Final Report:

Rationalizing the Decline in Lake Michigan-Huron Water Levels Using the Coordinated Great Lakes Routing & Regulation Model

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Table of Contents

1 Executive Summary

The specific behaviour of the Great Lakes investigated here is the progressive decline or drop in head difference between Lakes Michigan-Huron and Lake Erie. Based on the measured annual average lake levels (as calculated from the coordinated monthly average lake levels), there has been a drop of 0.51 m in this head difference between 1994 and 2007. A working assumption in this report is that post-1977 changes in the St. Clair River channel conveyance as well as the natural variability of water supplies to each lake, as measured through Net Basin Supply (NBS), both contribute to this 0.51 m drop in head difference. Various analyses were conducted to try and determine how much each factor independently contributed to this drop in head difference.

The Coordinated Great Lakes Routing and Regulation Model (CGLRRM) was utilized to simulate lake levels (and thus the drop in head difference) in a suite of comparative modelling experiments. The study was focused on simulating lake levels for Lake Erie, Lake St. Clair and Lakes Michigan-Huron. The first steps in the study were focused on building a robust and credible deterministic model of the Great Lakes system as follows:

1. Show that CGLRRM, based on component NBS, can replicate past lake levels.
2. Demonstrate that model predictions generate a head difference over time that tracks the observed head difference between Lake Michigan-Huron and Lake Erie.
3. Repeat 1. and 2. with different open water lake-to-lake stage-fall-discharge equations for St. Clair River flow for the 1963-1977 period and the 1996-2005 period such that two different conveyance regimes on the St. Clair were represented. Note that the equation for the 1996-2005 period was developed by David Fay of Environment Canada to specifically represent the current conveyance regime and thus derived on the basis of recent St. Clair River flow data for 1996-2006.

The second step was focused on various deterministic modelling runs that varied one model input factor at a time and then compare the simulated drop in head differences. This required the definition of various metrics that quantify the drop in head difference over time and the factor focused on was the different equations for St. Clair River flow (e.g. turning on and off the conveyance change). Various scenarios were also simulated with CGLRRM to demonstrate the potential impacts of various factors and more closely analyze the long term impacts of conveyance change on Lake Michigan-Huron.

The third step was focused on assessing the relative contribution of both climate (e.g. NBS) era change and conveyance change from a stochastic perspective that considers alternative sequences of NBS time series. Alternative sequences of NBS were sampled using a moving blocks bootstrap approach (pg. 101, Efron and Tibshirani, 1993) and thus functioned to maintain the spatial correlation of NBSs across all the lakes. Additional metrics for quantifying the drop in head difference over time were developed. The modelling experiments in this step involved isolating the impact of the 1996-2005 component NBS data and varying the equation for St. Clair River flow.

CGLRRM simulation results reasonably approximated the observed past lake level behaviour. More specifically:

1a. CGLRRM, based on component NBS, can reasonably replicate 1963-1977 lake levels (and head difference behaviour) with an open water lake-to-lake stage-fall equation developed by Fay and Noorbakhsh (2004) for the 1963-1999 period.
1b. CGLRRM, based on component NBS, can reasonably replicate 1996-2005 lake levels (and drop in head difference) with a new open water lake-to-lake stage-fall equation developed for the 1996-2006 period.
1c. The notable lake level prediction errors for the 2001-2005 period for Lake Michigan-Huron cannot solely be explained by an error in the assumed lake-to-lake stage-fall equation.

Deterministic modelling scenario analyses yielded the following findings:

2a. The post-1977 conveyance change on the St. Clair River was estimated to cause between 24% and 31% of three different change in head difference metrics considered. The metrics quantify the change in head difference for various periods and measures from 1996 to 2005. Other factors were attributed to be the cause of 69% to 76% of the metrics.
2b. A steady state analysis showed that with all flow inputs in the model set to their 1948-2005 average values, post-1977 conveyance change was estimated to decrease the steady-state Lake Michigan-Erie head difference by 9 cm. Compare this to the measured drop in head difference of 51 cm (1994 to 2007).
2c. In direct contrast to 2b, a similar type of steady state analysis showed an 18 cm drop in head difference could be completely attributed to observed shifts in average component NBS data. For example, relative to the average component NBS data for the 1963-1995 period, the average component NBS data for the 1996-2005 period decreased by 0.12 m/yr for Lake Michigan- Huron and only decreased by 0.03 m/yr for Lake Erie.
2d. The Great Lakes system response time to a one-time conveyance change of the St. Clair River was explicitly shown to be finite in that such a change will not cause continual loss of water from Lake Michigan-Huron and thus Lake Michigan-Huron levels will not continue to decrease through time. Furthermore, it was shown that so long as the assumed one-time change in conveyance occurred on or before 1996, the actual date of conveyance change has no impact after 2003 on the cumulative volume of water lost from Lake Michigan-Huron due to conveyance change.

The stochastic modelling analyses yielded the following findings:

3a. The system behaviour resulting from the actual 1996-2005 NBSs was very unique or extreme in comparison with the distribution of possible 10-yr NBS sequences sampled from the 1963-1995 period (1000 samples).
3b. Multiple extreme but plausible 10-yr NBS sequences were used to show that conveyance change on the St. Clair River controls 13% to 22% on average, to a maximum of 34% of the drop in head difference.

Considering all the findings, the post-1977 conveyance change on the St. Clair River was estimated to cause no more than 1/3 of the drop in head difference for the 1996-2005 period. Other factors (such as climate) control the substantial majority of the drop in head difference that was observed for the 1996-2005 period.

2 Introduction

The levels of the upper Great Lakes have been in a general decline for more than 10 years. Of great concern is the cause of the progressive decline in head difference between Lake Michigan-Huron and Lake Erie. Based on the measured annual average lake levels (as calculated from the coordinated monthly average lake levels), there has been a drop of 0.51 m in this head difference between 1994 and 2007. This report describes the relative contribution of changes to lake net basin supplies (NBS) and St. Clair River conveyance change in the decline in head difference between Lake Michigan-Huron and Lake Erie. NBS to each lake is the result of precipitation, runoff and evaporation and is thus subject to natural variability over time.

This study utilizes a mathematical simulation model of the upper Great Lakes (from Superior to Lake Erie) in order to assess the relative impacts of NBS and St. Clair River channel conveyance change on the recent behaviour of lake levels. The model used is the Coordinated Great Lakes Routing and Regulation Model (CGLRRM) that was originally developed by the National Oceanographic and Atmospheric Administration's (NOAA's) Great Lakes Environmental Research Laboratory (GLERL), in conjunction with the US Army Corps of Engineers (USACE) and Environment Canada (EC). The origin of CGLRRM was the work of Quinn (1978) and then the work of Cites and Lee (1998). Today, CGLRRM is sanctioned by all relevant agencies from Canada and the US that make up the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data. All references to "coordinated" data imply that the relevant coordinating agencies have agreed that it is the most representative description of the quantity or time series of interest.

The analyses in this report are designed and conducted with the following working assumptions which are generally based on findings to date of the Hydroclimate and Hydraulic Modelling Technical Work Groups (TWGs):

1) The conveyance of the St. Clair River has changed since the last dredging activities in 1962 and this change has occurred sometime between 1977 and 1995.
2) There are at least two different eras or periods of climate (as represented by the NBS time series) that have occurred across the Great Lakes since 1948 and a change point between two of these eras occurs sometime in the 1977 to 1996 period.

To be consistent with the overall study focus on the post dredging period, the data and modelling conducted in this study analyzes the period after 1962. Various analyses are conducted to best describe the changes in the above two factors and then determine how much each factor independently contributed to the drop in head difference between Lake Michigan-Huron and Lake Erie. For brevity, the remainder of the report will use the phrase "head difference" to refer to the head difference between Lake Michigan-Huron and Lake Erie. Section 3 focuses first on CGLRRM model development to ensure the model simulates the past measured behaviour of the lakes and then performs some deterministic scenario analyses to assess the contribution of the change in channel conveyance to the drop in head difference. In Section 4, the importance of both factors are independently assessed with a series of stochastic modelling experiments where multiple NBS time series are randomly generated using a bootstrap resampling approach.

3 Deterministic Modelling Analyses

CGLRRM is a hydrologic routing model of the Great Lakes and is comprised of continuity equations for each lake, solved using a second-order finite-difference technique (Quinn, 1978) with a numerical time step of one hour. It uses as inputs time series of NBS and any diversions, as well as initial outflows and lake levels, for each lake. The model calculates discharge from each lake from an open-water lake-to-lake stage-fall-discharge equation with regression-based coefficients. In the winter, flows in the connecting channels are naturally reduced by the presence of ice. CGLRRM does not explicitly simulate the ice retardation process and instead this phenomenon must be described by a time series of ice retardation rates (e.g. reduction in connecting channel flow in m^3/s) for each channel. Caldwell (2008) provides a detailed description of the ice retardation approach in CGLRRM and assesses the long term impacts of apparent roughness factors, which include ice retardation on lake levels. Inputs for CGLRRM in all analyses in this report are provided on a monthly time step (except for Niagara River ice retardation rates which were available at a quarter monthly time step). In the deterministic analyses in this section of the report, CGLRRM simulates the levels of Lakes Michigan-Huron (considered to be a single lake for hydraulic purposes), St. Clair and Erie and uses as input the estimated flows of the St. Marys River (coordinated monthly averages). The Chicago and Welland Canal diversions are also inputs to the model (coordinated monthly averages).

Outputs of CGLRRM include monthly mean lake levels, beginning-of-month levels, and monthly flow rates for the connecting channels. In this report, the simulated average monthly lake levels are the focus and thus compared to the measured coordinated monthly average lake levels. Given that other St. Clair River Task Team projects are focused on revising the historical coordinated Detroit and St. Clair river flows, CGLRRM predictions of these flows were not assessed and instead the simulated system outflows from Lake Erie (Welland Canal + Niagara River) are compared to the coordinated Lake Erie outflows.

The deterministic model analyses conducted in this section are focused on developing the most representative CGLRRM model of the midlakes as possible for the recent past (1996-2005). In addition, a second representative CGLRRM model of the 1962-1977 period is also identified. Although these two periods are assumed to exhibit a different conveyance regime, within each of these periods the conveyance of the St. Clair River was assumed to be constant. The representative 1996-2005 CGLRRM model will then form the basis for the deterministic (Section 3.3) and stochastic scenario analyses (Section 4). Demonstrating the model is representative essentially means simulating past time periods to check the model can approximately simulate the observed Lake Michigan-Huron, Lake Erie and Lake St. Clair water levels over time.

The most critical input to CGLRRM is the temporally varying net basin supply (NBS) for each lake. The two methods for estimating NBS are referred to as component and residual. Component NBS is net inflow to a lake and is calculated as NBS = over-lake precipitation + runoff into the lake – over-lake evaporation. Residual NBS is calculated from other components in the water balance equation (connecting channel flows, diversions and changes in storage over the NBS time step) and can be useful because these quantities are more reliably measured in comparison to the quantities in the component NBS estimate. See chapter 6.1.2 in IUGLS (2009) for a more complete description of residual and component NBS estimation methods. Because residual NBS estimates are derived from measured lake levels (beginning of month levels), using the model with historical residual NBS values as inputs and then evaluating model predictions against measured lake levels (average monthly or annual lake levels) is not a robust test of model performance. Therefore, this report focuses as much as possible on using component rather than residual NBS values for driving the model.

The focus of this study on the 1996-2005 period is based on a few considerations. Firstly, component NBS data is only available through the end of 2005. Secondly, the quantitative description of the current conveyance regime as described in Section 3.1 is based on a 1996 through 2006 data analysis. These considerations yield a simulation period of 1996-2005. In addition to these two considerations, there appears to be little trend in the head difference from 1963-1995 and as of 1995, the head difference is within a few centimetres of the 1963-1995 average.

3.1 St Clair River lake-to-lake stage-fall-discharge equations

The conveyance of the St. Clair River is represented in CGLRRM by a lake-to-lake stage-fall equation for open-water between Lake Michigan-Huron and Lake St. Clair. Prior to this study, the equation for St. Clair River flow was taken to be Eq. (1) from Fay and Noorbakhsh (2004):

$$Q=82.2((MH+SC)/2-166.98)^{1.87}(MH-SC)^{0.36} \tag{1}$$

where Q is the average monthly St. Clair River flow (m3/s), MH is the average monthly lake-wide average level for Lake Michigan-Huron (m) and SC is the average monthly lake-wide average level for Lake St. Clair (m).

The model is simulated with Eq. (1) along with the alternative component NBS (lake and land precipitation) estimates from the Great Lakes Environmental Research Laboratory (GLERL). Both of these simulated time series are compared to measured (coordinated) average monthly lake levels for the 1963-2005 period in Figure 1. GLERL NBS data is described in Hunter and Croley (1993) and the data used in these analyses are the updates as of Mar. 31, 2009 to component NBS. The lake precipitation derived component NBS is based on the precipitation of near lake rain gauges while land precipitation derived component NBS includes more inland rain gauges. See Hunter and Croley (1993) for further details.

Considering the entire simulation period, Figure 1 shows that lake precipitation derived component NBS is a slightly better predictor of lake levels for all three lakes. As such, all remaining analyses will utilize lake precipitation derived component NBS. Comparing simulated (LakePcp) lake levels to measured levels, it is also clear that between 1963 and 1977 the model predictions are relatively accurate for all three lakes. However, after 1977, the model predictions begin to diverge from the measured lake levels. On Lake Michigan-Huron, this divergence grows with time and is very pronounced in the mid 1990s (average monthly prediction error is 0.28 m between 1994-1997) and even more so after 2002 (average monthly prediction error is 0.31 m between 2003-2005).

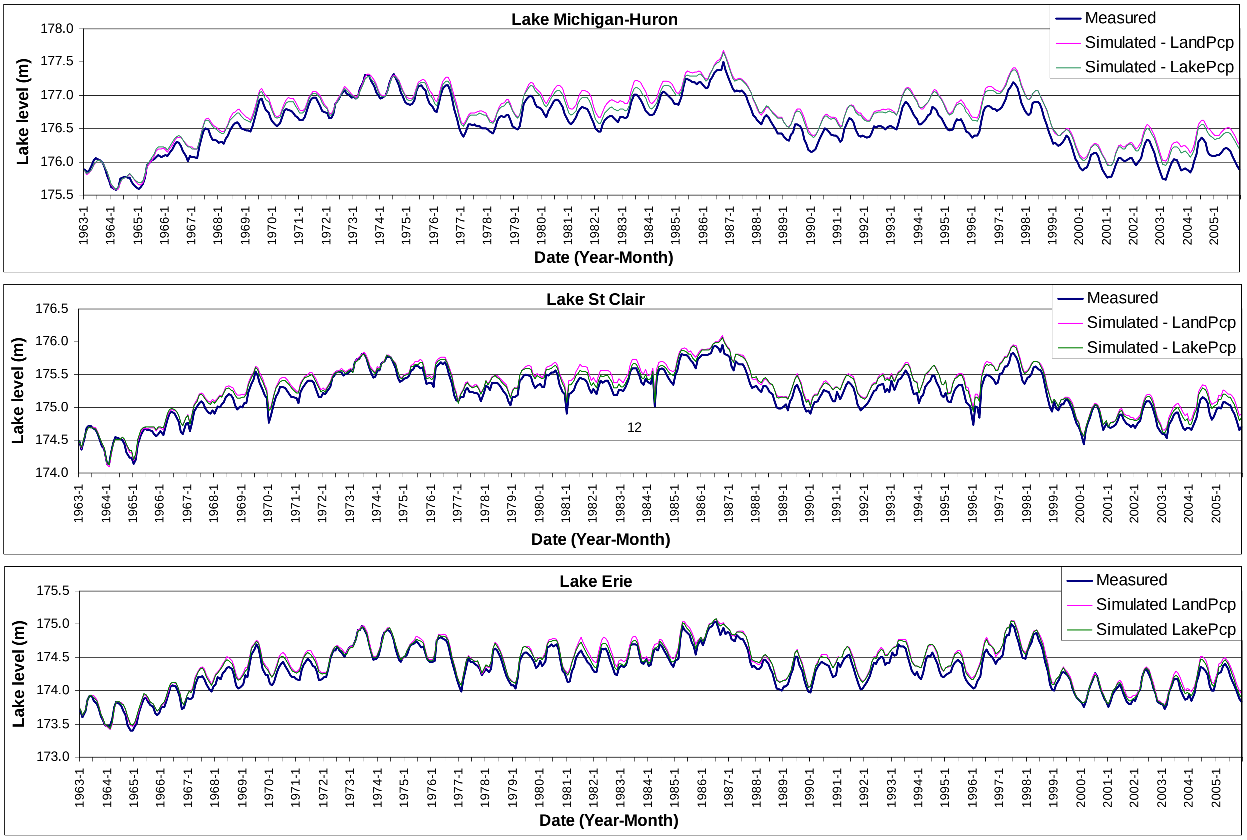

Figure 1. Comparison of measured (coordinated) and simulated average monthly lake levels for the middle Great Lakes from 1960 to 2005 using Equation (1) for St. Clair River flows.

Two potential causes (out of many) for the disagreement between model simulated and measured lake levels are 1) errors in the component NBS estimates and 2) changing St. Clair River channel conveyance over time. If errors in NBS were the main culprit and these errors were present for the entire time period, one would expect model prediction errors to be more prevalent than they are in the 1963-1977 period. Other studies in the St. Clair River TWG are finding that some channel conveyance change has occurred since 1977. Therefore, the CGLRRM improvement efforts in this study recognize a channel conveyance change has likely occurred after 1977 and as such focus on evaluating a revised lake-to-lake stage-fall equation to represent the current conveyance regime in the St. Clair River.

A revised lake-to-lake stage-fall-discharge equation (see Eq. (2) below) relating the flow of the St Clair River to levels of Lakes Michigan-Huron and St. Clair was developed by David Fay of Environment Canada based on recent 1996-2006 Acoustic Doppler Current Profiler (ADCP) flow measurements. This was a multi-step process. First, a set of stage-fall-discharge equations were developed for 8 reaches between gauge locations on the St. Clair River using a dataset of about 230 streamflow and water level measurements made between 1996 and 2006. These 8 stage-fall-discharge equations were then used to produce a set of monthly mean flows for the St. Clair River using monthly mean stages from 1962 to 2007 for the ice-free period (May – November). These monthly mean St. Clair River open-water flow estimates, along with monthly mean lake-wide average levels of Lakes Michigan-Huron and St. Clair, were then used to develop a lake-to-lake stage- discharge equation reflective of the recent conveyance capacity of the St. Clair River.

The assumption in the revised equation development is that for the 1962-2007 period, the relationship between the Michigan-Huron lake level and the level at the upstream river gauges in the set of river equations did not change significantly. The same assumption was made for the relationship between the Lake St. Clair level and the lower river gauges in the equations. Therefore, the revised equation is taken to represent only the 1996-2006 period and is given as follows:

$$Q=1450.92((MH+SC)/2-171)^{0.78472}(MH-SC)^{0.38388} \tag{2}$$

where Q is the average monthly St. Clair River flow (m3/s), MH is the average monthly lake-wide average level for Lake Michigan-Huron (m) and SC is the average monthly lake-wide average level for Lake St. Clair (m). The procedure for developing Equation (2) is described in more detail in Kerslake and Fay (2009).

Equation (2) is derived on the basis of ADCP flow data sampled during the 1996-2006 conveyance regime. As such, it is different than the previous lake-to-lake equation by Fay and Noorbakhsh (2004) fit to data from 1962-1999. In order to focus only on the period for which the equation was derived for, CGLRRM was initialized to measured (coordinated) beginning-of-month (BOM) lake levels from January 1996 and simulates lake levels through the end of 2005 under Eq. (2). Simulated lake levels with Equation (2) are compared to measured lake levels, as well as simulated lake levels with Equation (1), in Figure 2.

Results in Figure 2, like results in Figure 1, show that with Equation (1), CGLRRM does not simulate the measured (coordinated) average monthly Lake Michigan-Huron lake levels very accurately as the prediction error grows with time (after 2000, the model over-predicts lake Michigan-Huron levels by an average of 0.20 m). Simulated results with Equation (2) are a clear improvement in model prediction accuracy over Equation (1). For example, after 2000, the model now only over-predicts lake Michigan-Huron levels by an average of 0.10 m. With Equation (2), the model predictions after 2000 are still slowly diverging from the measured Lake Michigan-Huron lake levels. The largest simulation errors for Lake St. Clair and Lake Erie also are found after 2000. The differences between simulated Lake Michigan-Huron levels and the measured levels are most likely caused by the fact that there are errors and uncertainties in the component NBS estimates as well as the reality that a simplified lake-to-lake stage- equation will never perfectly represent the St. Clair River conveyance regime. Figure 2 also shows that the impacts of varying the lake-to-lake stage- equation for the St. Clair River have very little impact on the levels of Lake St. Clair and Lake Erie.

Rather than checking connecting channel flow prediction accuracy of the St. Clair and Detroit River, the model and measured data were compared against the coordinated estimates of Lake Erie outflow (Welland Canal + Niagara River flow). For both Equation (1) and (2), Figure 3a compares the simulated and measured Lake Erie outflow time series and Figure 3b compares cumulative simulated and measured (coordinated) outflow differences. Considering Equation (1) simulated results, the simulated Lake Erie outflows are much too low in this period as shown by the cumulative difference plot in Figure 3. This is consistent with the significant over-predictions of Lake Michigan-Huron (too much water is retained on Lake Michigan-Huron). Figure 3b demonstrates that changing to Equation (2) greatly reduces the cumulative under-prediction of Lake Erie outflows (by approximately 50%).

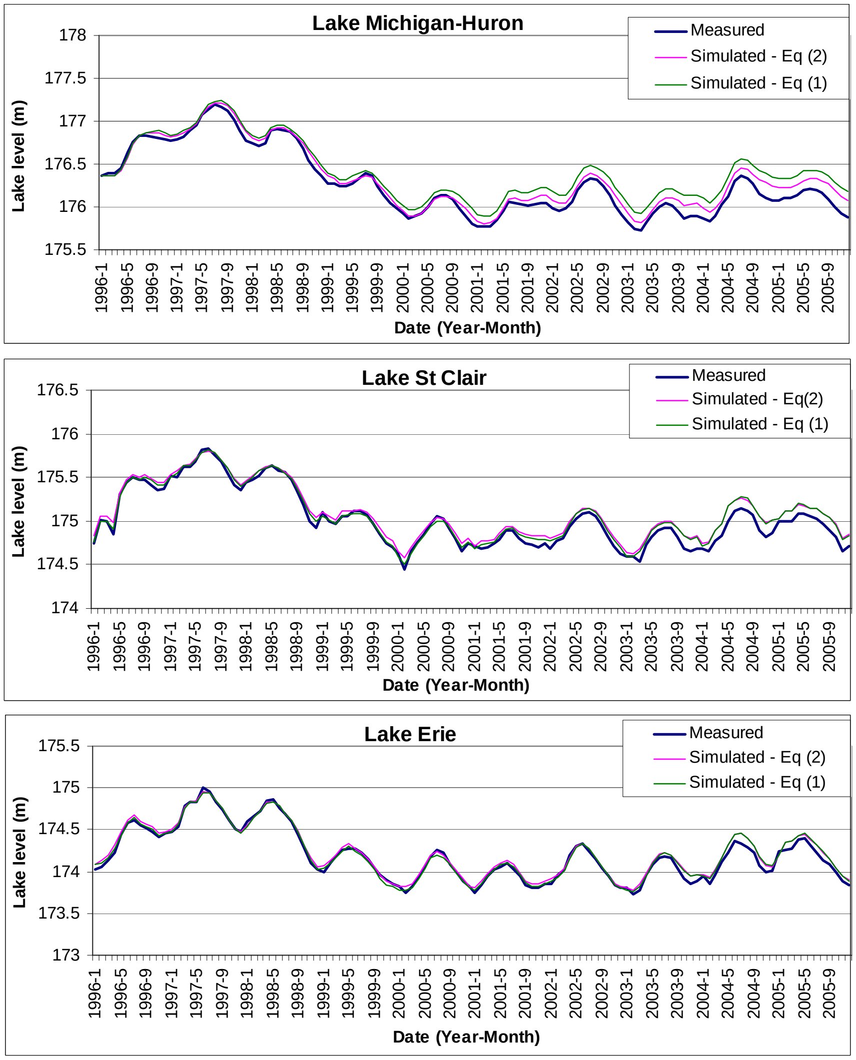

Figure 2. Comparison of measured (coordinated) and simulated average monthly lake levels for the middle Great Lakes from 1996 to 2005 using Equation 2 for St. Clair River flows.

When the simulation errors for the 2001-2005 period in Figure 2 and Figure 3b are both considered, it is apparent that the slowly diverging simulated Lake Michigan-Huron levels (relative to measured data) result from more than just an imperfect lake-to-lake stage-fall-discharge equation. Consider that by the end of 2005, all three lakes are simulated to store too much water (nearly 25 km^3 in total, 23.5 km^3 of which is in Lake Michigan-Huron). Figure 2 shows that the vast majority of this excess water accumulated in the three lakes between 2001-2005. If the only significant cause of Lake Michigan-Huron level over-predictions was that Equation (2) under-estimated the St. Clair River conveyance for the 2001-2005 period, and thus excess water remained in Lake Michigan-Huron, the cumulative volume of water leaving the system (draining from Lake Erie) for the same period should be under-estimated. The relatively flat line from 2001 to 2005 for Equation (2) in Figure 3b shows that this in fact does not occur and instead, the simulated cumulative outflow under-predicts the measured data by only 1 km^3

(compared to nearly 25 km^3 of excess water stored in the three lakes). Therefore, the over-predicted Lake Michigan-Huron levels for the 2001-2005 period cannot be solely attributed to Equation (2) under-estimating the conveyance of the St. Clair River.

Overall, the CGLRRM model with Equation (2) is deemed to replicate measured 1996-2005 lake levels with sufficient accuracy to assume that Equation (2) represents a reasonable approximation of the current conveyance regime on the St. Clair River. It is not clear when the change to this current conveyance regime took place. However, the accuracy of the CGLRRM model predictions with Equation (1) over the 1963-1977 period is sufficient to assume that Equation (1) represents a reasonable approximation of the previous conveyance regime on the St. Clair River. Therefore, the CGLRRM model with Equation (1) or Equation (2) forms the basis for all of the following scenario analyses that are modelled.

The CGLRRM input file for simulating 1996-2005 with Equation (2) is provided in Appendix 1.

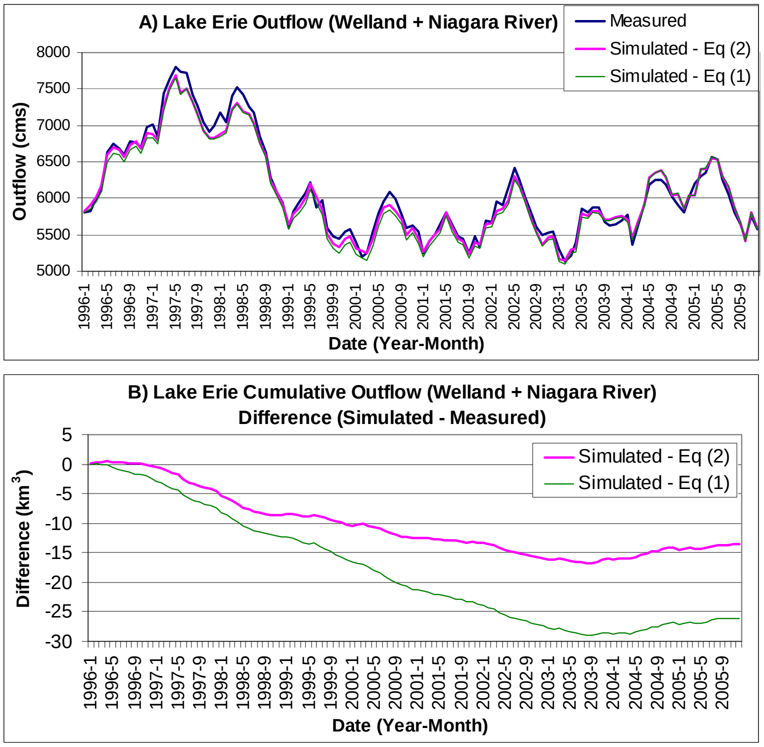

Figure 3. Comparison of measured and simulated Lake Erie outflows from 1996 to 2005 using Equation (2) for St. Clair River flows.

3.2 Metrics for quantifying the drop in head difference between Lake Michigan-Huron and Lake Erie

Prior to comparing the above two CGLRRM models with Equations (1) and (2) and making inferences regarding causes of the change in head difference between Lake Michigan-Huron and Lake Erie, it is necessary to consider the metrics that can be used to describe the change in head difference. Therefore, Figure 4 shows the measured head differences over time for various time steps. Figure 4 also shows the simulated head differences for Equation (1) and (2). A comparison of the accuracy of simulated head differences between Equations (1) and (2) in panels B, C, and D of Figure 4 reiterates the previous finding that Equation (1) does not accurately represent the current conveyance regime of the St. Clair River. More importantly, all four panels of Figure 4 demonstrate that the models assumed to approximate the two conveyance regimes on the St. Clair River also generally approximate the trend through time of the measured change in head differences for the various time steps. The recent (1996-2005) large drop in head difference over time is most apparent when the measured 3-yr moving annual averages are considered (Figure 4D). In fact, the trend downwards of the 3-yr moving annual average continues into 2006 when 2006 and 2007 average annual lake level data are considered (not shown in plot below).

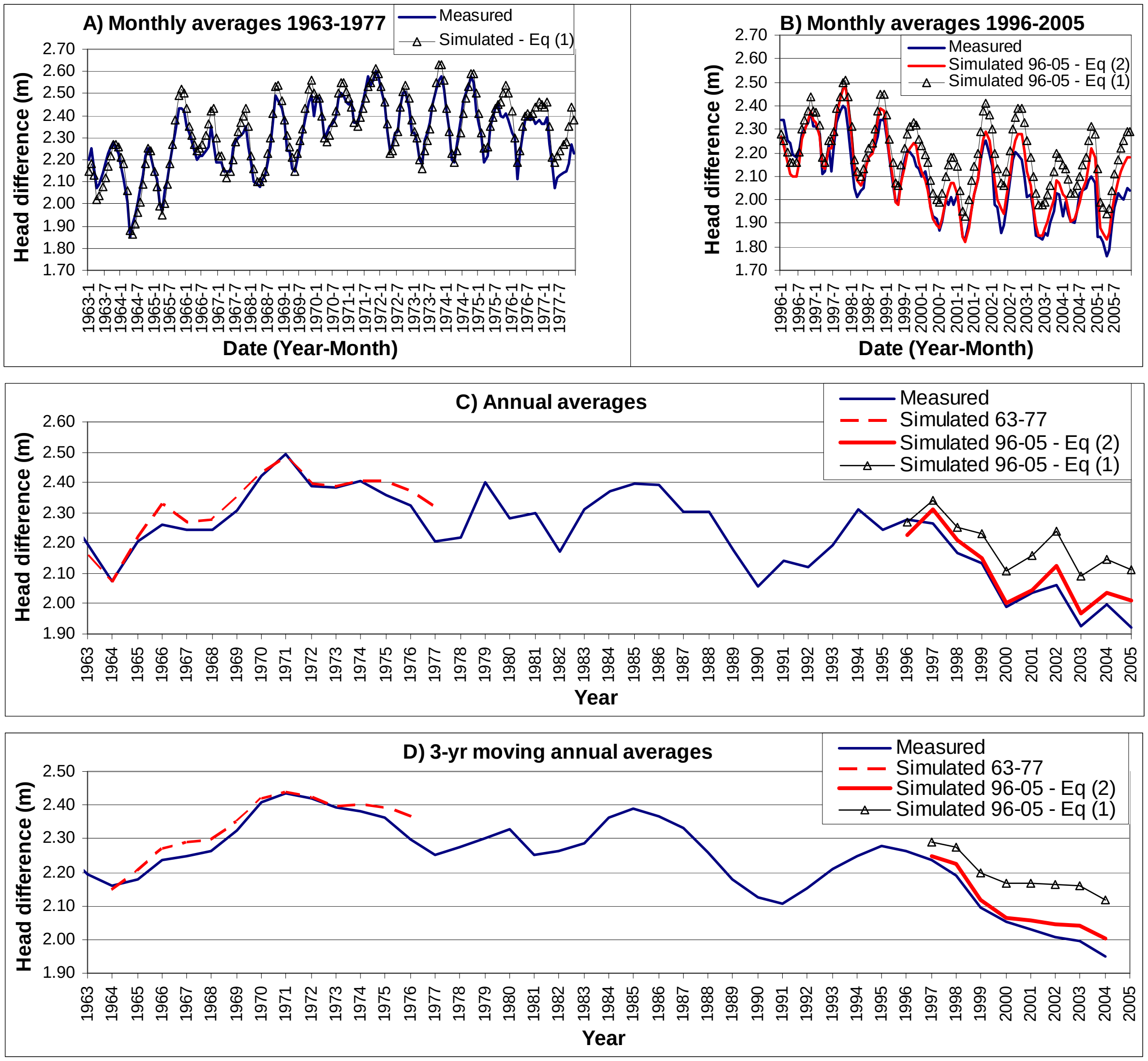

Figure 4. Simulated and measured head difference between Lake Michigan-Huron and Lake Erie for various time steps (monthly average lake levels, annual average lake levels, 3-year moving annual average lake levels). Measured head differences based on coordinated average monthly lake levels. The simulated 63-77 result with Eq. (1) represents pre-conveyance change, while the simulated 96-05 result with Eq. (2) represents post conveyance change.

Note that CGLRRM results are not evaluated between 1977 and 1996 because it is unclear when the change in St. Clair channel conveyance occurred and whether it was a relatively sudden or gradual change. For the purposes of the analyses in this report, determining exactly when the conveyance change occurred is not important. What is important is the accurate description of the two conveyance regimes: 1963-1977 and then 1996-2005.

Table 1 and Table 2 below depict a variety of potential head difference metrics for the measured and simulated lake levels. The numbers in these tables are based directly on the various time series in Figure 4.

Table 1. Listing of potential measured and simulated metrics for assessing change in head difference across different periods based on annual average lake levels.

Period	Change in **Measured** Head Diff. = Initial – Final avg. annual head difference over the period, m	Change in **Simulated** Head Diff. = Initial – Final avg. annual head difference over the period, m
1996-2005	0.36	0.22
1997-2005	0.35	0.30
1994-2007	0.51	NA[a, b]
1963-2007 regression line	0.34	NA[a]
1963-2005 regression line	0.26	NA[a]
1996-2005 regression line	0.35	0.28

a) Current conveyance regime CGLRRM model developed for 1996 through 2006 St. Clair River flow data and as such was not applied before 1996.

b) Component NBS estimates for 2006-2008 not available at the time this report was completed.

Table 1 shows that for the changes in measured head difference of greatest interest to the IJC and Great Lakes stakeholders (e.g. the drop between 1994-2007 of 0.51 m) is not replicated by CGLRRM as the model is not currently simulating this time period. Considering the time period being simulated in the model currently (1996-2005), the model does not accurately simulate the observed 1996-2005 change in head difference (under-predicts by 0.14 m or 39%). This error is in large part due to the under-predicted head difference for 1996 that can be seen in Figure 4C. Instead, if only the 1997-2005 period is considered, the simulated head difference trend closely tracks the measured head difference trend (coefficient of determination or $R^2 = 0.95$) and the simulated change in head difference for the period is only under-predicted by 0.05 m or 14%.

Three regression-based metrics are shown in the last three rows of Table 1 and are utilized here because other projects and documents in the overall IUGLS study have summarized the drop in head difference on the basis of the change in head difference predicted by a linear regression line through a set of head differences over time. For example, the 1963-2007 regression line change in measured head difference is calculated based on a linear regression equation developed using the annual average measured head differences from 1963 to 2007 (head differences calculated from coordinated average monthly lake levels) with the year as the independent variable. The value of 0.34 m in row 4 of Table 1 is then calculated as the regression equation prediction for the year 1963 minus the regression equation prediction for the year 2007. Of the three time periods considered for regression-based metrics in Table 1, only the 1996-2005 regression-based metric can be computed for the CGLRRM simulated head differences over time. The model under-predicts the measured 1996-2005 regression-based metric by 0.07 m (or 21%).

Table 2 shows similar results to Table 1 except it is based on 3-yr moving annual averages. The 3-yr moving average is utilized because it acts to smooth the time series of head differences and thus make the trends more apparent. This is an alternative to taking a regression-based approach for smoothing out the change in head over time. As such, no regression-based metrics are considered for the 3-yr moving average head differences. The model under-predicts the measured 1997-2004 change in head difference in Table 2 by 0.04 m (or 15%).

Table 2. Listing of potential measured and simulated metrics for assessing change in head difference across different periods based on 3-yr moving annual average lake levels.

Period (yr i moving avg is avg of yrs i-1, i, i+1)	Change in **Measured** Head Diff. = Initial – Final avg. head difference over the period, m	Change in **Simulated** Head Diff. = Initial – Final avg. head difference over the period, m
1997-2004	0.29	0.24
1995-2006	0.41	NA[a]

a) Component NBS estimates for 2006-2008 not yet available.

3.2.1 Baseline model metrics for quantifying the drop in head difference between Lake Michigan-Huron and Lake Erie

This section summarizes the set of selected metrics (a subset of the potential metrics listed in Table 1 and Table 2) that will be used as a baseline in which further modelling scenarios and experiments in later sections will be compared to. Establishing baseline simulated metrics are critical to determining the relative contribution of conveyance change and changes in climate (NBS) to the head difference of Lake Michigan-Huron and Lake Erie. By using simulated metrics as a baseline, the impact of each of the above two factors can be isolated. This is because factor impacts can be assessed by comparing model simulations with a factor changed (to generate a new value of the metric) relative to the baseline simulated metric. In contrast, if a measured metric value was selected as a baseline, the difference between model simulations with a factor changed relative to the baseline measured metric would be due to a combination of the factor and model error (i.e. if the model does not exactly simulate the baseline measured metric).

Table 3 below summarizes the metrics selected, their short names that will be used throughout the rest of the report and the corresponding baseline simulated values. Metric selection is largely determined based on the availability of a simulated metric. The metric values in Table 3 are based directly on the various simulated time series in Figure 4. Although the simulated metrics do not perfectly match the measured metrics, the simulated metrics are all within 14%-21% of the measured metrics as discussed in the previous section.

Table 3. Selected baseline simulated metrics that approximate the change in head difference between Lake Michigan-Huron and Lake Erie observed for the 1996-2005 period.

Metric Name	**Period**	**Notes**	**Baseline metric value (head difference) = Initial – Final avg. head difference, m**
$M_{1\ ann}$	1997[a] -2005	Based on annual average head differences	0.30
$M_{2\ reg}$	1996 - 2005	Calculated from linear regression of annual average head difference vs. year	0.28
$M_{3\ 3yr}$	1997 - 2004	Based on 3-yr moving average of annual average head differences	0.24

a) 1997 selected over 1996 as initial year because the difference between simulated $M_{1\ ann}$ is much closer to measured $M_{1\ ann}$.

3.3 Analysis of Conveyance Change Impact on Head Difference

3.3.1 Scenario analysis for 1996-2005 period

This section assesses what the model predicted drop in head difference would be if the conveyance regime for the 1963-1977 period, as described by Eq. (1) for the St Clair River flow, persisted from 1996 through 2005. In other words, the analysis attempts to predict what would have happened if there was no change in St Clair River conveyance (and thus Eq. (1) still applied). Therefore, this analysis simply compares the head differences simulated with Equation (1) and Equation (2) that are shown in Figure 4.

Results comparing the impact of conveyance are presented in Table 4 for each of the three metrics. The change from the baseline simulated change in head differences measures the impact of conveyance change on the St Clair River (as represented by the lake-to-lake stage-fall equation in CGLRRM). The last column in Table 4 shows that conveyance is responsible for between 24-31% of that change. All other factors taken together, such as change in climate and differential glacial isostatic rebound (GIA), have a more controlling influence on this change in head difference.

Table 4. Evaluation of conveyance change impact on the change in head difference using various simulated metrics.

Metric	BASELINE **Simulated change in** head diff. = Initial – Final avg. head difference, m	**Simulated** change in head diff. with Eq. (1) = Initial – Final avg. head difference, m	% of change in head difference due to conveyance change[a] (brackets are % attributed to other factors)
$M_{1\ ann}$	0.30	0.23	24 (76)
$M_{2\ reg}$	0.28	0.19	31 (69)
$M_{3\ 3yr}$	0.24	0.17	30 (70)

a) Attribution % column is calculated with more precision in head differences than appears in previous columns.

The analysis above for attributing relative cause of the drop to the change in head difference was repeated with the only difference being that residual NBS replaced component NBS in the

CGLRRM simulation. With residual NBS, the conveyance change was determined to be responsible for 21-22% of the simulated drop in head difference based on the three baseline metrics. Therefore, findings are consistent with both residual and component NBS.

It is also important to note the direct impact the conveyance change (as simulated in CGLRRM) has on Lake Michigan-Huron levels. On average, Lake Michigan-Huron levels between 1996-2005 would be 7 cm higher if no conveyance change in the St. Clair River had occurred between 1977-1995 (e.g. Equation 1 still accurately described St. Clair River conveyance). The largest impact of conveyance in terms of the annual average Lake Michigan-Huron level, is a difference in 2005 of 11 cm.

3.3.2 Scenario Analysis of Steady-State Lake Levels

The purpose of this steady-state analysis was to evaluate the importance of conveyance independent of any temporal variability in all other CGLRRM model inputs. For example, from the analysis in Section 3.3.1, it is not clear if the impacts of conveyance change would continue to increase beyond 2005. The steady-state analysis is one way to ensure the model evaluates the total or long-term impact of a change in St. Clair River conveyance.

The scenario analysis in Section 3.3.1 was repeated with all model inputs set to constant (steady-state) values starting Jan. 1, 1996. The constant values of CGLRRM inputs (NBS, ice and weed retardation factors, diversions, etc.) were set at the average monthly values of the 1948-2005 period and the model was simulated for 50 years, again starting with Jan 1, 1996 lake levels. Results are presented in Table 5 below. First, it is clear that approximate steady-state conditions were reached after 10 yrs. After 15 years, lake levels reach steady-state to two decimal places of precision (model output files only written with two decimal places of precision) as they are equal to the simulated lake levels after 50 years. At steady-state, a comparison of the head differences between using Eq. (1), the old 1963-1977 conveyance regime, and Eq. (2), the new 1996-2006 conveyance regime, shows that the change to the new conveyance regime induced a 9 cm decrease in the head difference. This steady-state change in head difference is only 18% of the 1994-2007 measured drop in head difference (51 cm) between Lakes Michigan-Huron and Erie.

Table 5. Evaluation of conveyance change impact on the steady state head difference between Lake Michigan-Huron (MH) and Lake Erie.

Equation	**Initial lake levels**		**Lake levels after 10 yrs**		**Lake levels after 50 yrs**		
	MH (m)	**Erie (m)**	**MH (m)**	**Erie (m)**	**MH (m)**	**Erie (m)**	**Head difference = MH – Erie, (m)**
Eq. 1, old conv.	176.36	174.06	176.55	174.30	176.56	174.31	2.25
Eq. 2, new conv.	176.36	174.06	176.46	174.30	176.47[a]	174.31	2.16
						Eq. 2 - Eq. 1:	0.09

a) Lake Michigan-Huron reached 176.47 m after 14 years.

Another reason to carry out the steady-state analysis is to look at how much water is lost from Lake Michigan-Huron as a result of conveyance change. An increase in St. Clair River conveyance causes water to drain at an increased rate from Lake Michigan-Huron. However, this increased flow of water is not permanent. The results of the steady state model demonstrate this explicitly.

For example, the steady state net inflows to Lake Michigan-Huron in both steady-state simulations (with and without conveyance change) summarized in Table 5 are the same and are equal to all inflows (St. Marys + NBS = 5570 m^3/s) minus all outflows before the St. Clair River (Chicago diversion = 91 m^3/s). All net inflows thus equal 5479 m^3/s. Simulation results for no conveyance change with Eq (1) show the system is at steady-state after about 14 years and the steady-state St. Clair River flow is also 5479 m^3/s. Of course, to reach steady-state levels on Lake Michigan-Huron, the net lake inflows must equal the lake outflow into the St. Clair River. After about 14 years, simulation results with a conveyance change using Eq (2) show the exact same result: net lake inflows = the lake outflow into the St. Clair River = 5479 m^3/s. This very clearly demonstrates that with steady-state inputs, if conveyance is not continually increasing on the St. Clair River, water is not continually lost from the lake. Instead, a one-time conveyance change causes temporary increases in outflows for a period of only 14 years. Although it is not quite as straightforward to demonstrate, the concept is exactly the same for non-steady-state inputs such that the full impacts of a one-time conveyance change will eventually be realized and at that point Lake Michigan-Huron will no longer be losing water due to conveyance change.

3.3.3 Scenario Analysis to evaluate time to full impacts of conveyance change

The purpose of this analysis is to evaluate the length of time required for the full impacts of a one-time conveyance change to be realized under the true dynamic, rather than steady-state, set of CGLRRM inputs taken to best represent the historical conditions across the Upper Great Lakes. The full impacts of any conveyance change are those that result in the long term. Impacts in this analysis are measured in terms of simulated St. Clair River flows.

Three pairs of model runs were evaluated in this experiment. The first pair of model runs involved simulating lake levels from 1963 to 2005 with Equation (1) to represent no conveyance change and then with Equation (2) to represent conveyance change occurring at the start of 1963. Each model run was initialized to Jan 1, 1963 coordinated lake levels. The second pair of model runs involved simulating lake levels from May 1984 to 2005 with Equation (1) to represent no conveyance change and then with Equation (2) to represent conveyance change occurring at the start of May, 1984. Each model run in this second pairing was initialized to May 1, 1984 coordinated lake levels. The May 1, 1984 date was selected because the date of a major St. Clair River ice jam was April, 1984 and as such represents a potential point in time where a sudden conveyance change did occur. Note however, that the analysis is hypothetical and not meant to suggest that the ice jam was 100% responsible for the change to the current conveyance regime on the St. Clair River. The last pair of model runs involved simulating lake levels from 1996 to 2005 with Equation (1) to represent no conveyance change and then with Equation (2) to represent conveyance change occurring at the start of Jan. 1996. Note that these model runs were already conducted in previous analyses.

For each pair of model runs the cumulative increase in St. Clair River flow (in km^3) due to conveyance change was then computed over the time period simulated. These three cumulative increases over time are shown in Figure 5 and results clearly demonstrate that the date of a one-time conveyance change happening on or before Jan. 1996 has no impact after 2002 on the total volume of water lost from Lake Michigan-Huron. All three pairs of simulations in Figure 5 converge to the same cumulative increase in St. Clair River flow. Analyzing lake levels rather than St. Clair River flows would yield the same findings.

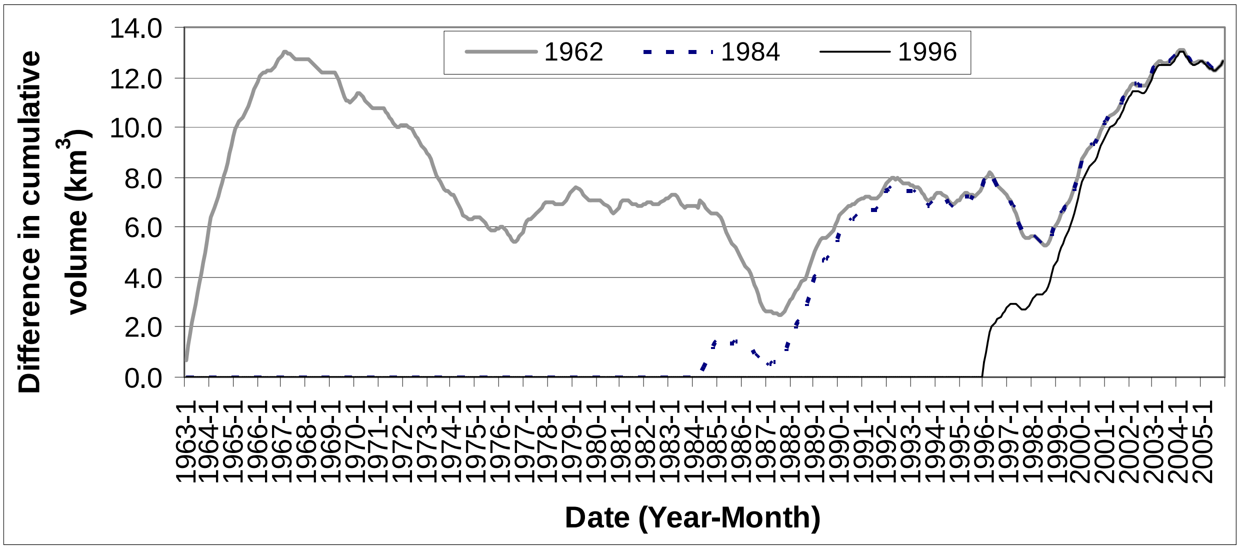

Figure 5. Cumulative increase in simulated St. Clair River flow due to a one-time conveyance change (Equation (2) instead of Equation (1) for flow St. Clair River flows) occurring on different dates.

Overall, the results demonstrate that even in non-steady-state conditions, after some initial period of time passes since the last conveyance change, increasing the length of time since the conveyance change has no impact on the total volume of water lost (increase in St. Clair River flow) due to the conveyance change. Assuming Equation (2) represents the conveyance change, so long as the change occurred on or before 1996, the full impacts of conveyance change on the St. Clair River flows and Lake Michigan-Huron level have been realized by approximately 2003.

3.4 Analysis of Observed NBS Change Impact on the Steady-State Head Difference

The purpose of this analysis is to focus on NBS rather than changing the conveyance regime. One very simple way to delineate two NBS regimes is to assume that there was a change in regimes at the start of the major decline in head difference (see measured data in Figure 4C or Figure 4D) in 1996. Thus, consistent with the previous analyses, the 1996-2005 period is analyzed separately. The 1996-2005 NBS data can then be compared to the 1963 (post-dredging) to 1995 NBS data. Component NBS data are analyzed for each of these periods and compared below in Table 6 where the NBS data are expressed as the average m/yr added to each lake (coordinated lake areas used to convert from m^3/s).

Results in Table 6 show that after 1995, NBS has declined on both lakes but more importantly show that NBS has declined much more quickly on Lake Michigan-Huron than it has for Lake Erie. If these NBS declines reflect the change in relative total supplies of each lake (e.g. Net Total Supplies), then the resulting response of the system would have to be a decrease in the head difference between the lakes since Lake Michigan-Huron depth would be decreasing faster than Lake Erie depths. The magnitude of such a decrease in relation to the observed decrease in head difference since 1996 is not clear. Actual NTS estimates are not considered here because they require connecting channel flow estimates which would confound the analysis by including the system response the St. Clair River conveyance change.

Table 6. Lake Michigan-Huron and Lake Erie component NBS averages for different time periods.

Period	Average Lake Michigan-Huron NBS	Average Lake Erie NBS
A: 1963-1995	0.96 m/yr	0.84 m/yr
B: 1996-2005	0.84 m/yr	0.82 m/yr
Decline in NBS: A – B	0.12 m/yr	0.03[a] m/yr

a) Difference row is calculated with more precision in NBS than appears in upper rows.

3.4.1 Scenario Analysis Comparing Steady-State Lake Levels due to 1963-1995 average NBS and 1996-2005 average NBS

A series of modelling experiments were designed to assess the steady-state response of the lakes to average component NBS values for different time periods independent of channel conveyance change. For these experiments, CGLRRM is simulated with Equation (1) which represents the St. Clair River with no change in conveyance. The first experiment simulated the lake level response to 50 years of steady-state inputs based on the average inputs for the 1963-1995 period (summarized in Table 7). The model was initialized to Jan 1, 1996 as in previous modelling analyses. The resulting simulated steady-state lake levels and head difference are given in Table 8. The second modelling experiment initialized all lake levels to the steady-state levels that resulted from the first experiment and then simulated the lake level response over 50 years of steady-state inputs based on the average inputs for the 1996-2005 period (summarized in Table 7). Simulation results for this second experiment are also given in Table 8.

The results in Table 8 shows the impact that observed changes in relative NBS between Lake Erie and Lake Michigan-Huron can have on the head difference. This change in head difference of 0.18 m should be contrasted with the magnitudes of the various baseline simulated metrics that apply to the 1996-2005 time period and range from 0.24 m to 0.30 m (see Table 3). Conveyance change on the St. Clair River would clearly exacerbate the change in head difference due to relative NBS changes. However, the purpose of this particular analysis is to demonstrate that the actual change in relative component NBS observed for the lakes (along with the corresponding differences in the other inputs in Table 7) is capable of inducing very substantial changes in the head difference without any conveyance change in the St. Clair River.

Table 7. Steady-state CGLRRM inputs for the 1963-1995 and 1996-2005 time periods.

CGLRRM Input	**1963-1995 average (m^3/s)**	**1996-2005 average (m^3/s)**
St. Mary's River flow	2266	2063
Lake Michigan-Huron NBS	3576	3129
Lake St. Clair NBS	161	154
Lake Erie NBS	687	664
St. Clair River Ice & Weed retardation	115	97
Detroit River Ice & Weed retardation	109	125
Niagara River Ice & Weed retardation	87	95
Chicago diversion	94	82
Welland Canal	229	229

Table 8. Evaluation of NBS change impact on the steady-state head difference between Lake Michigan-Huron and Lake Erie.

Period defining steady-state inputs	**After 50 yrs (Steady-state)**		
	Michigan-Huron level (m)	**Erie level (m)**	**Head difference (m)**
A: 1963-1995	176.83	174.48	2.35
B: 1996-2005	176.35	174.18	2.17
Difference: A – B	0.48	0.30	0.18

4 Stochastic Modelling Analyses

4.1 Model Input Changes for Stochastic Analyses

The analyses conducted in Section 4 are designed to assess the distribution of the drop in head difference metrics that would be observed under randomly sampled alternative time series of NBS inputs. As per the Hydroclimate Uncertainty peer review comments, bootstrap experiments (rather than simple Monte Carlo sampling) are conducted to generate the alternative NBS time series. Monte Carlo sampling is problematic here because it would require developing complex time series models that respect the temporal and spatial correlation structure among all inputs . Note that the analyses here are not designed to assess the impact of the uncertainty of historical component NBS estimates (the GLERL estimates of component NBS used in Section 3 are assumed correct). Instead, the analyses here are designed to evaluate the distribution head difference metrics that result from the observed variability in NBS over time. The analyses conducted differ by varying the sampling strategy and/or another factor in the model and these differences are described clearly at the beginning of each subsection below.

Prior to running CGLRRM under alternative NBS time series, it was necessary to change two of the model simulation settings relative to the inputs used to define the baseline metrics calculated in Table 3. These changes are as follows:

1. As per a recommendation and data provided by Yin Fan at Environment Canada (Personal communication), Welland Canal diversions are assumed not to respond to Lake Erie water levels and are thus fixed at the 12 monthly average values. To ensure the monthly averages are representative for the simulation time period (1996-2005), the average monthly flows for this period are used as model input.
2. Similar to 1 above, Chicago diversions are assumed not to respond to Lake Michigan-Huron levels. As such, the average Chicago diversion rate for the 1996-2005 period of 83 m^3/s was input to CGLRRM as the constant diversion rate for all stochastic experiments.
3. Lake Superior levels are simulated and the flow of the St Marys River is the result of Plan 1977A regulation strategy that is encoded in the regulation portion of CGLRRM. In other words, CGLRRM is capable of simulating the regulation strategy that determines the monthly flows of the St. Marys River into Lake Michigan-Huron. The initial Lake Superior level is set to the coordinated measured level for Jan 1, 1996 and the previous month’s St. Marys River flow is set to the Dec. 1995 average monthly flow estimate.

Changes 1-3 above were evaluated for their impact on the simulated metrics for the 1996-2005 period by implementing the two changes above and then running the model under all the same inputs determined to be representative of the 1996-2005 period (i.e. Equation (2) for St. Clair River flows). Lake level simulations are compared with historical lake levels, including Lake Superior, in Figure 6 below. The results in Figure 6 demonstrate that changes 1 and 2 do not inhibit the model from simulating the variation in time of Michigan-Huron and Erie lake levels. Instead, all lake levels, including Lake Superior, are now simulated quite well relative to the measured lake levels. In fact, simulated lake levels for Lakes Michigan-Huron, St. Clair and Erie now appear slightly closer to their measured lake levels later in the simulation in comparison to simulations without changes 1-3 (see previous results for Equation (2) in Figure 2).

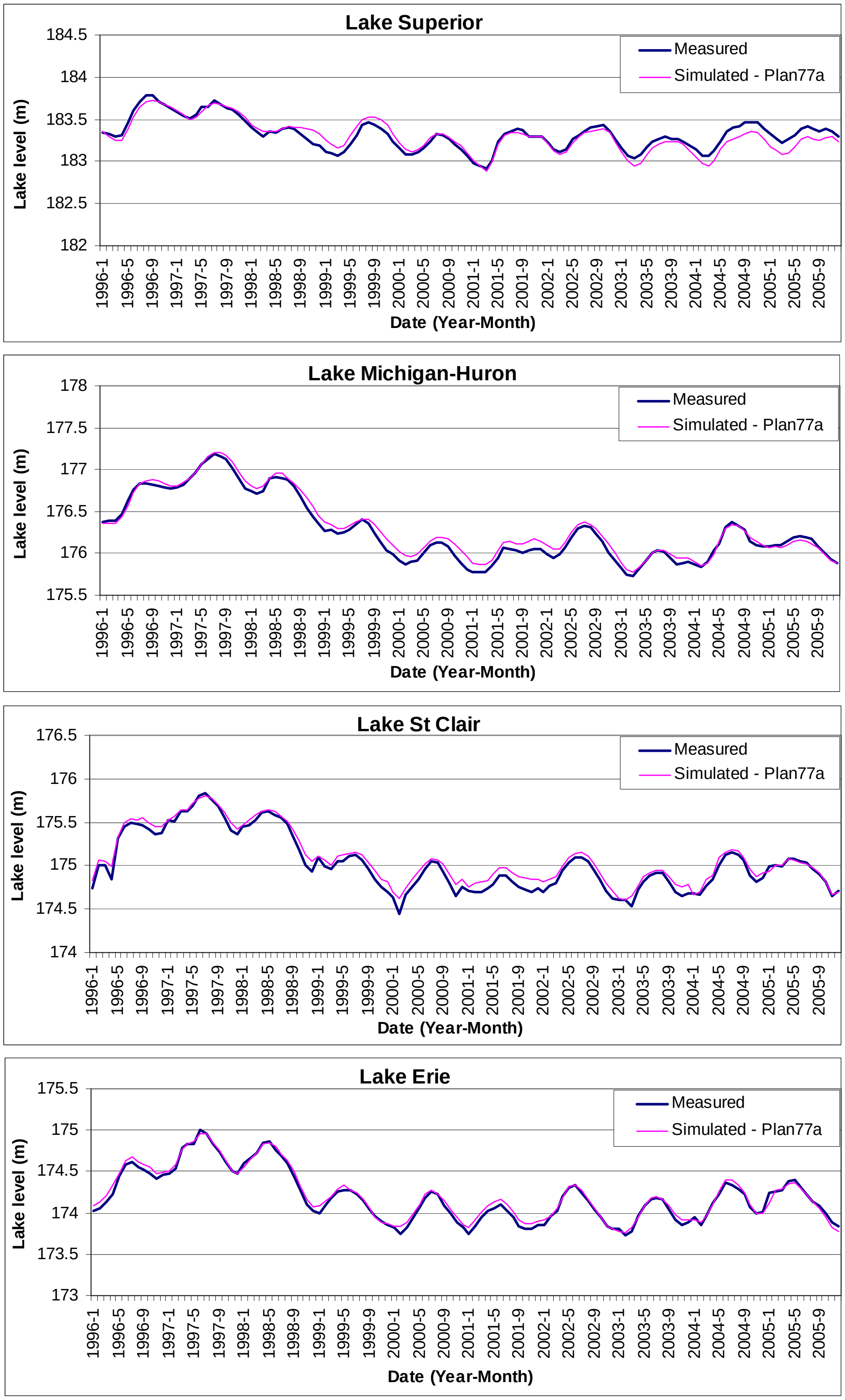

Figure 6. Comparison of measured (coordinated) and simulated average monthly lake levels for Lakes Superior, Michigan-Huron, St. Clair and Erie. The Plan 77a designation is used to indicate that both model changes 1-3 as described in Section 4.1 were implemented. These simulated lake levels are used to calculate updated head difference metrics in Table 9.

4.2 Metrics for quantifying the drop in head difference between Lake Michigan-Huron and Lake Erie in stochastic experiments

The three previous baseline drop in head difference metrics ($M_{1\ ann}$, $M_{2\ reg}$ and $M_{3\ 3yr}$) are recomputed in Table 9 based on the simulation results in Figure 6 and Figure 7 and demonstrate some small variations from the previous baseline simulation metric values. However, these small deviations (0.05 to 0.07 m) are unavoidable. The updated baseline metric values are now in fact much closer to the measured metric values for $M_{1\ ann}$, $M_{2\ reg}$ and $M_{3\ 3yr}$ (within 0.0-0.02 m). Therefore, each of these metrics are utilized to assess stochastic simulation experiments.

In analyzing the stochastic simulation experiments, two additional metrics for describing system behaviour were identified and thus utilized in all results below. Metric M_4 is defined as the number of years when the average annual head difference is less than or equal to the low value of 2.051 m for the measured data in 1990 (see Figure 7). Metric M_5 is defined as the number of years when the 3-yr moving average of the annual head differences is less than or equal to the low value of 2.101 m for the measured data in 1991 (see Figure 7). These values are deemed to be on the basis of the 1963-1998 period in Figure 7. Metrics M_4 and M_5 are also tabulated for the measured and simulated data in Table 9.

Table 9. Measured and updated (for stochastic experiments) baseline simulated metrics for assessing change in head difference across different periods based on annual average lake levels.

Metric Name	**Period**	**Notes**	Change in **Measured** Head Diff. = Initial – Final avg. annual head difference over the period, m	Baseline metrics for stochastic analyses. Change in **Simulated** Head Diff. = Initial – Final avg. annual head difference over the period, m
$M_{1\ ann}$	1997[a] -2005	Based on annual average head differences	0.35	0.37 (0.30)[b]
$M_{2\ reg}$	1996 - 2005	Calculated from linear regression of annual average head difference vs. year	0.35	0.35 (0.28)[b]
$M_{3\ 3yr}$	1997 - 2004	Based on 3-yr moving average of annual average head differences	0.29	0.29 (0.24)[b]
M_4	1996 - 2005	Count of yrs where ann. avg. head diff. below 1990 value of 2.051 m	6 (count of yrs, not m)	4 (count of yrs, not m)
M_5	1996 - 2005	Count of yrs where 3-yr moving annual avg head diff below 1991 value of 2.101 m	6 (count of yrs, not m)	5 (count of yrs, not m)

a) 1997 selected over 1996 as initial year because the difference between simulated $M_{1\ ann}$ is much closer to measured $M_{1\ ann}$.
b) Brackets contain previous metric value for deterministic analyses as presented in Table 3.

In order to calculate comparable metrics from the stochastic simulation results, the calculation of the simulated metrics must be slightly modified. The simulated and measured $M_{1\ ann}$ and $M_{3\ 3yr}$ metrics in Table 9 are based on a fixed-year to fixed-year change in head difference and these fixed years become irrelevant when simulating alternative sequences of NBS. For example, the baseline $M_{1\ ann}$ compares 1997 with 2005 (9-yr period) and $M_{3\ 3yr}$ compares 1997 and 2004 (8-yr period). With stochastic sets of NBS, a 4- or 5-yr period rather than the fixed 1997-2005 9-yr period might yield the most extreme drop in simulated head difference. Therefore, in order to assess the most extreme change in head difference behaviour, the calculation of the simulated $M_{1\ ann}$ metrics for the stochastic simulations is taken to be the maximum change in head difference of all the possible 3-, 4-, …, 10-yr periods during the 10-year (1996-2005) stochastic simulations. Similarly, the calculation of the simulated $M_{3\ 3yr}$ metrics for the stochastic simulations is taken to be the maximum change in 3-yr moving average head difference of all the possible 3-, 4-, …, 8-yr periods from 1997 to 2004.

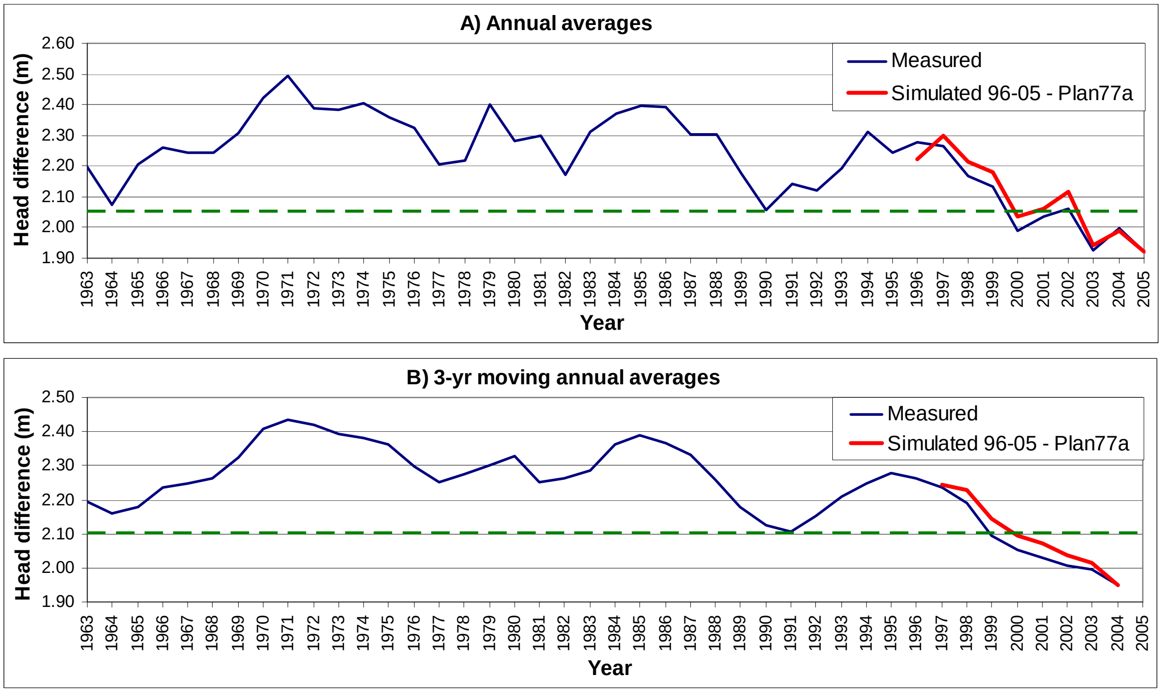

Figure 7. Illustration and rationale for additional head difference metrics (M_4 and M_5). The dashed lines are the lows in the measured data for the 1960-1995 period.

4.3 Bootstrap sampling description and data analysis

In order to randomly sample alternative time series for NBS and the ice and weed retardation factors, a moving blocks bootstrap approach was selected. The moving blocks bootstrap is an approach for resampling from a univariate time series of data (pg. 101, Efron and Tibshirani, 1993) and is simply a way of resampling (by reordering) plausible alternative sets of time series. Being able to sample alternative time series enables the repeated sampling of some statistics of interest (in this case, the metrics for change in head difference over the 1996-2005 period) that are calculated as a function of sampled time series. This repeated sampling of the statistics enables the estimation of the probability distribution of the statistic (Vogel and Shallcross, 1996). The basic idea is to select an appropriate block length (number of time steps) and consider all contiguous blocks of time of this length (e.g. *N* blocks) as the population of blocks from the original time series that can be resampled. Alternative time series are then created by repeatedly sampling at random, with replacement, one of the *N* blocks and then concatenating the blocks together until a time series of the desired length has been generated.

Vogel and Shallcross (1996) note that the moving blocks bootstrap can be easily extended to multivariate time series. In this application, the entire set of upper Great Lakes NBS time series (Lakes Superior, Michigan-Huron, St. Clair and Erie) as well as the ice and weed factor retardation factor time series (for the St. Clair, Detroit and Niagara Rivers) are bootstrapped together. This means that sampling a block length of three years for example, would take the same three-year period from all seven time series. In this way, the moving blocks bootstrap is powerful because it automatically preserves the spatial correlation structure of the NBS (and ice and weed factors) across the four upper Great Lakes.

The original time series to be resampled are defined to be the 1948-2005 period since this is the period of time for which component NBS data are available. The block length, *L*, of the bootstrap should be selected large enough such that data more than *L* time steps apart will be nearly independent but the autocorrelations present in the original time series less than *L* time steps apart are retained (pg. 102, Efron and Tibshirani, 1993). Since this study is focused on a multivariate data set, the block length determination considers the cross correlations in addition to the autocorrelations.

In this analysis, block lengths less than 12 months in length were not considered. Blocks lengths are measured in units of years (12 consecutive months) and so the monthly data need to be first assessed for which month to define the start of each block length unit. The month-to-month correlation coefficients for all seven time series were computed and showed that the only pair of consecutive months where all seven time series have a statistically insignificant correlation coefficient (at the 5% significance level) is March and April. The lack of correlation between March and April NBS makes hydrological sense because this coincides with the beginning of the snowmelt/ice-free period for the Great Lakes basin. The switch from winter climate conditions to spring melt conditions should generate NBS that are not correlated since baseflow type flow conditions at the end of winter are not good predictors of the spring time snowmelt induced flood magnitudes. Therefore, the monthly time series data are aggregated to annual average data (weighted by days in each month) based on a year from April 1 – Mar 31.

The next analysis was to determine the appropriate block lengths based on an autocorrelation and then cross correlation analysis to assess the annually averaged (with year defined Apr-Mar) time series. Both of these correlation analyses only focused on the four NBS time series as they are one to more than two orders of magnitude larger than the ice and weed retardation factors (which average around 10 m^3/s) on an annual basis. Lag-1, lag-2 and lag-3 autocorrelations and cross correlations were computed to assess the validity of blocks lengths up to three years in length. Block lengths more than three years were considered too long given that the length of the time series to be constructed by the moving blocks bootstrap is 10 years in length. None of the lag-1 through lag-3 autocorrelations for the four NBS time series were statistically significant at the 5%

significance level (for example, the strongest lag-1 correlation coefficient was 0.18 for Lake Michigan-Huron). The lag-1 cross correlations between Lake Michigan-Huron (yr i+1) and Lakes St. Clair and Erie (yr i) were both statistically significant at the 5% level. All lag-2 and lag-3 cross correlations were not statistically significant at the 5% level. Therefore, a block length of two years (with April 1 to March 31 defining each year) was selected for all bootstrap analyses in this report. Note that minimizing the block length used maximizes the variation in the sampled alternative time series.

Unless otherwise reported, all moving block bootstrap experiments sample 1000 10-yr sets of input time series and thus involve 1000 CGLRRM simulations. The bootstrap experiments described below vary the historical data period sampled from. Note that since the component NBS data is unavailable after Dec. 2005, the 2005 Apr-Mar year is not complete and thus not sampled from.

4.4 Bootstrap experiment set 1

Experiment set 1 was conducted for two main purposes. First, it is used to assess how unique or extreme the baseline behaviour of the system was under the actual set of 1996-2005 NBS and other input time series. Uniqueness is measured relative to the distribution of possible alternatives (1000 of them). Second, it is used to assess if 1000 bootstrap samples is sufficient in size. The entire 1948-2005 period is sampled from to create the 10-yr length input time series. Note that CGLRRM inputs are as described in Section 4.1 and the lake-to-lake stage-fall equation given in Eq. (2) is taken to describe the current St. Clair River conveyance regime.

Table 10 summarizes three experiments in terms of the average metric values where in each experiment, the number of sampled 10-yr input time series was varied (500, 1000 and 2000) and each were conducted independently (i.e. different random seeds). Based on these averages, it can be seen that the average values after 1000 samples are very close (within 0.01m for all metrics with units of m) to the average values of 2000 samples. Therefore, for the remaining stochastic experiments, only 1000 samples were utilized.

Table 10. Average simulated stochastic change in head difference metrics for bootstrap experiment set 1 (# bootstrap samples varied). Each simulation length is 10 years and all simulations initialized to Jan. 1, 1996 lake levels.

# of bootstrap samples in Experiment	**$M_{1\ ann}$ (m)** max of all 3-, 4-, …, and 10-yr decreases in ann. avg. head difference	**$M_{2\ reg}$ (m)** decrease in head difference from 1996 to 2005 by linear regression	**$M_{3\ 3yr}$ (m)** max of all 3-, 4-, …, and 8-yr decreases in 3yr moving. avg. head difference	**M_4** # yrs with avg. head difference ≤ 1990 extreme	**M_5** # yrs with 3yr moving avg. head difference ≤ 1991 extreme
500	0.24	-0.04	0.12	1.3	1.5
1000	0.25	-0.03	0.13	1.4	1.7
2000	0.25	-0.03	0.13	1.3	1.6

Since the average values metric values in Table 10 are notably smaller or less extreme than the baseline metrics in Table 9, it can be concluded that the actual head difference behaviour was somewhat extreme (more than average). Note that the negative average values for $M_{2\ reg}$ means that on average, the regression line slope is positive such that a regression line measure of change in head would suggest increasing rather than decreasing head differences over time. The fact the average regression line metric is negative indicates that the regression line metric is a relatively poor metric for this type of analysis where the head difference variations of concern can occur over a shorter period than what is included in the regression. As such, the all results for the regression metrics should be given less weight than the results for the $M_{1\ \mathrm{ann}}$ and $M_{3\ \mathrm{3yr}}$ metrics.

Overall, average metric values are imperfect measures for quantifying how extreme the baseline system behaviour is. Instead, the stochastic results were also analyzed to estimate the probabilities that equal or more extreme stochastic simulated metrics relative to the baseline metric values derived in Section 4.2 are sampled. For example, for the $M_{3\ \mathrm{3yr}}$ metric, only 74 of 1000 simulations (from experiment with 1000 samples) generated a metric value that was equal to or larger than the baseline of 0.293 m. As such, the probability that any sampled 10-yr set of input time series yielded an equal of more extreme value of 0.293 m for $M_{3\ \mathrm{3yr}}$, denoted $\Pr(M_{3\ \mathrm{3yr}} \geq 0.293)$, is 74/1000 = 0.074. These probabilities calculated for all five metrics ($M_{1\ \mathrm{ann}}$, $M_{2\ \mathrm{reg}}$, $M_{3\ \mathrm{3yr}}$, M_4, and M_5) using the 1000 sample size experiment are 0.148, 0.034, 0.074, 0.141 and 0.143, respectively. Given the range of probabilities is between 0.03 to 0.15, it is clear the system behaviour resulting from the actual 1996-2005 NBS time series was fairly unique.

4.5 Bootstrap experiment set 2

In this set of experiments, the independent impacts of both the NBS (climate) and the conveyance change are both controlled so that their relative importance could be assessed. The conveyance change for the St. Clair River is already assumed to be completely described by changing the equation for St. Clair River flow from Eq. (1) to Eq. (2). The NBS influence in these experiments is defined to be the 1996-2005 period of NBS values on the basis of results in Table 6 which show average Lake Michigan-Huron NBS values from the 1996-2005 period are notably smaller than average Lake Michigan-Huron NBS values from the 1963-1995 period. Therefore, the influence of the 1996-2005 NBS data can be removed by bootstrap sampling from past years not including this period (sampling from years before 1996 only).

In order to focus on the past NBS conditions observed since the last significant dredging of the St. Clair River (1962), the bootstrap sampling period for all experiments in this section begins in 1963. Three bootstrap sampling experiments were conducted and are described as follows:

- <u>Experiment 2a)</u> samples 10-yr sets of input time series for CGLRRM from the 1963-2005 period and simulates St. Clair River flows with the current conveyance equation - Eq. (2). This experiment then forms a baseline from which the impacts of conveyance and NBS can be assessed by comparing with the two following experiments.
- <u>Experiment 2b)</u> samples 10-yr sets of input time series for CGLRRM from the 1963-1995 period and simulates St. Clair River flows with the current conveyance equation - Eq. (2). Thus, experiment 2b is the exact same as experiment 2a except that the 1996-2005 period is not sampled from and thus isolates the impact of 1996-2005 NBS data.
- <u>Experiment 2c)</u> samples 10-yr sets of inputs for CGLRRM from the 1963-2005 period and simulates St. Clair River flows with the conveyance equation for the 1960-1977 conveyance regime - Eq. (1). Thus, experiment 2c is the exact same as experiment 2a

except that the conveyance equation is modified and thus isolates the impact of conveyance change.

Note that the same 1000 10-yr sets of input time series are utilized in Experiment 2a and 2c since they sample from the same period of time. This enables a more precise assessment with regard to the conveyance change impact.

The results of experiment set 2 are summarized the same way as experiment set 1 results using a table of average metric values for each of the three experiments (Table 11) and also table of probabilities of equal or more extreme stochastic simulated metrics relative to the baseline metric values (Table 12).

Table 11. Average simulated stochastic change in head difference metrics (across 1000 simulations) for bootstrap experiment set 2 (conveyance regimes and NBS sampling periods varied). Each simulation length is 10 years and all simulations initialized to Jan. 1, 1996 lake levels.

Experiment #	**$M_{1\ ann}$ (m)** max of all 3-, 4-, …, and 10-yr decreases in ann. avg. head difference	**$M_{2\ reg}$ (m)** decrease in head difference from 1996 to 2005 by linear regression	**$M_{3\ 3yr}$ (m)** max of all 3-, 4-, …, and 8-yr decreases in 3yr moving. avg. head difference	**M_4** # yrs with avg. head difference ≤ 1990 extreme	**M_5** # yrs with 3yr moving avg. head difference ≤ 1991 extreme
2a (baseline)	0.21	-0.07	0.10	0.7	1.0
2b (change NBS)	0.17	-0.12	0.07	0.3	0.4
2c (change conveyance)	0.19	-0.08	0.08	0.1	0.1

Comparing the average metrics in Table 11 shows that the change in NBS sampling period (not sampling from 1996-2005) has a slightly larger impact (compare 2b results to 2a results) on the $M_{1\ ann}$, $M_{2\ reg}$ and $M_{3\ 3yr}$ metrics than the change in conveyance (compare 2c results to 2a results). The count metrics in Table 11 respond slightly more to the change in conveyance than they do the change in NBS sampling period. The probabilities in Table 12 show similar relative results between 2b and 2c. The very small probabilities (all less than 0.065) in Table 12 for experiments 2a and 2b, both of which simulate the conveyance change with Eq. (2), demonstrate even more than the previous results in section 4.4 that the sequence of actual climate or NBS for the 1996-2005 period was very unique. For example, only 5 of 1000 (0.005) sets of 10-yr input time series sampled from the 1963-1995 period yielded more extreme $M_{3\ 3yr}$ metric values than the baseline simulated results for the actual input time series observed from 1996-2005.

The impact of conveyance change in terms of a percentage of the baseline metric values can be made precise based on the correlated sampling approach between experiments 2a and 2c (same 1000 input data sets are used). This allows a pairwise comparison of the change in head difference metrics between experiments 2a and 2c. In addition, since the majority of simulation results showed lake level behaviours that were not at all extreme (for example see probabilities in Table 12), this more refined conveyance change impact is focused only on those pairs of simulations when the result in experiment 2a was deemed to be extreme. The criteria for extreme behaviour for a given metric is defined as previously: when the simulated metric value is equal or exceeding the baseline metric value.

Table 12. Probabilities that the simulated metric value is equal or more extreme than the baseline metric value for bootstrap experiment set 2 (conveyance regimes and NBS sampling periods varied). Each simulation length is 10 years and all simulations initialized to Jan. 1, 1996 lake levels.

Experiment #	**Pr($M_{1\ ann} \geq 0.373$)**	**Pr($M_{2\ reg} \geq 0.348$)**	**Pr($M_{3\ 3yr} \geq 0.293$)**	**Pr($M_4 \geq 4$)**	**Pr($M_5 \geq 5$)**
2a (1963-2005, Eq. 2)	0.055	0.008	0.023	0.050	0.065
2b (1963-1995, Eq. 2)	0.020	0.001	0.005	0.011	0.017
2c (1963-2005, Eq. 1)	0.018	0.001	0.008	0.002	0.004

Considering $M_{1\ ann}$, 55 extreme behaviours were observed in experiment 2a. Conveyance change (comparing 55 pairs from experiments 2c with 2a) controlled an average of 13% (0.05 m) of the $M_{1\ ann}$ metric value (up to a maximum of 24% or 0.10 m). Considering $M_{2\ reg}$, 8 extreme behaviours were observed in experiment 2a. Conveyance change (comparing 8 pairs from experiments 2c with 2a) controlled an average of 22% (0.09 m) of the $M_{2\ reg}$ metric value (up to a maximum of 34% or 0.12 m). Considering $M_{3\ 3yr}$, 23 extreme behaviours were observed in experiment 2a. Conveyance change (comparing 23 pairs from experiments 2c with 2a) controlled an average of 17% (0.06 m) of the $M_{3\ 3yr}$ metric value (up to a maximum of 30% or 0.09 m). These results demonstrate that the conveyance change impacts across a range of extreme but plausible NBS inputs are fairly consistent with conveyance change controlling 13% to 22% on average, to a maximum of 34% of the decrease in head difference. These values are also quite consistent with the deterministic attribution percentages (24% to 31%) calculated in Table 4 on the basis of the actual 1996-2005 climate (NBS) inputs. As such, it seems unlikely that the observed or actual 1996-2005 NBS data functioned to temporarily mask the overall conveyance change impact on the upper Great Lakes.

5 Discussion

Every modelling exercise has limitations and problems of some degree that should be acknowledged. These acknowledgements provide the basis for continued model improvement in the future. The most important limitations noted throughout the previous sections include the following:

- The new conveyance equation for the 1996-2006 period should be assessed more closely to determine the uncertainty in the coefficients and perhaps generate alternatives that fit the data nearly as well as the final regression-based coefficients. Due to time constraints, this was not possible in this report. However, experiments should eventually be repeated for any new coefficient sets that are found to be equally justifiable as those in Eq. (2).

- Component NBS are estimates derived from models and subject to a fairly large amount of uncertainty. Ideally, this uncertainty should be explicitly quantified and then utilized in this report to derive findings that are also subject to some uncertainty. Note that there are ongoing IUGLS hydroclimate projects working to quantify NBS uncertainties (e.g. see http://www.iugls.org/en/St_Clair_Reports/Publications_StudyReports_HydroclimaticStudy.aspx)
- The ice and weed retardation factors used currently should eventually be updated as they have been derived on the basis of Eq. (1) rather than Eq. (2) which better represents the current conveyance regime.
- Another issue is that the calculation of the ice and weed factors requires the measured connecting flows such that one type of system behaviour must be observed in order to quantify other types of system behaviour (lake levels). In the future, CGLRRM would be more robust if these ice and weed factors could be simulated instead of derived from the measured data that the model is designed to predict.
- Under ideal conditions, the analyses conducted would have simulated the 1996-2007 (instead of 2005 period). When the component NBS data becomes available for this period, it would be prudent to extend the deterministic predictions in Section 3 through the end of 2007 to see if the trend in head difference is reasonably captured by CGLRRM. This would build even more confidence in the general findings of this report.

6 Conclusions

CGLRRM prediction quality of historical measured lake levels was high and CGLRRM was deemed to be an adequate tool for making inferences regarding the relative importance of conveyance change and changes to the climate (NBS). Specific findings regarding model quality are as follows:

1a. CGLRRM, based on component NBS, can reasonably replicate 1963-1977 lake levels (and head difference behaviour) with an open water lake-to-lake stage-fall equation developed by Fay and Noorbakhsh (2004) for the 1963-1999 period.
1b. CGLRRM, based on component NBS, can reasonably replicate 1996-2005 lake levels (and drop in head difference) with a new open water lake-to-lake stage-fall equation developed for the 1996-2006 period.
1c. The notable lake level prediction errors for the 2001-2005 period for Lake Michigan-Huron cannot solely be explained by an error in the assumed lake-to-lake stage-fall equation.

Deterministic modelling scenario analyses yielded the following findings:

2a. The post-1977 conveyance change on the St. Clair River was estimated to cause between 24% and 31% of three different change in head difference metrics considered. The metrics quantify the change in head difference for various periods and measures from 1996 to 2005. Other factors were attributed to be the cause of 69% to 76% of the metrics.
2b. A steady state analysis showed that with all flow inputs in the model set to their 1948-2005 average values, post-1977 conveyance change was estimated to decrease the

steady-state Lake Michigan-Erie head difference by 9 cm. Compare this to the measured drop in head difference of 51 cm (1994 to 2007).

2c. In direct contrast to 2b, a similar type of steady state analysis showed an 18 cm drop in head difference could be completely attributed to observed shifts in average component NBS data. For example, relative to the average component NBS data for the 1963-1995 period, the average component NBS data for the 1996-2005 period decreased by 0.12 m/yr for Lake Michigan- Huron and only decreased by 0.03 m/yr for Lake Erie.

2d. The Great Lakes system response time to a one-time conveyance change of the St. Clair River was explicitly shown to be finite in that such a change will not cause continual loss of water from Lake Michigan-Huron and thus Lake Michigan-Huron levels will not continue to decrease through time. Furthermore, it was shown that so long as the assumed one-time change in conveyance occurred on or before 1996, the actual date of conveyance change has no impact after 2003 on the cumulative volume of water lost from Lake Michigan-Huron due to conveyance change.

The stochastic modelling analyses yielded the following findings:

3a. The system behaviour resulting from the actual 1996-2005 NBSs was very unique or extreme in comparison with the distribution of possible 10-yr NBS sequences sampled from the 1963-1995 period (1000 samples).

3b. Multiple extreme but plausible 10-yr NBS sequences were used to show that conveyance change on the St. Clair River controls 13% to 22% on average, to a maximum of 34% of the drop in head difference.

Multiple analyses were conducted to attribute some percentage of responsibility to the change in conveyance for the drop in head difference between Lake Michigan-Huron and Lake Erie. The various deterministic analyses yielded estimates of 24%, 30% and 31%. The various stochastic analyses yielded average estimates of 13%, 17% and 22%. In the most extreme stochastic simulation, a value of 34% was calculated. Considering all these percentages, the post-1977 conveyance change on the St. Clair River is estimated to cause no more than 1/3 of the drop in head difference for the 1996-2005 period. Other factors (such as climate via NBS variability) control the substantial majority of the drop in head difference that was observed for the 1996-2005 period.

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APPENDIX 1 – Input file for CGLRRM simulation with Equation (2) in Figure 3.

```
#   CGLRRM version 1.40 modified & compiled with gfortran 4.2 on 02Dec2008 by Travis Dahl

 #   ........................   System Settings    ........................
        Message Database: C:\run_CLGRRM\messbase.txt
           Only One Open:                    F
            Modeler Name: Bryan Tolson

 #   ........................   Job Titles    ........................
                 Title 1: 1996-2005 run.  Supplemental Superior flows.
                 Title 2: Using updated Ice Retardation, NEW *** 2009 St Clair equation
 #                Title 3: (not used)

      Lakes To Solve For:                    MCE

 #   ........................   Simulation Period    ........................
              Start Date:             1996,  1,  1
                End Date:             2005, 12, 31
            Month Length:                  actual

 #   ........................   Output File Characteristics    ........................
        Output Directory: C:\run_CLGRRM\out\
        Output Extension:                    .out

 #   ........................   Misc Levels of Debugging Output    ........................

       General Verbosity:                      3
       TS Data Verbosity:                      3
         Check Verbosity:                      3

 #   ........................   General Rounding    ........................
              Flow Round:                    -99
             Level Round:                    -99
               BOM Round:                    -99

 #   ........................   Lake Superior not modeled    ........................

 #   ........................   Middle Lakes Settings    ........................

       Midlake Verbosity:                      3
           Routing Title: Quarter-Monthly Routing through Middle Lakes Using Monthy Supplies
       MidLake Time Step:                qmonthly
            MidLake Inc.:                 Hourly
        MidLake Solution:                iterative

 #   ........................   Lakes Michigan-Huron data    ........................

        MHu Output Files:                      M
          St. C. Riv Eqn: 1450.92000, 171.00000, 0.78472, 0.38388, 0.50000,  0.000
         MHu Start Level:             176.3600000 M
           MHu Area/Elev:         117470753820.000 M2
   St. M. Riv. Flow Data: C:\run_CLGRRM\supflowm.dat
            MHu NBS Data: C:\run_CLGRRM\MH_comp1_nbsm_48_05.prn
       Chicago Div. Data: C:\run_CLGRRM\Diversion_Chicago.dat
```

```
#     MHu Other Div. Data:              (not used)
#       MHu Con. Use Data:              (not used)
#    MHu. Other Sup. Data:              (not used)
#       Mic Con. Use Data:              (not used)
#     Mic Other Div. Data:              (not used)
#    Mic. Other Sup. Data:              (not used)
#      Hur. Con. Use Data:              (not used)
#    Hur. Other Div. Data:              (not used)
#    Hur. Other Sup. Data:              (not used)
#      MHu EOP Level Data:              (not used)
  St. C. Riv. Retr. Data: C:\run_CLGRRM\stc_ice_1900_2006.dbf
#    St. C. Riv. Ice Data:              (not used)
#    St. C. Riv. Ice Data:              (not used)

#    ........................    Lake St. Clair data    ........................

     St. C. Output Files:                         M
            Det. Riv Eqn:   26.20000, 164.95000, 2.33000, 0.36000, 1.00000,  0.000
      St. C. Start Level:              174.8200000 M
        St. C. Area/Elev:           1122901542.000 M2
#   St. C. Riv. Flow Data:              (not used)
           St. C. NBS Data: C:\run_CLGRRM\SC_comp1_nbsm_48_05.prn
#    St. C. Con. Use Data:              (not used)
#  St. C. Other Div. Data:              (not used)
#  St. C. Other Sup. Data:              (not used)
#   St. C. EOP Level Data:              (not used)
#      Det. Riv. Ice Data:              (not used)
#     Det. Riv. Weed Data:              (not used)
    Det. Riv. Retr. Data: C:\run_CLGRRM\det_ice_1900_2006.dbf

#    ........................    Lake Erie data    ........................

       Eri. Output Files:                         M
      Write Erie Outflow:                         T
            Nia. Riv Eqn:  558.30000, 169.86000, 1.60000, 0.00000, 1.00000,  0.000
        Eri. Start Level:              174.0600000 M
          Eri. Area/Elev:          25692618420.000 M2
#     Det. Riv. Flow Data:              (not used)
          Eri. NBS Data: C:\run_CLGRRM\ER_comp1_nbsm_48_05.prn
#    Eri. Other Sup. Data:              (not used)
#      Eri. Con. Use Data:              (not used)
      Welland Canal Data: C:\run_CLGRRM\Diversion_Welland.dat
#    Eri. Other Div. Data:              (not used)
#     Eri. EOP Level Data:              (not used)
#    CGIP Avg. Level Data:              (not used)
    Nia. Riv. Retr. Data: C:\run_CLGRRM\nia_ice_1900_2006.dbf
#      Nia. Riv. Ice Data:              (not used)
#     Nia. Riv. Weed Data:              (not used)

#    ........................    Lake Ontario not modeled    ........................
```