist (8 months)—will assist Drs. DeMarchi and Lofgren in the hands-on operations of preparing and running the models.
Graduate Research Assistant (GRA, 5 months) —will assist Drs. DeMarchi and Lofgren in the hands-on operations of preparing and running the models. Salary and benefits calculations were done according to University of Michigan specifications.

Data procurement ($10,000)—some of the needed data may require fees to procure it.
Travel ($9,100)—travel for DeMarchi and Lofgren to attend IUGLS workshops, assuming 2 workshops during year 1, plus 3 trips already taken by Lofgren and paid for by GLERL during 2007, and 3 during year 2, at an average cost of $700 each.

<table>
<thead>
<tr>
<th>Year 1</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>GLERL</td>
<td></td>
</tr>
<tr>
<td>Lofgren 3 months--$23,824</td>
<td></td>
</tr>
<tr>
<td>Computer specialist 4 months--$30,641.</td>
<td></td>
</tr>
<tr>
<td>Benefits--$13,072</td>
<td></td>
</tr>
<tr>
<td>NOAA/GLERL indirect costs--$38,120</td>
<td></td>
</tr>
<tr>
<td>Travel--$3,500</td>
<td></td>
</tr>
<tr>
<td>Data procurement--$10,000</td>
<td></td>
</tr>
<tr>
<td>Computer for graduate research assistant--$2,000</td>
<td></td>
</tr>
<tr>
<td>GLERL total--$121,157</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CILER</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>DeMarchi 7 months--$24,150</td>
<td></td>
</tr>
<tr>
<td>Graduate student research assistant 5 months--$14,804</td>
<td></td>
</tr>
<tr>
<td>Benefits--$8,933</td>
<td></td>
</tr>
<tr>
<td>Travel--$1,400</td>
<td></td>
</tr>
<tr>
<td>Indirect costs--$13,800</td>
<td></td>
</tr>
<tr>
<td>CILER total--$63,088</td>
<td></td>
</tr>
</tbody>
</table>

Year 1 total--$184,245

<table>
<thead>
<tr>
<th>Year 2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>GLERL</td>
<td></td>
</tr>
<tr>
<td>Lofgren 2 months--$16,439</td>
<td></td>
</tr>
<tr>
<td>Computer specialist 4 months--$31,714</td>
<td></td>
</tr>
<tr>
<td>Benefits--$11,557</td>
<td></td>
</tr>
<tr>
<td>NOAA/GLERL indirect costs--$33,701</td>
<td></td>
</tr>
<tr>
<td>Travel--$2,100</td>
<td></td>
</tr>
<tr>
<td>GLERL total--$95,511</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CILER</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>DeMarchi 3 months--$10,661</td>
<td></td>
</tr>
<tr>
<td>Benefits--$3,443</td>
<td></td>
</tr>
</tbody>
</table>

---

Travel--$2,100
Indirect costs--$4,537
CILER total--$20,741

Year 2 total--$116,252

### Proposal timeline

<table>
<thead>
<tr>
<th>Activity</th>
<th>t0+3</th>
<th>t0+6</th>
<th>t0+9</th>
<th>t0+12</th>
<th>t0+15</th>
<th>t0+18</th>
<th>t0+21</th>
<th>t0+24</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.b Analysis of NBS Component Uncertainty and Their Impact on NBS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.c Thiessen interpolation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NCEP MPE Stage IV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NCEP reanalysis CDAS Complete analysis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.c-ii NCEP reanalysis CDAS LLTM recalibration completed Complete analysis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.c-iii LBRM data sets Complete Analysis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.a Comparative analysis of historical data with CHARM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.b Conventional downscaling of IPCC IV GCM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Annex C

**Plan of Study:** Closing the water balance of the Upper Laurentian Great Lakes: a coupled land, lake, and atmosphere modelling approach

**Principal investigators:** Environment Canada – Science and Technology Branch
- Dr. Vincent Fortin, Meteorological Research Division
- Dr. Murray MacKay, Climate Research Division
- M. Jean-Guy Zakrevsky, Water Survey of Canada

**Executive Summary:**

This plan of study develops a fully coupled land, lake and atmosphere modelling system which will be used to simulate as well as forecast individual terms of the water budget of the Laurentian Great Lakes basin.

This system is comprised of the well established Global Environmental Multiscale (GEM) atmospheric model (for analysis and short-term forecasting) and Canadian Regional Climate Model (CRCM) for reanalysis and climate prediction. Both of these models can be coupled with a land-surface Hydrology Scheme (MESH). Within the land-surface hydrology scheme, two sophisticated land surface modules can be used within this system: the Canadian version of ISBA (Interation-Sol-Biosphère-Atmosphère), and the Canadian Land Surface Scheme (CLASS). Different options for the treatment of the lakes themselves are also available. In addition, a channel routing scheme for the surrounding watershed, along with a water balance and stage-discharge module, allows for analysis of the complete water balance of each of the Great Lakes.

The modelling system will be used to provide estimates and forecasts of the individual terms of the water budget (precipitation, evaporation and runoff), assess the impact of natural climate variability in lake level fluctuations, and downscale climate change scenarios generated by a Global Climate Model, in order to provide projections of future water level regimes. The historic estimates will be compared against other model outputs GLERL and companion studies within the framework of the entire IJC plan of study.

**Proposal Rationale:**

The Great Lakes basin is home for some 40 million inhabitants, hundreds of billions of dollars worth of commercial activity annually, as well as extensive and varied natural ecosystems. Because of this, understanding water level and flow regimes is of great interest both for purely scientific and practical reasons.

Lake levels, which have been monitored for more than 100 years, show a large degree of variability due to both natural climate variability as well as direct human intervention (such as dredging, diversions etc.), and levels tend to oscillate between relatively high water periods and relatively low water periods. The attribution of lake level fluctuations to specific causes is not straightforward, though recent record low levels in Lake Superior and Michigan-Huron have prompted some public outcry for immediate remedial
action. The possibility of bulk water exports of Great Lakes water to outside the basin is a contentious political issue that is also raised from time to time. All of these issues are further complicated by the possibility of ongoing climate change, which could conceivably drive lake levels into regimes not previously recorded. Thus regulation based on historical patterns might not be suitable in a future climate.

In order to enable a rational dialogue on all of these issues it is essential to have a deeper understanding of the water balance of the Great Lakes region historically, as well as plausible projections into the coming decades. Current estimates of water balance components are fraught with uncertainty: over – lake precipitation and evaporation observations are nearly non – existent, some contributing tributaries are ungauged, etc. Because of these problems, a water balance is frequently determined indirectly via net streamflow and lake level measurements (the “residual” method), though such an approach cannot be used to elucidate specific mechanisms implicated in a hydrologic regime shift (e.g. increased evaporation due to warmer surface temperatures).

**Project description**

**Regional Climate Predictions**

In this study a regional climate model is enhanced and used to analyze the water balance of the Great Lakes system, both over the recent past and into the next 3 decades.

(a) **Climate predictions over the recent past**

The regional climate model to be developed is based on the very well established Canadian Regional Climate Model coupled with the latest version of the Canadian Land Surface Scheme (CLASS). Amongst the numerous improvements this latest version entails, CLASS can now better represent hydrological controls on soil moisture with the addition of surface runoff, subsurface flow, and groundwater recharge parameterizations. Furthermore, CLASS will be coupled to the WATROUTE model to simulate baseflow and allow for channel and lake routing. Lake evaporation is modeled via an aerodynamic roughness formulation (based on satellite observed lake surface temperature/lake ice conditions), or modeled explicitly within 1-D thermal lake modules. An initial simulation will focus on the 10 year period 1997-2007 in order to complete analysis in a timely fashion to be of use to the St. Clair River Task Team. This simulation will be analyzed alongside a comparable simulation generated by the GLERL model CHARM in order to assess confidence in the simulated results.

(b) **Climate projections over the next 30 years**

This Great Lakes Regional Climate Modeling System will be used in GCM downscaling experiments of both present and future climate in order to develop some understanding of current Great Lakes water availability and plausible future projections out to about 2040.

**Hindcast and Forecast of Water Balance Components**

In order to evaluate the quality of the simulations generated by the regional climate model, we propose to develop a 5–year (June 2004 - May 2009) daily hindcast of over – lake precipitation and evaporation, as well as basin runoff for the upper Great Lakes, based on Environment Canada’s operational numerical weather prediction and data assimilation systems along with supporting remotely sensed observations. The goal is to produce a high quality, though relatively short, data set of water balance components based on advanced numerical models and all available observational data. Once in place, it will be possible to use the same system to provide experimental ensemble forecasts of the water balance components up to two weeks.

in advance. Furthermore, in order for the forecasts to be more useful for water management, and given the response time of the watersheds (in particular during the spring freshet), a climatology-based procedure will be tested to increase the lead time of the ensemble forecasts from 15 to 30 days. For weeks 3 and 4, instead of forcing the surface model with ensemble weather forecasts, the 30-year reanalysis produced by the regional climate model will be used. This will allow the forecasting system to take advantage of the remaining signal in the initial conditions of the land-surface and hydrological models.

**Participants:**

This project is based on a number of parallel research strands whose activities are based out of Environment Canada's Meteorological Research Division (Dorval), Climate Research Division (Toronto), Hydrometeorological and Arctic Lab (Saskatoon), Water Survey of Canada (Ottawa).

In collaboration with the Hydrometeorological and Arctic Lab, the Meteorological Research Division will be responsible for setting up a coupled hydrometeorological modelling system that will be used to generate the 2004-2009 daily hindcast using a surface data assimilation system as well as provide ensemble forecasts of the water balance components.

Water Survey of Canada will help calibrate the land-surface model, provide the routing model and verify the hindcast and forecasts against observations of snow water equivalent, streamflow and lake levels.

The Climate Research Division will be responsible for providing the regional climate modelling system and analyzing the results of the climate simulations over the past 30 years and next 30 years. In addition, the Climate Research Division will work closely with the OURANOS consortium (Montreal) to analyze their existing suite of ensemble regional climate model simulations over the Great Lakes Region.

**Output of the project:**

This project will provide the best long term climate simulations for the Great Lakes region to date, and experiments will help determine whether natural climate variability, along with known diversions and consumptive use is sufficient to explain lake level variability. Furthermore, the climate predictions for the next 30 years will be useful for evaluating the robustness of regulation rules for the Great Lakes.

The surface data assimilation system and experimental ensemble forecasting system will then provide useful information from which more robust rules can be built. Indeed, it will be possible to provide users analyses and forecasts of each component of the water budget, as well as net basin supply (NBS), from time step of one day to one month. This is particularly important in a period of rapid climate change, as the differences between the monthly forecast of NBS and the average NBS of the past one hundred years will tend to increase even without improvements in the skill of weather and hydrological forecasting systems.

**Deliverables:**

March 2008: First version of the daily hindcast for the period June 2004 - Dec 2007 based on an archive of short-term forecast

March 2009: Second version of the daily hindcast for the period June 2004 - Dec 2008 10 year current climate simulation completed and analyzed First progress report

March 2010: Final version of the daily hindcast (June 2004 - May 2009)
March 2011: Experimental ensemble forecasting system for the Great Lakes
30 year future climate GCM downscaling experiments completed with CRCM

**Time frame:**

Ramp-up: November 2007 - March 2008
Execution: April 2008 - September 2010
Wrap-up: October 2010 - March 2011

**Budget:**

*Human resources per task*

(a) 5-year daily hindcast of water balance components: 1.5 person-year
(b) Experimental ensemble forecasting system: 1.5 person-year
(c) Climate predictions over the past 30 years: 1.5 person-year
(d) Climate predictions over the next 30 years: 1.5 person-year

Total cost of human resources (6 person-years at 80k$/person-year) 480 k$

*Other expenses (O&M)*

Project management and travel expenses ~2 k$/month

*Budget needed per fiscal year*

FY 2007-2008: 10 k$
FY 2008-2009: 185 k$
FY 2009-2010: 185 k$
FY 2010-2011: 185 k$
Total 565 k$

**In-kind contributions:**

This study contributes directly to Environment Canada’s ongoing national Regional Climate Model development environmental prediction programmes. Hence, the financial contribution of the IJC essentially serves to accelerate these programmes and focus the efforts in model development and testing on a specific geographical area that is of interest to the IJC. For this reason, it is estimated that Environment Canada will contribute at least three person-years to the project, an in-kind contribution estimated at 250 k$ over three years, and will provide access to its supercomputing facility, a contribution estimated at 30 k$ over three years.
Annex D

*Analysis of changes in net basin supply components*

*T. B.M.J. Ouarda & O. Seidou*

**Principal investigator (with contact and affiliation):**
Taha B.M.J. Ouarda,
Canada Research Chair on the Estimation of Hydrological Variables,
Hydro-Quebec/NSERC Chair in statistical Hydrology,
INRS-ETE,
490, de la Couronne, Quebec (QC) G1K 9A9, CANADA
Phone: (418) 654 3842
Fax. (418) 654 2600
E-mail: taha_ouarda@ete.inrs.ca

**Methodology**

The objective of the first component of this study is to **analyse changes in net basin supply components and explanatory variables** (evaporation, runoff, inflow, temperature, precipitations, etc.). For this objective we propose to:

- Analyse and access previous NBS stochastic modeling efforts. This includes the recent efforts that dealt with the use of the shifting level model, but also previous efforts such as Chadid et al. (2002) and Fagherazzi et al. (2005). This effort will allow confirming or revising information concerning detected shifts. During this first step, a collaboration will be established with Laura Fagherazzi (Hydro-Québec) with whom the principal investigator is already collaborating under the framework of the Chair in statistical hydrology.

- In addition to the shifting level model, use traditional trend and shift detection tests of hypothesis such as Spearmann’s Rho test (Sprent, 1989), Mann-Kendall test (Ouarda et al., 1999), modified Mann-Kendall test for seasonal data (Hirsch et al., 1982) and the segmentation procedure (Hubert et al., 1989) to analyse changes in the NBS components. All components of the Great Lakes System will be considered, including Lake Ontario supplies.
• Use recent developments in Bayesian changepoint detection (Seidou et al., 2007; Seidou and Ouarda, 2007) to analyse past modifications and attribute them to the known causal factors. This work will be based on corrected data sets, and involves the application of Bayesian procedures to investigate modifications in the parameters of the relationships between key variables, and the attribution of the changes to plausible causal factors (such as dredging or deforestation). The last step involves the estimation of future conditions if they are different from present ones.

The second component of the study deals with the analysis of atmospheric teleconnections. Climate oscillations such as ENSO were shown to affect rainfall and runoff in Canada and the US in several papers. There is clearly room to develop more complex dependence models between climate indices and hydrological variables in the study area and develop non-stationary frequency analysis tools for the region of study [El-Adlouni et al., 2007]. All observed data sets, as well as derived data sets (precipitations, temperature, evaporation, channel flows, etc.) will be analysed. Ice cover information will also be analysed. Analysis of atmospheric teleconnections will lead to better explanation of the fluctuations of precipitations, inflows and lakes levels, and help predict these variables in the future. This activity involves a) identifying the climatic indices that have impacts on key elements of the net basin supply, b) develop a statistical model of the variable of interest conditioned by the climate index c) quantify the benefits of using this dynamical modeling versus a static approach. Several linear and non-linear approaches will be considered including the use of wavelet analysis and neural network models (Lin and Derome, 2002, Lin et al., 2005; Hsieh et al., 2006)

Expected outcomes

The Great Lakes system dynamics may be changing due to both climatic and anthropogenic causes. These changes can represent different responses of streamflows to lake levels because of ongoing sedimentation processes and/or crustal movements, or changes in the net basin supply relationship to precipitation because of changes in land-use. Of course, the relative importance of these factors is presently unknown, and we do not even know with certitude if there are significant ongoing changes. At the end of the activities of the first component, we will be able to answer the
question about whether or not there are ongoing changes in the great lakes system and attribute these changes to some causal factors. Trend in the modification as well as short term predictions of the system state will also be provided. At the end of the activities related to the second component, we anticipate providing the ICJ better models for estimating the key components of the net basin supply. All source codes for the developed methodology will also be provided. One report presenting the details of all the results of the study will be submitted to the IJC.

**Team and Budget**

**a) Employment costs at INRS-ETE/U OF Ottawa**

<table>
<thead>
<tr>
<th>Employee</th>
<th>Title</th>
<th>Annual salary</th>
</tr>
</thead>
<tbody>
<tr>
<td>T. Ouarda</td>
<td>Professor</td>
<td>$100000</td>
</tr>
<tr>
<td>O. Seidou</td>
<td>Assistant Professor</td>
<td>$80000</td>
</tr>
<tr>
<td>C. Chu</td>
<td>Postdoctoral Student</td>
<td>$40000</td>
</tr>
</tbody>
</table>

**b) Budget**

The duration of the project will be 1 year. The budget will be **$750000**. It covers an annual salary for Dr. C. Chu ($400000), 50% of the annual salary of Dr. Annick Doucet ($200000) and a contribution to the salary of professors T. Ouarda and O. Seidou ($75000 each).

**References**


Annex E

Direct Observations of Lake Superior Evaporation

Letter of Intent in Support of the International Joint Commission’s International Upper Great Lakes Study

Peter Blanken, Associate Professor
University of Colorado
Boulder, CO 80309-0260

Chris Spence, Research Scientist
National Water Research Institute
Environment Canada
Saskatoon, SK

1. Why study evaporation from Lake Superior?
Lake Superior has the greatest depth, volume and surface area of the Laurentian Great Lakes, and is arguably the most important of all the Great Lakes. Evaporation is a critical component of a lake’s water balance, and understanding the magnitude and physical controls of evaporative water losses are important for several reasons. Recently, low water levels have had socioeconomic, ecological, and even meteorological impacts (e.g. water quality and quantity, transportation, invasive species, recreation, etc.). Accurate, reliable measurements of lake evaporation are vital to properly understand the water balance of the lake.

2. What is known about evaporation from Lake Superior?
Surprisingly almost nothing; no direct measurements of evaporation have been made from any of the Laurentian Great Lakes. Evaporative water losses are likely large; for example, the long-term (51-yr) calculated water budget indicates a shift in the seasonal pattern of evaporation (Lenters, 2004). Using a water budget approach to calculate evaporation, however, suffers from significant uncertainties since evaporation is solved as the residual and hence accumulates all errors in the other water budget terms.

Understanding the magnitude and controls of lake evaporation is critical information for proper water resource policy decisions (e.g. water quantity and quality, transportation costs, ecology, etc.). To-date, studies on Lake Superior have focused on water quality and ecology (especially exotic species), and some synoptic-scale meteorology (e.g. lake-effect snow; Kristovitch and Spinar, 2005). Examples of such studies on Lake Superior include examining the risk of ballast water disinfectant discharge, and copper mining impacts on lake ecology. Accurate evaporation measurements are required to make an informed decision regarding regulation of Lake Superior outflows.
3. How will we measure lake evaporation?
Lake evaporation is usually estimated as a residual of the long-term (e.g. annual) water budget (e.g. Lenters, 2004), or from buoy-based meteorological data (e.g. Laird and Kristovich, 2002; Redmond, 2007). The former approach suffers from the daunting and uncertain task of determining lake-wide precipitation, run-off, and run-in estimates; the latter approach suffers from the need to first parameterize the equations which requires independent evaporation measurements to begin with, and the failure to resolve high-frequency turbulent events which can be responsible for up to 65% of the total evaporation (Blanken et al., 2003).

Due to importance of making accurate measurements of lake evaporation, and the uncertainties described above for the traditional methods, we propose to directly measure evaporation using the eddy covariance method. This method, based on solid and tested theory, is essentially based on the degree of covariance between high-frequency (e.g. 10 Hz) measurements of vertical wind and water vapor density. Blanken has successfully used this method to make long-term (e.g. 5 years) continuous (e.g. 30-min) evaporation measurements over a variety of challenging surfaces including boreal forests, wetlands, prairie grasslands, and alpine and arctic tundra. Blanken and Spence were the first to successfully measure lake evaporation from Great Slave Lake, which is similar in size and volume to Lake Superior, yet located in a region with a much harsher environment with much greater logistical complications and costs than Lake Superior. After a nearly 6-year-long observation period, some of the highlights from our results were that evaporation from Great Slave Lake; increased during strong El Niño events (Blanken et al., 2000); was enhanced by the mixing of warm, dry air from aloft (Blanken et al., 2003), and had a fractal nature in terms of the time scale (Blanken et al., 2007). Numerous other publications have resulted from our initial research on Great Slave Lake (cited below), and we are presently analyzing eddy covariance evaporation data we collected over Great Bear Lake. We have the necessary experience and expertise to deploy the required instruments, analyze and achieve the data, and produce products (including publications).

4. Where will we measure evaporation?
An ideal site to located the instruments is Stannard Rock Light (47.1834 N; 87.225 W), located 24 miles southeast of Manitou Island; 45 miles north of Marquette, and owned by the US Coast Guard. Stannard Rock is located far from the shore and is 35-m tall, providing excellent fetch and security. In addition, Stannard Rock is National Data Buoy Center Site (Station STM4) providing current and historic (since 1984) meteorological data. We will use these data, along with data provided from the NOAA buoy network (4 sites), to extrapolate our evaporation measurements in space and time using parameters developed through simultaneous meteorological and evaporation measurements.

5. What will it cost to measure evaporation?
The preliminary budget provided below (Table 1) lists costs including instruments and transportation to Stannard Rock for a summer through late-fall field campaign (e.g. June-October, and longer if feasible). We anticipate several opportunities for cost sharing and collaboration with the US Coast Guard and NOAA for site visits and data telemetry. Also, in-kind support may be available through the Blanken and Spence’s existing instrumentation. The use of the Stannard Rock lighthouse would greatly reduce costs. The exact dates of the field program and budget are pending discussion of the letter of intent.
Table 1. Estimated costs associated with direct evaporation measurements from Lake Superior.

<table>
<thead>
<tr>
<th>Item</th>
<th>Estimated Cost (US Dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eddy Covariance Instruments (sonic anemometer, gas analyzer, data logger)</td>
<td>30,000</td>
</tr>
<tr>
<td>Communication Radio and antennas</td>
<td>5,000</td>
</tr>
<tr>
<td>Mounting hardware (3-m mast, hardware)</td>
<td>1,000</td>
</tr>
<tr>
<td>Travel to Site from Marquette, MI (4 trips @ $500 from a local charter company)</td>
<td>2,000</td>
</tr>
<tr>
<td>Travel from PI’s to Marquette (4 trips @ $500 airfare)</td>
<td>2,000</td>
</tr>
<tr>
<td>PI’s per diem (food, lodging @ 100/day x 10 days)</td>
<td>2,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>42,000</strong></td>
</tr>
</tbody>
</table>

6. What are the qualifications of the investigators?
This study involves both a US (Blanken: University of Colorado) and Canadian institutions (Spence: Environment Canada), so representation from both countries as well as higher education and government are presented. The investigators were the first and to-date only individuals to design and install eddy covariance instruments on a large lake very similar to Lake Superior (Great Slave Lake). They overcame significant logistical challenges to successfully make these measurements. The success and quality of their measurements is evident from the several publication cited below in the references section (indicated by an asterisk).

7. References


National Data Buoy Center – Stannard Rock Station STDM4
http://www.ndbc.noaa.gov/station_page.php?station=stdm4


Annex F

Linking Climate Scenarios and Teleconnections to Great Lakes Ice, Precipitation, and Water Levels
Linking Climate Scenarios and Teleconnection to Great Lakes Ice, Precipitation, and Water Levels

Principal Investigator: Jia Wang

NOAA Great Lakes Environmental Research Lab (GLERL)
2205 Commonwealth Blvd
Ann Arbor, MI 48105
734-741-2281 - Voice
734-741-2055 - FAX
Email: Jia.Wang@noaa.gov
http://www.glerl.noaa.gov

Arctic Modeling Group:
http://www.frontier.iarc.uaf.edu/~jwang/amg/main.html

Researcher (postdoc): Xuezhi Bai, CILER, UoMich

Collaborators: Carlo DeMarchi (UoMich, CILER), Brent Lofgren, Cynthia Sellinger, Ray Assel, and George Leshkevich (GLERL)

A supplemental proposal submitted to:

International Joint Commission’s International Upper Great Lakes Study (IUGLS)

In line with the major project “Comparative Analysis of Net Basin Supply Components and Climate Change Impact on the Upper Great Lakes” by Drs. DeMarchi and Lofgren

Start date: May 1, 2008    End date: August 30, 2010

Fund Requested: Year 1: $30,344,    Year 2: $37,630,    Year 3: $38,100

Total Fund Requested: $106,074

Executive Summary:
We will use conventional statistical methods to analyze the NCEP/NCAR reanalysis (1948-present) and climate GCM products (IPCC AR4), along with historical sea ice observations including recent satellite measurements and gage runoff to examine the statistical relationship between lake ice cover, water level and climate patterns in both spatial and temporal spaces. First, the empirical orthogonal function (EOF) analysis will be applied to sea-level pressure (SLP), surface air temperature (SAT), surface precipitation, and 700 hPa geopotential height fields to reveal the Arctic Oscillation/North Atlantic Oscillation (AO/NAO; first leading mode of Wang and Ikeda 2000) and Pacific-North America (PNA) pattern (second mode). The time series of these two modes can be used to conduct linear regression of sea ice cover and water level. The composite analyses of lake ice and water level will be conducted based on the indices. Then the difference between the +AO/NAO and -AO/NAO phases will be tested using a Student t-test. A similar ice composite analysis will be applied to the +PNA and -PNA phases. Furthermore, a linear regression of lake ice and water level will be applied to SLP, SAT, precipitation, and 700 hPa height fields to map the spatial correlation. Generalized relationships between lake ice cover, water level and atmospheric circulation patterns will be revealed.

The projections of future lake ice cover and precipitation along with SAT, SLP, and 700 hPa height will be conducted using the IPCC AR4 climate scenarios in 2045-2055 and 2090-2100. (Note that “CHARM was proposed to run for the time period 1980-1999 and for a 20-year period in the future appropriate for comparison with AHPS and CRCM run”, the exact time in the future will be decided in a workshop). The same statistical analyses will be applied to the IPCC AR4 model outputs to select the “best” models using the criterion that the AO/NAO and PNA must be reproduced, compared to the NCEP/NCAR reanalysis. For example, a projected warming (southward-migration) climate scenario will shorten lake ice season, which enhances evaporation and leads to a drop in lake water level, and prolongs ecosystem growth season, resulting in the long-term adaptation of upper trophic-level ecosystems.

**Scientific Rationale:**

**Summary of Previous Climate Research Results:** Correlations between average winter 700 mb heights at grid points in the northern hemisphere and annual maximum ice extent provided evidence of ice cover teleconnections (Assel and Rodionov, 1998). Teleconnections were further investigated using Classification and Regression Trees (CART) methodology (Rodionov and Assel 1999; Rodionov and Assel, 2000; Rodionov et al. 2001). In general warm winters and below average ice covers were associated with zonal (west - east) atmospheric circulation, whereas cold winters and above-average ice covers were associated with a meridional (north - south) circulation. Combinations of threshold values (both positive and negative) of the Polar/Eurasian Index, the Pacific/North American index (PNA), and the Tropical Northern Hemisphere (TNH) index accounted for much of the inter-annual variation of winter severity, whereas threshold values of the Multivariate ENSO index and the TNH index were found to be useful in modeling Great Lakes annual maximum ice cover variations. The positive PNA index was found to have a nonlinear relationship with Great Lakes winter severity and ice cover (Rodionov and Assel 2001). Two types of atmospheric circulation over North America are associated with a high positive
Pacific/North American (PNA) index. The first type is the true PNA pattern (amplified ridge-trough system). The second type, which is associated with strong warm El Niño and Southern Oscillation (ENSO) events, is characterized by a flattening of the Polar jet stream and southward shift of the subtropical jet. These nonlinear teleconnections with winter severity and annual maximum ice cover make their use in models and forecasts of ice cover (winter severity) a much greater challenge. In a subsequent study of the nonlinear effects of ENSO and the Pacific Decadal Oscillation (PDO) on winter severity the PDO is found to modulate the effect of the ENSO on a Great Lakes Winter Severity Index (WSI) (Rodionov and Assel, 2003). The correlation between ENSO and the WSI is weak (-.13) during the cold PDO phase and strong (.70) during the warm PDO phase. During the warm phase PDO without a strong ENSO, winters are colder. This occurred in the late 1970s and early 1980s and was responsible for the high ice cover regime during those years.

An analysis was made to develop long-range (30-day) prediction models of ice cover on Beginning Of Month (BOM) date for the Great Lakes (Assel et al. 2004). Lake-averaged ice covers were calculated for each Great Lake for BOM dates in January, February, March, and April for winters 1973-2002 and statistics for these data were analyzed (average, median, maximum, minimum, standard deviation). Predictor variable data sets were assembled and four types of statistical models were developed for lake averaged BOM ice concentration on each Great Lake: 1) the climatological model, 2) the anomaly propagation model, 3) the observational linear regression model, and 4) the Perfect AFDD linear regression model. Predictor variables included Freezing Degree Day (FDD) accumulations and indices of atmospheric circulation. It was also shown that parameters output from GLERL’s lake evaporation model also have high correlations with BOM lake-averaged ice cover. The Perfect AFDD model has the highest overall forecast skill but it requires an accurate 30-day air temperature forecast.

The Generalization of Impacts of Multiple Atmospheric Patterns on the GL:
The Great Lakes ice severity conditions are determined by surface air temperature (SAT), water temperature, heat flux, and water heat storage that is directly proportional to water depth. These factors are associated with global (hemispheric) and regional climate patterns, such as the Arctic Oscillation (AO) or the North Atlantic Oscillation (NAO), and Pacific-North America (PNA) pattern. Note that the PDO is thought to be a phenomenon similar to PNA, although the definition differs from PNA. This indicates PDO may not be independent of PNA. Similarly, the TNH pattern and the East Atlantic (EA) pattern (Rodionov and Assel 2000) may not be independent of the AO/NAO. Nevertheless, the Great Lakes are located at the edge of the Icelandic Low, far away from the action center (see Fig. 1). Thus, although being influenced by the Icelandic Low whose intensity is associated with AO/NAO (+/-AO means a stronger/weaker Icelandic Low), ice cover may not have a statistically significant relationship with AO/NAO due to the remote distance of the Great Lakes from the center of the Icelandic Low.
Figure 1. The AO/NAO pattern during its positive phase in terms of sea-level pressure (SLP) anomaly. L (Icelandic Low) is intensified and H (Azores High) is also intensified, and vice versa during the negative AO/NAO phase. The intensified Icelandic Low associated with AO/NAO+ advects warm, moist Atlantic air to the European sector, and at the same time brings down dry, cold Arctic air to eastern Canada, including Hudson Bay and the Great Lakes. Nevertheless, the Great Lakes are far away from the Icelandic Low, which is hypothesized to be marginally statistically significant.

A similar doubt/hypothesis is also applied to the PNA pattern (see Fig. 2). Based on previous research (Wang et al. 1994; Mysak et al. 1996), the PNA pattern may have a marginally significant impact on ice cover in the Great Lakes, because the Great Lakes are located between the Alberta High and the SE-US Low. During the +PNA (i.e., EL Nino), the Alberta High (anticyclonic) advects cold, dry Arctic air to the Great Lakes region (in particular, the upper lakes), while the SE-US Low transports warm, moist Atlantic (Gulf Stream) air to the Great Lakes (in particular, the lower lakes). These two air masses converge in the Great Lakes region, producing above-normal precipitation. In contrast, during the –PNA (La Niña), the signs of the centers in Figure 2 are reversed, indicating that the Great Lakes region will experience a warm, dry season. Thus, we propose to conduct climate research to test the above hypotheses. If a statistically significant linkage between ice conditions and one or more climate patterns can be verified, then a generalized statistical hindcast model can be developed to predict ice conditions based on climate pattern indices (Wang et al. 2005). Otherwise, we have to 1) study lake ice cover and its linkage to the atmospheric circulation patterns on a case-to-case and/or an extreme event basis, and 2) rely heavily on numerical ice model forecasts.
Figure 2. The positive PNA pattern in 500 hPa height anomaly. Red indicates a positive (anticyclonic) anomaly, blue indicates a negative (cyclonic) anomaly, and vice versa during the negative PNA pattern. During the El Nino (+PNA) event, the intensified low center in the southeastern US would advect warm, moist Atlantic air to the northeastern US including the Great Lakes region, while the Alberta High brings down dry, cold Arctic air to eastern Canada, including Hudson Bay and the Great Lakes. These two different air masses converge in the Great Lakes area, causing heavy precipitation (snow) and winter storms in the northeastern US. Nevertheless, during the La Niño (-PNA) event, an opposite scenario occurs, i.e., the Great Lakes area would have less precipitation. The Great Lakes are located between these two action centers, which is hypothesized to be a statistically significant linkage between lake ice and PNA pattern.

**Hypothesis:**
Lake ice cover and precipitation in the Great Lakes region may not be statistically significantly related to individual climate teleconnection pattern such as AO/NAO or PNA. But the combination of AO/NAO and PNA should have significant impacts on the Great Lakes ice, precipitation, and water levels.

**Proposed Work (Approach)**
Our overall approach is to conduct empirical orthogonal function (EOF) analysis of climate datasets to derive the AO/NAO and PNA patterns and indices. Then, the cross composite analyses will be performed to determine significant responses of lake ice, runoff, and water level to the following four climate states using the Student t-test (Wang et al. 1994; Watanabe et al. 2006; Wu et al. 2006):
<table>
<thead>
<tr>
<th>Climate States</th>
<th>+AO/NAO</th>
<th>-AO/NAO</th>
</tr>
</thead>
<tbody>
<tr>
<td>+PNA (El Niño)</td>
<td>I) Extreme cold, wet, high water level (significant)</td>
<td>II) Not significant to marginally</td>
</tr>
<tr>
<td>-PNA (La Niña)</td>
<td>III) Not significant to marginally</td>
<td>IV) Extreme warm, dry, low water level (significant)</td>
</tr>
</tbody>
</table>

These climate states are characterized by the following forcing: SLP, SAT, atmospheric circulation (i.e., 700 hPa height), surface wind velocity/direction, and precipitation. Lag correlations/regressions will be performed between lake ice, runoff, and water levels and atmospheric forcing fields.

**FY2007-08: May-August 2008**
We will conduct statistical analyses of both ice and atmospheric data. We will conduct the lake ice analysis in all five lakes, including in situ observations and satellite measurements for ice-covered area, EOF and linear regression analyses between the atmospheric (NCEP/NCAR) reanalysis data and ice cover. Based on the indices derived, the years will fall into one of four climate states. Then the cross composite analyses will be performed first for SAT, SLP, precipitation, and 700 hPa height, and then for lake ice, water level, and/or runoff.

We also plan to measure ice thickness in Lake Erie using a USCG helicopter each year in February (ice max period) and in Lake Superior using a USCG icebreaker (Leshkevich and Wang).

**FY2008-09: September 2008-August 2009**
We will conduct climate scenarios of selective years of +/-AO/NAO and +/-PNA, and the simultaneous extremes such as the winters of 1972/73, 82/83, and 91/92 (State I) during which +NAO and ENSO (+PNA) occurred at the same time (Mysak et al. 1996). Similarly, we will focus on the climate State IV.

We will analyze IPCC AR4 model output for the Great Lakes area for the 20th century. EOF and linear regression analyses between atmospheric forcing and ice cover will be conducted for the 20th century to examine the possible relationship to lake ice, water level, and precipitation, and the models’ hindcast capability.

**FY2009-10: September 2009-August 2010**
We will analyze IPCC AR4 model output for the Great Lakes area for the 21st century. Similarities and differences of the climate patterns between the past and this centuries will be identified. Using IPCC model output as forcing, we will project Great Lakes ice cover, precipitation, and water level for periods 2050 and 2010. Some new findings will be obtained.

**Government/societal Relevance:** Knowledge of the lake ice dynamics and
thermodynamics in the Great Lakes is important not only to winter navigation, recreation safety, and rescue efforts, but also to predict lake circulation, lake water level variability, and environmental preconditioning for phytoplankton and zooplankton blooms.

**Relevance to Ecosystem Forecasting:** The results from this project will aid this effort by providing knowledge of the important processes in lake ice affecting lake circulation and ecosystems in the lakes.

16. **Timeline:**
Three years.

17. **Budget and justification:**
The budget includes
- Salary/benefits+overhead (~50%): $21,000/$10,500 per year (~5 months)
- Scientific travel to meetings: $3,000 (Bai; $3000/each)
- Administrative (PI meeting) travel: $1,000 (Wang)
- Supplies: $600/year
- Computer equipment: $400/year

**Total Budget Requested:** ~$38,000/year

We request 4, 5, and 5 months of salary for Bai’s years 1, 2, and 3, respectively, with 3% infliction increase. Wang contributes 1 month each year to the project at no cost. Other budgets are directly seen above.

**References:**


