Full Draft Report v4:

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

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1 Introduction

The levels of the 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 (MH) 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 is designed to help shed some light on the relative contribution of changes to lake Net Basin Supplies (NBSs) and St. Clair River conveyance change in the to this decline in head difference. NBS to each lake is the result of precipitation, runoff and evaporation and is thus subject to a natural variability over time.

This study utilizes a mathematical simulation model of the 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 NOAA Great Lakes Environmental Research Laboratory, 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.

The analyses in this report are designed and conducted with the following working assumptions which are generally based on findings to date of the St. Clair Hydroclimate and Hydraulic technical working groups:

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 between 1977 and 1995.

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. Section 2 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 3, the importance of both factors are independently assessed with a series of stochastic modelling experiments where multiple NBS time series' are stochastically generated using a bootstrap sampling approach.

2 Deterministic Modelling Analyses

CGLRRM is a hydrologic routing model of the Great Lakes. It uses as inputs the NBSs 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 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 MH, St Clair and Erie and uses as input the measured flows of the St. Marys River (coordinated monthly average flows). The Chicago diversion was taken to be a constant 91 m^3/s over the simulation period.

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 historically measured 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 measured Lake Erie outflows. CGLRRM 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.

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 2.5) and stochastic scenario analyses (Section 3). Demonstrating the model is representative essentially means simulating past time periods (hindcasting) to check the model can approximately simulate the observed Lake 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). 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. 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 good test of the model. 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. First of all, component NBS data is only available through the end of 2005. Secondly, the quantitative description of the current conveyance regime as described in Section 2.1 is based on a 1996 through 2006 data analysis. These considerations generate a simulation period of 1996-2005. In addition to these two considerations, there appears to be little trend in the MH-Erie lake fall difference from 1962-1995 and as of 1995, the fall difference is within a few cm of the 1962-1995 average.

The data file specifying the model inputs is provided in Appendix 1. This data file is what is used to generate what is ultimately determined to be the most representative deterministic model and input set for the 1996-2005 period.

2.1 St Clair River Lake to Lake Stage Fall Equation Alternatives

The conveyance of the St. Clair River is represented in CGLRRM by the lake to lake stage fall equation for open water between Lake MH 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) which is given as follows:

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

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) as NBS inputs. Both of these simulated time series are compared to measured lake levels for the 1962-2005 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 Oct. 24, 2008 and thus do not include the significant Mar. 31, 2009 revisions 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 1960 and 1977 the model predictions are quite 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 a maximum during the 2002-2005 period.

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 1960-1977 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 stage-fall-discharge equation (see Eq. (2) below) relating the flow of the St Clair River to levels of Lakes MH 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 the 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-fall-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 MH 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 the only the 1996-2006 period and is given as follows:

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

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).

Equation (2) is derived on the basis of ADCP flow data taken from the conveyance regime from 1996-2006. 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 are compared to measured lake levels in Figure 2.

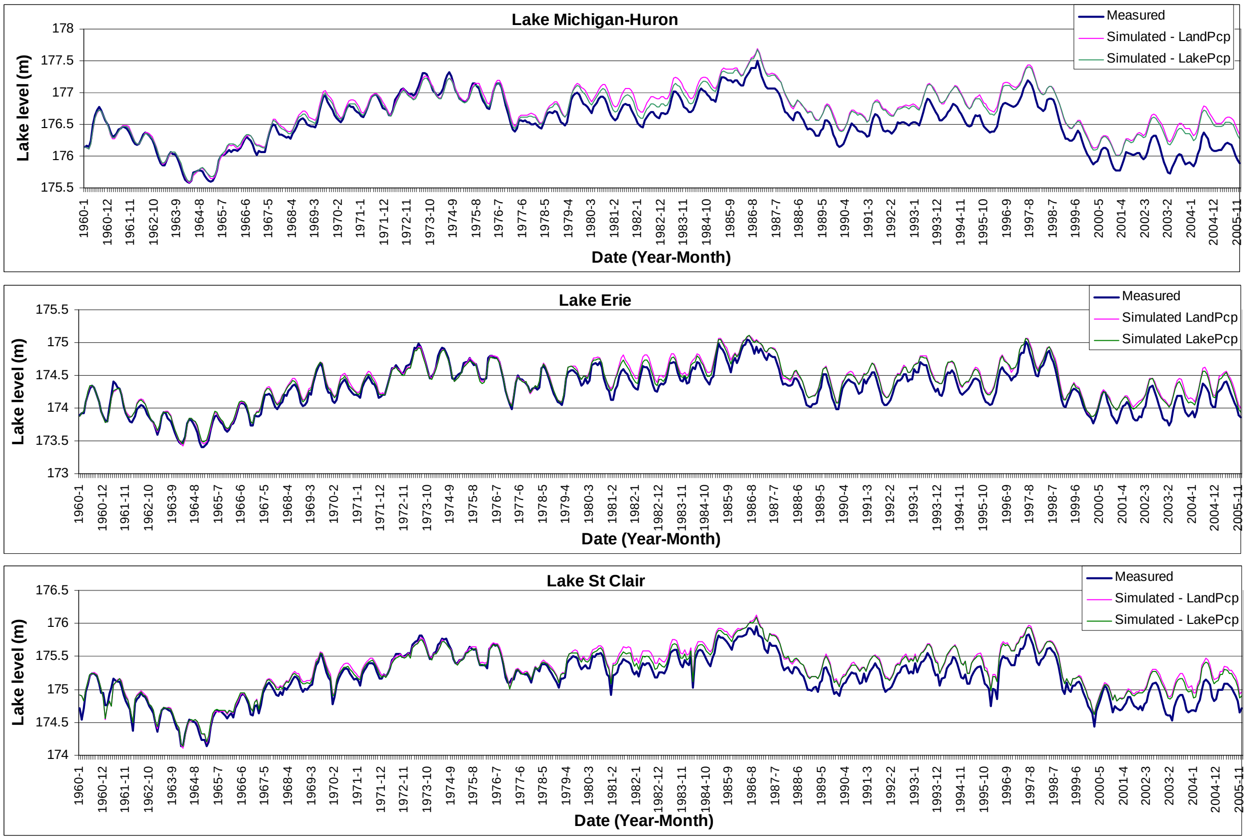

Figure 1. Comparison of measured (coordinated) and simulated average monthly lake levels for the middle Great Lakes from 1960 to 2005 using Equation (1) for St. Clair River flows.

Figure 2 clearly shows that for the first five years of the simulation (1996-2000) the simulated and measured lake levels agree quite well. For example, the average absolute difference between simulated and measured lake levels on Lake MH for 1996-2000 is 6 cm. However, by late 2001 and afterwards, the model is significantly over-predicting all lake levels as the average absolute difference between simulated and measured lake levels on Lake MH for 2001-2005 is 24 cm. It is not clear why the model predictions diverge so much from the measured lake levels.

Rather than checking connecting channel flow prediction accuracy of the St. Clair and Detroit River, the model and measured data were compared for the total system (Lake Erie) outflow (Welland Canal + Niagara River flow as provided by Yin Fan of Environment Canada, Personal communication) in Figure 3. Consistent with over-predicted lake levels in 2001-2005, the simulated Lake Erie outflows are much too high in this period as shown by the cumulative difference plot in Figure 3.

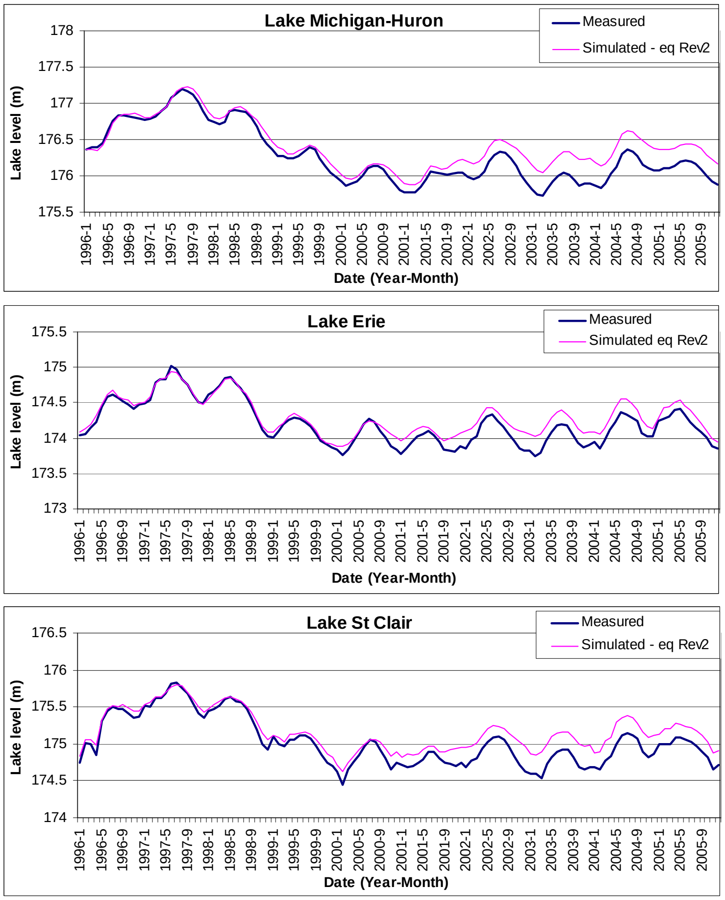

Figure 2. Comparison of measured (coordinated) and simulated average monthly lake levels for the middle Great Lakes from 1996 to 2005 using Equation 2 for St. Clair River flows.

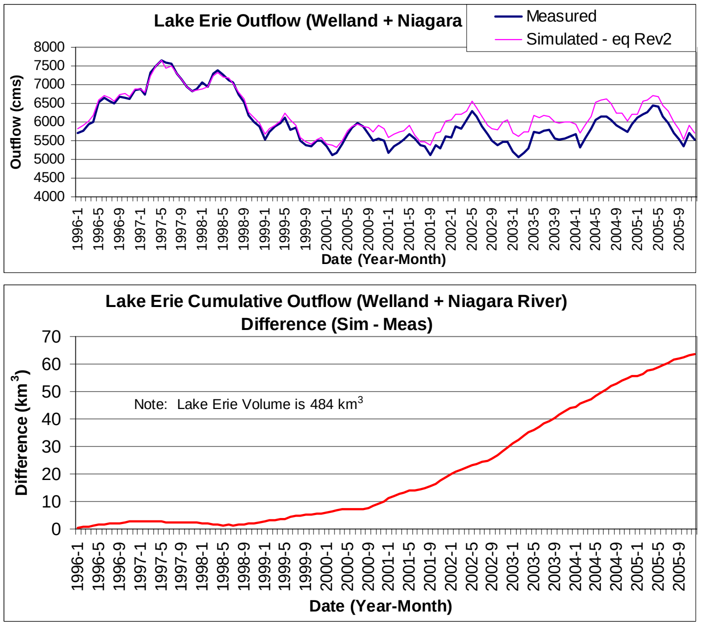

Figure 3. Comparison of measured and simulated Lake Erie outflows from 1996 to 2005 using Equation (2) for St. Clair River flows.

2.2 2001-2005 Prediction Error Analysis

In an effort to resolve the 2001-2005 CGLRRM prediction errors, a synthetic modelling analysis was conducted to simulate the 1996-2005 period. First of all, a synthetic truth was defined by assuming the true NBS values are the component NBSs for the 1996-2005 period and assuming the lake to lake stage fall equation below (Eq. 3) exactly predicts St Clair River flows. Under these assumptions, the synthetic or 'true' system behaviour is described by the simulated lake levels and Lake Erie outflows. Note that the only difference between Eq. (3) and Eq. (2) is the first coefficient (1600 instead of 1450.92). This new coefficient was defined only to make the synthetic lake levels look more like the observed lake levels during the 2001-2005 period.

$$Q=1600.0((MH+SC)/2-171)^{0.78472}(MH-SC)^{0.38388} \tag{3}$$

The next step involved introducing some artificial errors in CGLRRM to see how these errors change predictions relative to the synthetic truth. The two artificial errors were to:

- use an "incorrect" lake to lake stage fall equation relative to the true equation (Eq. 3). The incorrect lake to lake equation is chosen to be Eq. (2) as it simulates too little St Clair River flow relative to the true equation and thus would lead to over-estimated Lake Michigan-Huron levels.
- use an "incorrect" time series of Lake Michigan-Huron NBS such that the monthly NBS estimates are overestimated by 10% which would lead to overestimated Lake Michigan-Huron levels.

Note that each of these artificial errors mimic a potential cause for the 2001-2005 observed CGLRRM prediction errors in Figure 2 and Figure 3.

The impact or pattern of disagreement induced by these two artificial errors is assessed in Figure 4 below. In comparison with actual CGLRRM prediction errors observed for the 1996-2005 simulation period in Figure 2 and Figure 3, we can see that the same pattern of disagreement is induced by the synthetic MH NBS error (consistent 10% over-prediction). For example, the actual lake level prediction errors for all three lakes (Figure 2) are over-predictions and only the synthetic MH NBS error case (Figure 4) generates the same pattern of disagreement on all lakes. More compelling is the fact that the cumulative Lake Erie outflow difference plot in Figure 4 with the synthetic St. Clair River equation error shows a completely opposite pattern to the actual errors against the historical measured data (Figure 3) and therefore shows that it is unlikely that the disagreement we see in 2001-2005 is due to errors in the St. Clair River lake to lake equation for that period.

One extension to this analysis would be to consider the impact of simultaneous synthetic St. Clair River equation error and over-estimated Lake Erie NBS estimates. Although this scenario was not explicitly simulated, consider that if Lake Erie NBS was overestimated by 10%, this is an increase in average annual NBS of only 70 m^3/s. Adding 70 m^3/s to the Lake Erie outflow plot (left side of Figure 4) would not generate synthetic prediction errors with the same magnitude as the actual prediction errors found in the Lake Erie outflow plot of Figure 3 (300-500 m^3/s for much of 2001-2005).

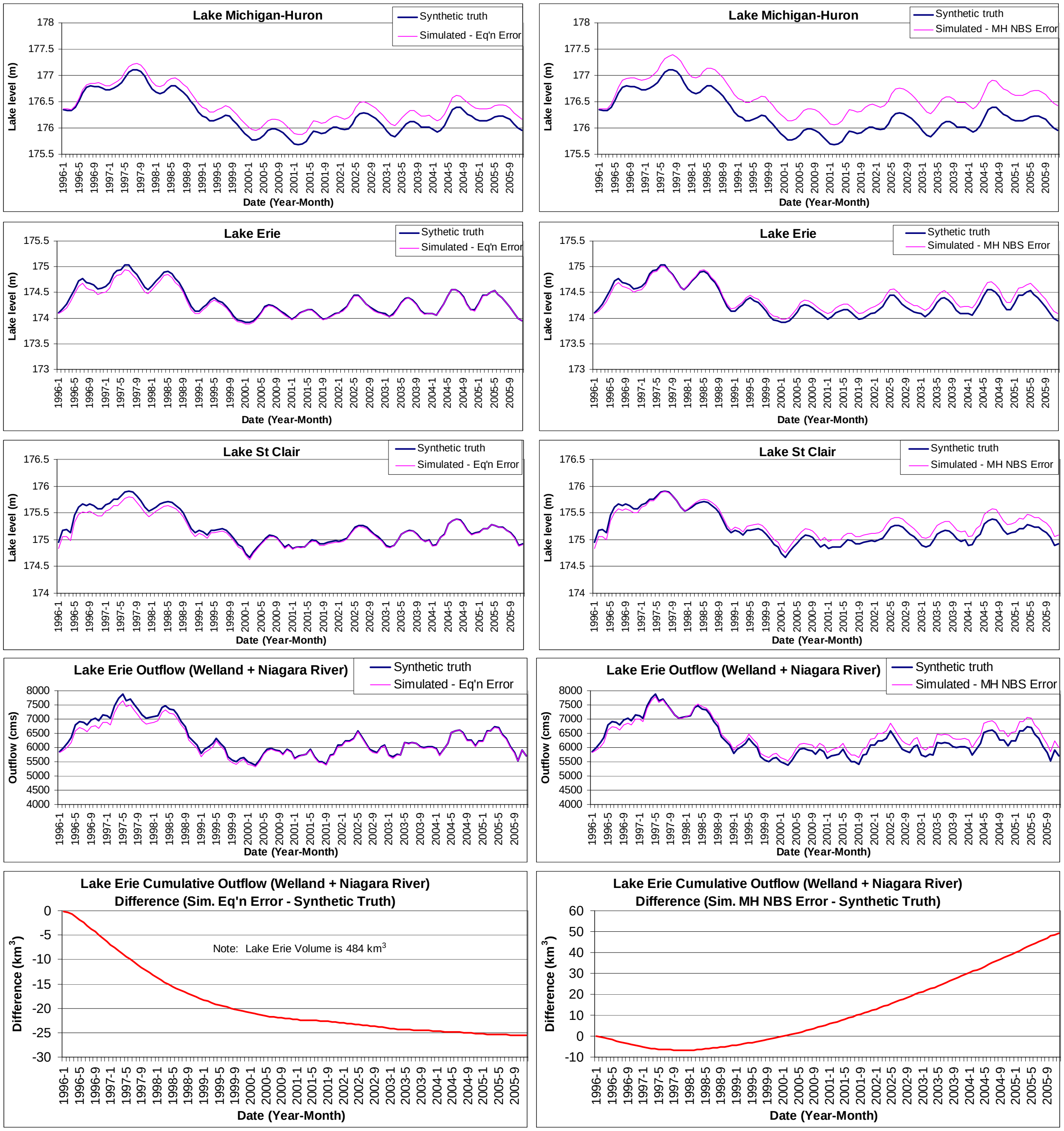

Figure 4. Results of synthetic error analyses for the 1996-2005 period. The plots on the left hand side of the figure utilize a lake to lake stage fall equation that has an error (simulates too little St Clair flows). The plots on the right hand side of the figure utilize Lake Michigan-Huron NBSs that are overestimated by 10%. Compare pattern of synthetic errors to those errors observed against real 1996-2005 lake levels and Erie outflow data in Figure 2 and Figure 3.

On the basis of this analysis, it seems likely that the 2001-2005 CGLRRM prediction errors are largely driven by over-estimated component NBS values for Lake MH. More evidence that component NBS estimates for 2001-2005 may be in error is the fact that for all three lakes, Figure 1 shows that for the 2001-2005 period, lake precipitation derived component NBS differs noticeably from land precipitation derived component NBS. Smaller differences between land and lake derived component NBS are observed for much of the 1960-2001 period. Furthermore, a comparison of residual and component NBS for Lake MH for 1996-2005 shows that the differences between these estimates are highest in 2002-2005 (see Section 2.4 for more detail). Therefore, efforts to improve CGLRRM predictions in 2001-2005 via refinements to the lake to lake stage discharge equation for the St. Clair River are not recommended. More equation refinements should only be evaluated in conjunction with other CGLRRM improvements (e.g. revised NBS and other model inputs).

Other potential causes of for the 2001-2005 prediction errors include any model inputs for that period that would generate a relative increase in flows into Lake MH. Examples include:

- Under-estimating Chicago diversion flows
- Over-estimating St. Mary's River flows
- Over-estimating the St. Clair River ice and weed retardation coefficients (how much open water flows are reduced by the presence of ice and weeds)

In the future, all of the above model inputs, in conjunction with MH component NBS, should be critically evaluated for accuracy and their measurement or estimation uncertainty should be quantified to enable a rigorous uncertainty analysis.

In conclusion, the best current deterministic model of the midlakes (MH, St. Clair and Erie) levels during the 1996-2005 period using component (lake-based precipitation) NBS is CGLRRM using Equation (2). The corresponding CGLRRM predictions in comparison with measured data are summarized in Figure 2 and Figure 3.

Based on the results in Figure 1, it seems reasonable to conclude that Equation (1) in CGLRRM generates a good description of lake levels for the 1962 (last year with dredging activities on the St. Clair River) through 1977 time period. As such, Equation (1) seems to adequately describe the conveyance regime of the St. Clair River for the 1962-1977 period. There are a few alternative lake to lake stage fall equations being generated by David Fay at Environment Canada (Personal communication) that apply specifically to periods prior to 1984 that may prove more accurate than Eq. (1) with respect to 1960-1977 lake level predictions. Future work should assess if these alternative equations improve CGLRRM accuracy (with lake-based component NBS) for 1960-77 and should thus replace Eq. (1) as a descriptor of the 1962-1977 conveyance regime. However, due to the good performance of Eq. (1) in 1962-1977, any update to the lake to lake equation for the 1962-1977 period is limited to making only minor improvements in lake level accuracy. Therefore, the findings in this report would not be expected to change significantly with any such equation update for 1962-1977 period.

2.3 Metrics for quantifying the fall (head difference) between Lake Michigan-Huron and Lake Erie

Prior to comparing the above two CGLRRM models (1960-1977 model versus 1996-2005 model) and making inferences regarding causes of the change in fall between Lake MH and Lake Erie, it is necessary to consider the metrics that can be used to describe the change in fall. Figure 5 shows that the simulated and measured head differences between Lake MH and Lake Erie are in reasonably close agreement with respect to their patterns over time (with the clear exception of 2002 through 2005 which is consistent with the model prediction errors assessed earlier). The recent (1996-2005) large drop in head difference over time is most apparent when the measured 3 yr moving annual averages are considered (bottom of Figure 5). 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).

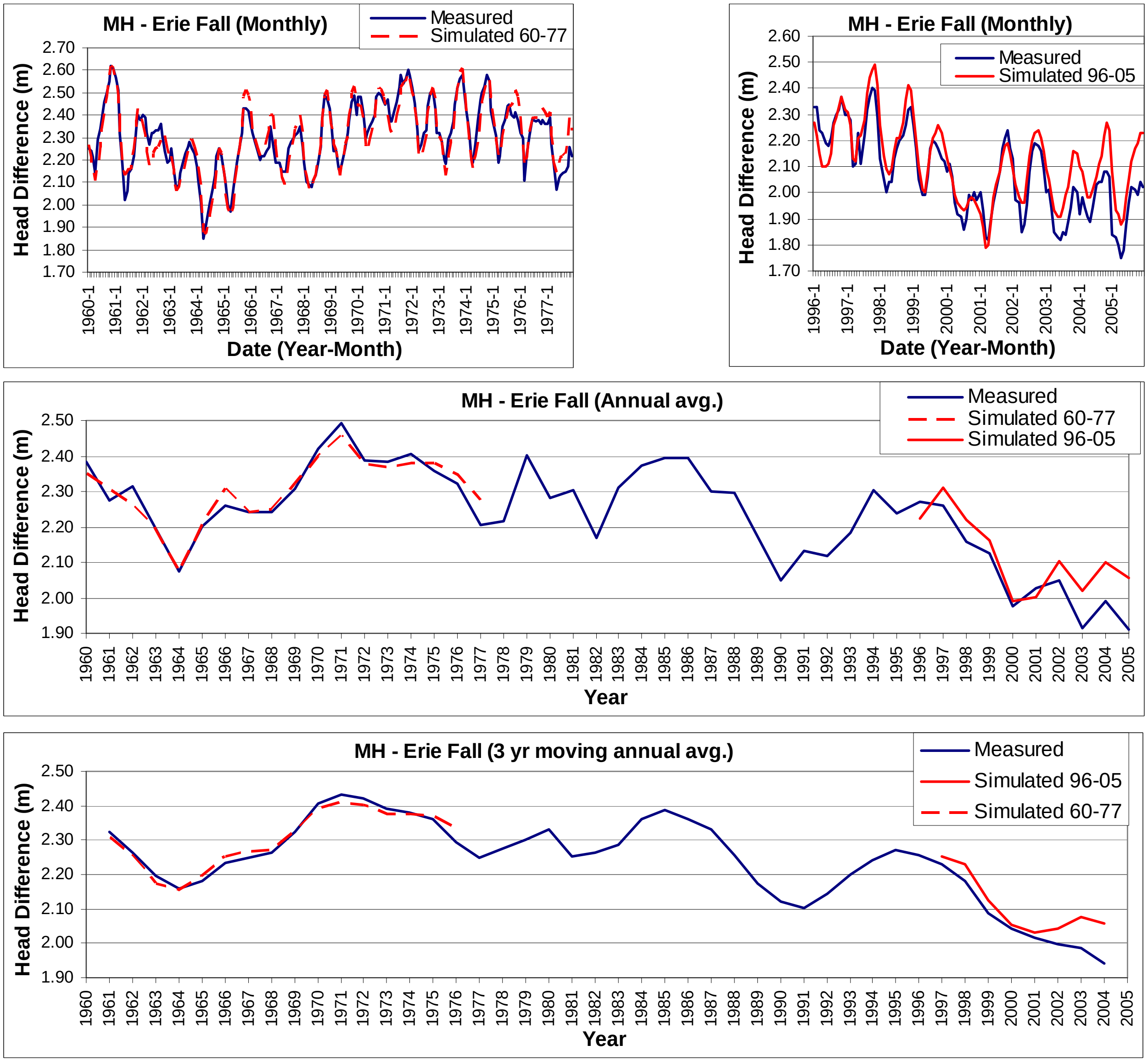

Figure 5. Simulated and measured lake fall (head difference) between Lake Michigan-Huron and Lake Erie for various time steps (monthly average lake levels, annual average lake levels, three year moving annual average lake levels). Measured lake falls based on coordinated average monthly lake levels. The simulated 60-77 result uses Eq. (1), pre-conveyance change, while the simulated 96-05 result uses Eq. (2), 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: before 1977 and then 1996-2005.

Tables 1 and 2 below depict measured and simulated annual average and three yr moving annual average based changes in the head difference for various time periods. The numbers in these tables are based directly on the various time series in Figure 5.

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, m	Change in **Simulated (96-05 model)** Head Diff. = Initial – Final avg. annual head difference, m
1996-2001	0.25	0.22
1996-2000	0.30	0.23
1997-2000	0.28	0.32
1996-2005	0.36	0.17
1997-2005	0.35	0.25
1994-2000	0.33	NA[a]
1996-2007	0.48	NA[b]
1994-2007	0.51	NA[b]

a) Current conveyance regime model (96-05) developed for 1996 through 2006 St. Clair river flow data and as such was not applied to 1994 or 1995.

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

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 or 1996-2007 of 0.51 m or 0.48 m, respectively) are not replicated by CGLRRM as the model is not currently simulating these time periods. Considering the time period being simulated in the model currently (1996-2005), the model is only capable of capturing the change in head difference for periods of time between 1996 and 2001. For example, if the metric/system behaviour of most concern to stakeholders is the 0.51 m drop in head difference from 1994-2007, the current model could only be used to assess the cause of a portion of this drop. Any analysis based on the current model would only be assessing 55% (e.g. measured 97-00 drop / measured 94-07 drop) of the issue. Table 2 shows similar results to Table 1 except it is based on 3 yr moving annual averages.

Table 2. Listing of potential measured and simulated metrics for assessing change in head difference across different periods based on three year 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. annual head difference, m	Change in **Simulated (96-05 model)** Head Diff. = Initial – Final avg. annual head difference, m
1997-2000	0.19	0.20
1997-2001	0.21	0.22
1997-2004	0.29	0.19
1995-2006	0.42	NA[a]

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

Given that only 55% of the key metric of interest to stakeholders (the drop in head difference between 1994-2007 or 1996-2007) is accurately simulated by CGLRRM, it was deemed necessary to evaluate if these current CGLRRM predictions could be improved. This effort is described in the next section (2.4) and then key baseline model metrics for quantifying the change in head difference are determined in Section 2.4.1.

2.4 Improving CGLRRM Predictions for 2001-2005

Section 2.2 highlights the errors in model predicted lake levels for 2001-2005 and Section 2.3 demonstrates the impacts these errors have on predicting the change in head difference between Lakes MH and Erie from 2001-2005. The inability of the CGLRRM to simulate this change in head difference raises questions about the efficacy of the model to inform decision makers of the relative impacts that changes in climate (via NBS) versus changes in St. Clair channel conveyance had on the change in fall difference observed between Lakes MH and Erie over the 10 year simulation period. The main concern is that CGLRRM predicts an increase in head difference of 6 cm between 2001 and 2005 while the observed data show the head difference decreased over that period by 12 cm (see annual lake fall difference plot in Figure 5).

As described in Section 2.2, the MH component NBS data appears a likely cause of the errors. This section of the report first provides evidence, independent of CGLRRM results, to suggest that 2001-2005 NBS data for MH are potentially flawed. Then, a correction to the 2001-2005 NBS data for MH is proposed and evaluated using CGLRRM.

As noted in Section 2.2, the fact that the two component NBS estimates (lake- versus land-based precipitation station focus) generate lake levels for MH (see Figure 1) that deviate more noticeably from one another in 2001-2005 in comparison to much of the 1960-2000 period, suggests potential component NBS errors. In addition, Quinn (2008), who compared differences in component versus residual NBS, notes that a significant disagreement is evident between NBS estimates for 2001-2005, as well as for 1987-2000. The 2001-2005 disagreement is highlighted in Figure 6 below showing that in late 2001, there is a change in the pattern of cumulative differences between component (lake-based) and residual NBS for the 1996-2005 period. The change to larger deviations (different slope) in late 2001 in Figure 6 shows that the component and/or residual NBS are likely subject to higher errors for this period.

It is beyond the scope of this work to determine the reason for the increased deviation. However, future work aimed at rationalizing the NBS deviations from 2001-2005 should include a compilation of residual and component NBS estimation methodological changes that occurred in this period. For component NBS this might include for example a change in the number of rainfall stations or stream gauging stations. For residual NBS this might include for example a change in coordinated connecting channel flows due to a rating curve update.

Given these two indications (one of which is independent of CGLRRM results) that the MH component NBS time series for 2001-2005 may have increased errors, it was deemed reasonable to consider a simple adjustment for correcting MH NBS for the 2001-2005 time period. The adjustment strategy accepts the premise that in the absence of better information, a reasonable estimate of the true NBS would be to average the component and residual NBS inputs. Since the CGLRRM-independent indications of problematic MH component NBSs are only for 2001-2005, the averaging of component and residual NBS is only computed for 2001-2005 NBS inputs. Lake MH NBS inputs for 1996-2000 are kept at component NBS estimates.

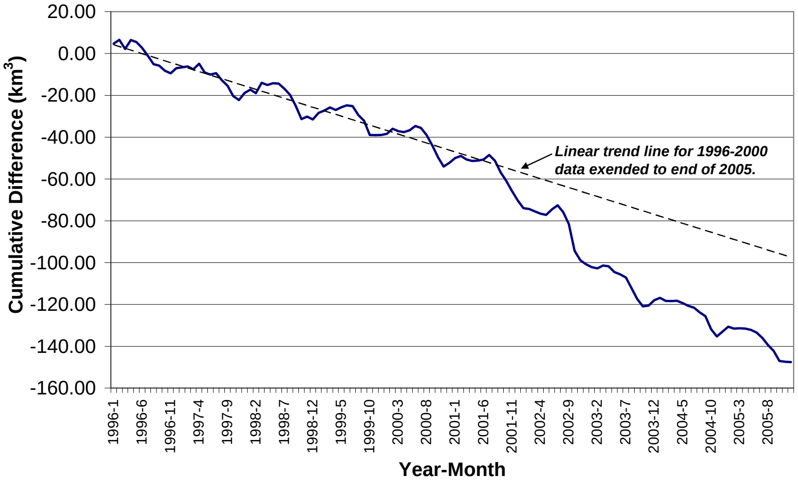

Figure 6. Cumulative difference of residual and component NBS for Lake Michigan-Huron for 1996 through 2005 (residual - component).

The result of the above MH NBS averaging strategy on simulated lake level predictions is shown in Figure 7 and demonstrates that it is fairly effective as average absolute model prediction errors for 2001-2005 are reduced from 24 cm to 11 cm for Lake MH, 16 cm to 10 cm for Lake Erie and 22 cm to 13 cm for Lake St. Clair. Although not shown, the cumulative differences in simulated and measured Lake Erie outflows are also reduced as a result of the NBS adjustments (cumulative differences as of end of 2005 are reduced by approximately 33%). Since there is no justification for further NBS adjustments (beyond fitting more precisely to observed lake levels) no further adjustments are considered and the 2001-2005 monthly NBS inputs to CGLRRM are taken as the average of residual and component NBS in the remainder of this report unless otherwise noted. Also note that for reasons described at the beginning of Section 2, the analyses in this work are based on component NBS rather than residual NBS whenever possible.

Figure 8 shows the simulated versus measured MH-Erie lake fall over time for various time steps and demonstrates that using the adjusted NBSs for 2001 through 2005 enables the model to much better replicate the measured data trend in MH – Erie lake fall for this period. Furthermore, instead of predicting a 6 cm increase in lake fall between 2001 and 2005, the adjusted MH NBSs for 2001-2005 generate a 2 cm decrease in lake fall for this period which is more consistent with the observed lake fall decrease of 12 cm.

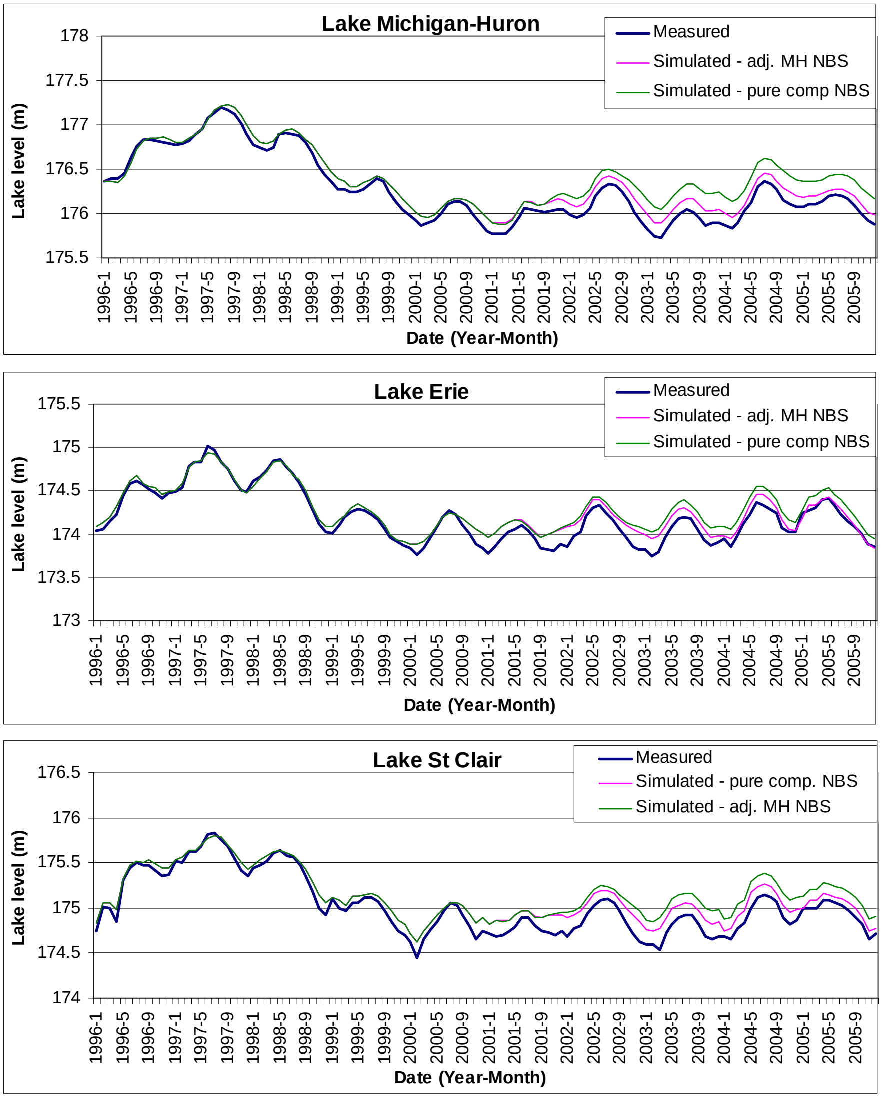

Figure 7. Comparison of measured (coordinated) and simulated average monthly lake levels for the middle Great Lakes using Lake MH component NBS for 1996-2000 and average of Lake MH component and residual NBS for 2001-2005.

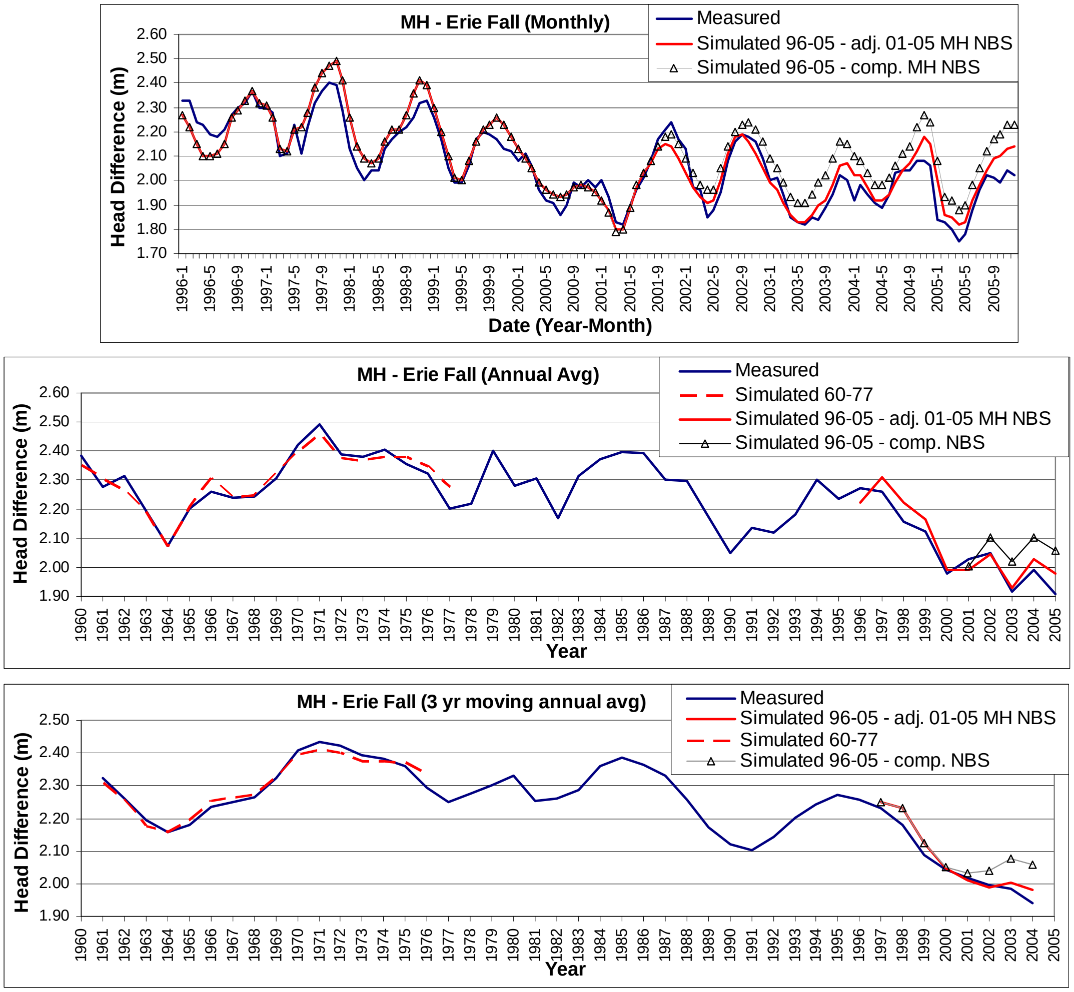

Figure 8. Simulated and measured lake fall (head difference) between Lake Michigan-Huron and Lake Erie for various time steps (monthly average, annual average, and three year moving annual average lake levels). The “Simulated 96-05 – comp. NBS” series’ are the same simulated results using only component NBS from Figure 5.

2.4.1 Baseline Model Metrics for quantifying the fall (head difference) between Lake Michigan-Huron and Lake Erie

This section summarizes the set of selected metrics (a subset of the potential metrics listed Tables 1 and 2) that will be used as a baseline in which all further modelling scenarios and experiments in later sections will be compared to. Table 3 below compares the measured and simulated change in lake fall metrics. The numbers in these tables are based directly on the various time series in Figure 8.

The first metric, referred to as M_1, covers the 1997-2000 period and is equal to the (1997 average lake fall) - (2000 average lake fall). M_1 is an important metric because the simulated metric is not impacted by the adjustment to MH NBS for the 2001-2005 period. The second metric, referred to as M_2, covers the 1997-2005 period and is equal to the (1997 average lake fall) - (2005 average lake fall). The third metric, referred to as M_3, is based on the 3-yr moving average of annual average lake fall and covers 1997 (average of 96, 97 and 98) through 2004 (average of 96, 97 and 98). All metrics are simulated within -6% to 13% of the measured values.

Table 3. Measured and simulated metrics for assessing change in head difference across different periods based on annual average lake levels.

Metric Name	Period	Change in **Measured** Head Diff. = Initial – Final avg. annual head difference, m	Change in **Simulated (96-05 model with adj. NBS, Eq. 2)** Head Diff. = Initial – Final avg. annual head difference, m	Simulation Error in m (%)[a]
M_1	1997-2000	0.28	0.32	0.04 (13%)
M_2	1997[b] -2005	0.35	0.33	-0.02 (-6%)
M_3	97 $_{\text{3-yr moving avg}}$ – 04 $_{\text{3-yr moving avg}}$	0.29	0.27	-0.02 (-7%)

a) Error computed as Simulated – Measured and use more precision than shown in previous two columns.
b) 1997 selected over 1996 as initial year because difference simulated M_2 is much closer to measured M_2.

The model with adjusted MH NBS shows an improvement in simulating the lake fall metrics. For example, Table 3 shows the simulated M_2 metric of 0.33 m more closely matches the measured M_2 metric of 0.35 m in comparison to the 0.25 m result of the unadjusted NBS model in Table 1. Now, in comparison to the 0.51 m measured drop in lake fall between 1994-2007, the model is assessing 69% (e.g. measured 97-05 drop / measured 94-07 drop), rather than 55% of the behaviour of concern when predictions were based on component NBS for Lake MH.

2.5 Analysis of Conveyance Change Impact on Lake Fall

2.5.1 Scenario Analysis for 1996-2005 Period

This section assesses what the model predicted lake falls would be if the conveyance regime for the 1962-1977 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). All model inputs were the same as those used to simulate the results in Figure 8 (adjusted 01-05 MH NBS) and the only change was reverting back to Eq. (1).

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 22-25% of that change. All other factors taken together, such as change in NBS and differential isostatic rebound, have a more controlling influence on this change in head difference.

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

Table 4. Evaluation of conveyance change impact on the change in head difference using various simulated metrics. Note that metric M_1 is based on only component NBS while the other two are influenced by the adjustment to 2001-2005 MH NBS inputs.

Metric, Period	BASELINE Change in **Simulated (w Eq. 2)** Head Diff. = Initial – Final avg. annual head difference, m	Change in **Simulated (w Eq. 1)** Head Diff. = Initial – Final avg. annual head difference, m	% of baseline change in head difference due to conveyance change[a] (brackets are % attributed to other factors)
M_1, 1997-2000	0.32	0.24	23 (77)
M_2, 1997-2005	0.33	0.26	22 (78)
M_3 (3 yr moving avg), 1997-2004	0.27	0.20	25 (75)

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

It is also important to note the direct impact the conveyance change (as simulated in CGLRRM) has on Lake MH levels. On average, MH lake 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 MH lake level, is a difference in 2005 MH lake level of 10 cm.

2.5.2 Scenario Analysis of Steady-State Lake Levels

The scenario analysis in Section 2.5.1 was repeated with all model inputs set to constant (steady-state) values starting Jan. 1, 1996. The constant values of CGLRRM inputs (NBSs, 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 outputs files written with two decimal places of precision) as they are equal to the lake levels after 50 years of steady-state inputs were simulated. At steady-state, a comparison of the fall differences between using Eq. (1), the old 1962-1977 conveyance regime, and Eq. (2), the new 1996-2006 conveyance regime, shows that the conveyance change to the new regime induced a 9 cm decrease in the fall difference. This steady-state change in fall difference is only 18% of the 1994-2007 measured change in fall difference (51 cm) between Lakes MH and Erie.

Table 5. Evaluation of conveyance change impact on the steady state MH-Erie fall difference.

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)**	**Fall difference (m)**
Eq. 1, old conv.	176.36	174.06	176.54	174.30	176.54	174.30	2.24
Eq. 2, new conv.	176.36	174.06	176.44	174.30	176.45[a]	174.30	2.15
						Eq. 2 - Eq. 1:	***0.09***

a) Lake MH reached 176.45 m after 15 years.

3 Stochastic Modelling Analyses

3.1 Model Input Changes for Stochastic Analyses

The analyses conducted Section 3 are designed to assess the distribution of MH-Erie lake fall 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) will be conducted to generate the alternative NBS time series. Note that the analyses are not designed to assess the impact of the uncertainty of historical NBS estimates (our best estimates of historical NBS developed in Section 2.4 are assumed correct). Instead, the analyses here are designed to evaluate the distribution MH-Erie lake fall 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 coordinated routing 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 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 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. Lake superior levels are simulated and the flow of the St Marys River is the result of Plan77A regulation strategy that is coded into the model. In other words, CGLRRM is capable of simulating the flow 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 months St. Marys River flow is set to the coordinated measured Dec. 1995 average monthly flow.

Changes 1 and 2 above were evaluated for their impact on the simulated metrics for the 1996-2005 period by implementing the changes and then running the model with the adjusted MH NBS inputs. Lake level simulations are compared with historical lake levels in Figure 9 below. The results in Figure 9 demonstrate that the changes do not inhibit the model from simulating the variation in time of MH and Erie lake levels. In fact, simulated lake levels for Lakes MH and

Erie are now appear slightly closer to their measured lake levels later in the simulation in comparison to simulations without changes 1 and 2 (see Figure 7).

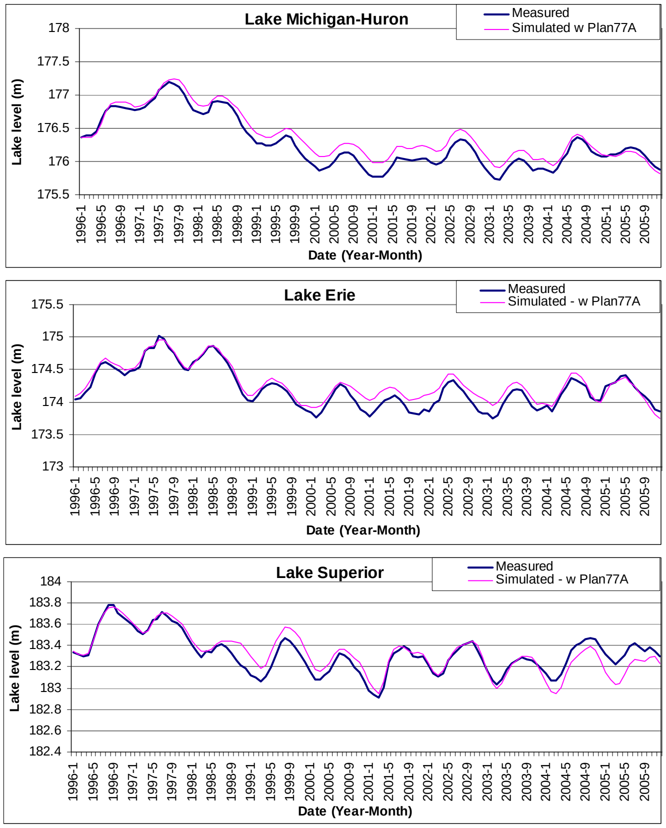

Figure 9. Comparison of measured (coordinated) and simulated average monthly lake levels for Lakes Superior, Michigan-Huron and Erie. The Plan 77A designation is used to indicate that both model changes 1 and 2 as described in Section 3.1 were implemented. These simulated lake levels are used to update the change in lake fall metrics in Table 6.

3.2 Metrics for quantifying the fall (head difference) between Lake Michigan-Huron and Lake Erie in Stochastic Experiments

The three previous baseline simulation metrics (M_1, M_2 and M_3) are recomputed (and renamed with a subscript "s" for stochastic) in Table 6 and demonstrate some small variations from the previous deterministic baseline simulation metrics. However, these small deviations are unavoidable. The M_{2s} metric shows the largest deviation from the previous metric value and in fact is now further from the measured M_2 metric (+0.05 m instead of -0.02 m). Therefore, the stochastic simulation results will not be evaluated with respect to M_{2s}. The simulated baselines therefore become M_{1s} = 0.27 m and M_{3s} = 0.31 m for comparison against all stochastic simulation results.

In order to calculate comparable metrics from the stochastic simulation results, the calculation of the simulated metrics must be modified. The simulated and measured M_{1s} and M_{3s} metrics in

Table 6 are based on a fixed year to fixed year change in fall difference and these fixed years become irrelevant when simulating alternative sequences of NBS. For example, M_{1s} compares 1997 with 2000 (4 yr period) and M_{3s} compares 1997 and 2004 (8 yr period). The calculation of the simulated M_{1s} metrics for the stochastic simulations is thus taken to be the maximum change in fall of all the 3 yr or 4 yr periods during the 10 year (1996-2005) simulation. Similarly, the calculation of the simulated M_{3s} metrics for the stochastic simulations is thus taken to be the maximum change in fall of all the 3, 4, 5, 6, 7 and 8 yr periods during the 10 year (1996-2005) simulation.

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 MH-Erie lake fall difference is less than or equal to the historically low value of 2.051 m for the measured data in 1990 (see Figure 10). Metric M_5 is defined as the number of years when the 3-yr moving average of the MH-Erie lake fall differences is less than or equal to the historically low value of 2.101 m for the measured data in 1991 (see Figure 10). Metrics M_4 and M_5 are also tabulated for the measured and simulated data in Table 6.

Table 6. Measured and updated (for stochastic experiments) simulated metrics for assessing change in head difference across different periods based on annual average lake levels.

Metric Name	Period and description	Change in **Measured** Head Diff. = Initial – Final avg. annual head difference, m	Baseline metrics for stochastic analyses. **Simulated** Head Diff. = Initial – Final avg. annual head difference, m
M_{1s}	1997-2000	0.28	0.27 (0.32)^b
M_{2s}	1997^b -2005	0.35	0.40 (0.33)^b
M_{3s}	97 $_{\text{3-yr moving avg}}$ – 04 $_{\text{3-yr moving avg}}$	0.29	0.31 (0.27)^b
M_{4s}	Count of yrs where ann. avg. head diff. below 1990 value of 2.051 m	6 (count of yrs, not m)	5 (count of yrs, not m)
M_{5s}	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 difference simulated M_2 is much closer to measured M_2.
b) Brackets contain previous metric value for deterministic analyses as presented in Table 3.

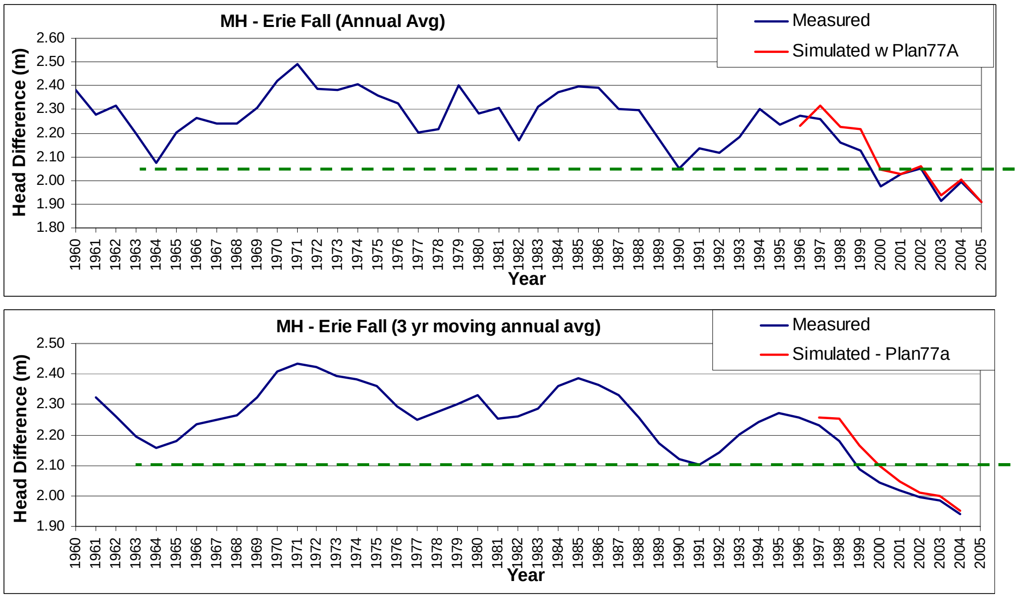

Figure 10. Illustration and rationale for additional change in lake fall metrics (M_4 and M_5). The dashed lines are the lows in the measured data for the 1960-1995 period.

3.3 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 statistic of interest (in this case, the metrics for change in MH-Erie lake fall difference over the 1996-2005 period) that is calculated as a function of sampled time series. This repeated sampling of the statistic 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 with uniform probability and with replacement one of the *N* blocks and concatenating the blocks together until a time series of the desired block length has been generated.

Vogel and Shallcross (1996) note that In this application of the bootstrap, the entire set of NBS time series (Lakes Superior, MH, St. Clair and Erie) and 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 NBSs (and ice and weed factors) across the four 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. Note that the 2001-2005 MH NBS data sampled in the bootstrap experiments are the adjusted values (average of residual and component) as described in Section 2.4. 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 involves 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 NBSs make hydrological sense because this coincides with the beginning of the snow melt / ice free period for the Great Lakes basin. The switch from winter climate conditions to spring melt conditions should generate NBSs that are not correlated since baseflow type flow conditions at the end of winter are not good predictors of the spring time 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 (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 four years in length. Block lengths more than four years were considered too long given that the length of the time series to constructed by the moving blocks bootstrap was 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 0.19 for lake MH). However, when the total NBS of all four lakes was considered, the lag-1 autocorrelation was statistically significant. (5% level). The lag-1 cross correlations between Lake MH (yr i+1) and all other lakes (yr i) were 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 (April 1 to March 31) 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.

All moving block bootstrap experiments sample 1000 10-yr sets of input time series and thus involve 1000 CGLRRM simulations. The 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.

3.4 Bootstrap Experiment set 1: Sample 1948-2005 then 1948-2000 periods

Experiment set 1 was designed for two main purposes. First, it is used to assess the potential impact of the MH NBS data adjustment on the stochastic modelling findings. Second, it is used to assess how unique or extreme the baseline behaviour of the system was under the actual set of 1996-2005 NBS time series. Uniqueness is measured relative to the distribution of possible alternatives (1000 of them). Experiment 1a samples from the entire 1948-2005 period while experiment 1b samples from the 1948-2000 period. Note that CGLRRM inputs are as described in Section 3.1 and Eq. (2), describing the current St. Clair River conveyance regime of the, is the equation for simulating St. Clair River flows.

Table 7 summarizes the two experiments in terms of the average metric values. Based on these averages, it can be seen that there are only very small differences in the metrics if the MH NBS adjustment years are ignored and not sampled from in the bootstrap experiment. Therefore, it appears that the inclusion of the adjustment period for MH NBS data does not change the metrics very much and as such, the remaining bootstrap experiment set will sample from the 2001-2005 period of model inputs.

Table 7. Average simulated stochastic change in head difference metrics (across 1000 simulations) for bootstrap experiment set 1 (sample periods varied). Each simulation length is 10 years and all simulations initialized to Jan. 1, 1996 lake levels.

Experiment #	**M_{1s} (m)** max 3-yr or 4-yr fall w ann. avg.	**M_{3s} (m)** max 3-yr to 8-yr fall w moving avg.	**M_4** (count of yrs with avg. lake fall ≤ 1990 low lake fall)	**M_5** (count of yrs with moving avg. lake fall ≤ 1991 low lake fall)
1a (sample 1948-2005 period)	0.24	0.14	1.7	2.0
1b (sample 1948-2000 period)	0.23	0.13	1.4	1.7

The averages in Table 7 are imperfect measures for assessing how extreme the baseline system behaviour is. Instead, Table 8 gives the probabilities that equal or more extreme stochastic simulated metrics are observed relative to the baseline metrics derived in Section 3.2. For example, for the M_{3s} metric, 8 of 1000 simulations in Experiment 1a generated a stochastic metric that was equal to or larger than 0.31 m. Considering all the metrics in Experiment 1a, the system behaviour resulting from the actual 1996-2005 NBS time series' was fairly "unique". Considering experiment 1b, which does not sample from half of the unique period, the probabilities not surprisingly go down in Table 8. This would continue to further decrease if the sampling was restricted to pre-1995 data.

Experiment 1a results are also analyzed to begin to shed some light on the role NBS inputs have on generating conditions on Lake MH that stakeholders might be concerned about. For the purposes of this analysis, two hypothetical conditions defining non-extreme behaviours are assumed to be:

1. Assume a 0.10 m or less M_{3s} drop metric over the 10-yr simulation period would not generate stakeholder concerns given that the baseline stochastic metric for 1997-2004 is 0.31 m.
2. Assume that any simulation with annual average 1996-2005 lake MH levels that are always above 176.35 m would not generate stakeholder concerns given that the historical 1990 low annual average lake level for the 1960-1995 period was 176.35 m.

The 1000 simulations were evaluated for both of these conditions and it is assumed that lake behaviour resulting in condition 1 and/or condition 2 would not generate anywhere near the concern that stakeholders voiced under the actual 1996-2005 lake MH behaviour. Under the above conditions, just over 50% of all simulated MH lake levels would not have created any concern (one or both condition 1 or 2 occurred). Regardless of the accuracy of hypothetical conditions 1 and 2, what this analysis shows is that climate (NBS) variability clearly plays a controlling role in the behaviour of lake levels.

Table 8. Probabilities that the simulated metric value is equal or more extreme than the baseline metric value for bootstrap experiment set 1 (sample periods varied). Each simulation length is 10 years and all simulations initialized to Jan. 1, 1996 lake levels.

Experiment #	**Prob($M_{1s} \geq 0.27$ m)**	**Prob($M_{3s} \geq 0.31$ m)**	**Prob($M_4 \geq 5$ yrs)**	**Prob($M_5 \geq 5$ yrs)**
1a (sample 1948-2005 period)	0.36	0.08	0.12	0.18
1b (sample 1948-2000 period)	0.33	0.06	0.09	0.14

3.5 Bootstrap Experiment set 2

In this set of experiments, the independent impacts of both the NBS (climate) era 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). Section 3.5.1 below outlines how the climate (NBS) factor can be described and thus controlled in the modelling experiments similar to conveyance change. Just like conveyance, two distinct periods of climate (NBS data) are identified: the latest climate era during which the extreme lake fall behaviour has been observed and the previous climate era.

3.5.1 Climate Era Identification

Evidence to suggest the existence of multiple different eras of climate in the Great Lakes basin over the past 60 years can be found in the Ouarda (2008) report to the Hydroclimate TWG, and the some important findings in this report are summarized as follows:

- a statistically significant change point occurs in component NBS to lake Superior in 1966
- a likely change point in the Lakes MH – Erie fall difference time series occurred around 1988, however, no change points in any of the NBS time series' around 1988 were identified

- a statistically significant change point identified for Lake Erie component NBS in 1981 was identified

These change point findings in Ouarda (2008) provide some guidance on the definition of the two most recent climate eras. The change point analysis for each time series is multivariate in nature and therefore identifies change points on more information than the time series being examined (e.g. Lake MH NBS).

The first decision was to use the statistically significant change point for Lake Superior (1966) as the start of climate era 1 such that the NBS data from 1948-1965 is disregarded in this experiment set. Then, the two other change point findings in Ouarda (2008) were evaluated to assess the point in time to divide the last two climate eras. The Lake Erie change point of 1981 is not a good candidate because it does not appear consistent with the NBS data as shown in Figure 11A where it could be argued that data from 1981 to 1986 fall on the linear trend line of the previous period. Furthermore, the 1981 change point generates a trend in the current climate era Lake Erie NBS that is potentially inconsistent, from a hydraulic perspective, with the observed behaviour of the recent lake fall difference – especially when an alternative point in time of 1987 is considered as the division between climate era 1 and 2 (see Figure 11B). Based on the 1988 lake fall difference change point and the 1981-1986 data in Figure 11, 1987 became an obvious choice for the alternative change point. 1987 is considered a more representative change point in large part because it generates a trend in the current climate era NBS for Lake Erie that is hydraulically consistent with the observed MH-Erie change in fall difference over time. Note that during the 1987-2005 period, although not shown here, Lake MH trend is downwards and thus Lake Erie supplies are increasing as Lake MH supplies are decreasing. The same result (change in trend that is hydraulically consistent with observed behaviour) occurs when the 1981 versus 1987 change points are considered on Lake St. Clair.

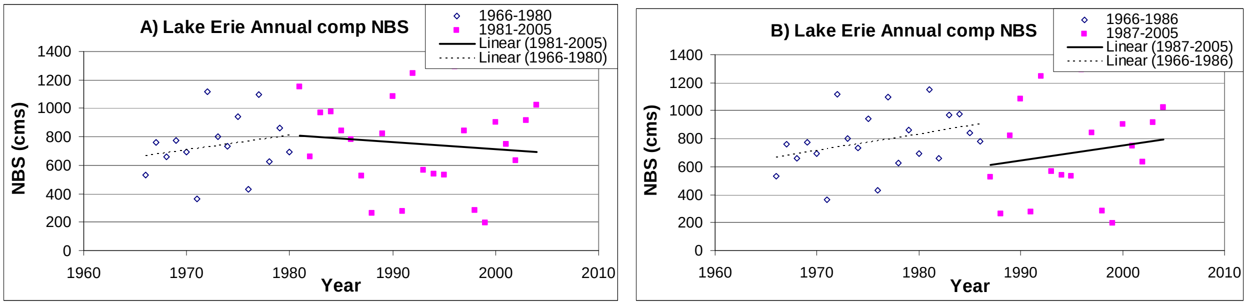

Figure 11. Comparison of Lake Erie annual NBS (Apr-Mar year) with 1981 (A) and 1987 (B) as the dividing year between climate era 1 and climate era 2 (current era). Note that data in both A) and B) are exactly the same, the only difference is whether the years 1981-1986 are considered to belong in climate era 1 or 2.

The above analysis does not consider whether the differences between the climate eras (e.g. sloes of trend lines, average NBS etc.) under either change point are statistically significant. Instead, the analysis is based on an understanding that if Lake MH NBS decreases and Lake Erie NBS increases, the MH-Erie lake fall difference *will* decrease. This is observed using the 1987 change point and therefore, the question of statistical significance in this context is at most a secondary concern. Therefore, the two climate eras for experiment set 2 are defined as 1966-1986 and

1987-2005. As such, the impact of climate era, can be assessed by performing two bootstrap sampling experiments that differ only in the climate eras they sample from.

3.5.2 Results

Three bootstrap sampling experiments were conducted and are described as follows:

- Experiment 2a) samples 10-yr sets of inputs for CGLRRM from the 1987-2005 climate era and simulates St. Clair River flows with the current conveyance equation - Eq. (2).
- Experiment 2b) samples 10-yr sets of inputs for CGLRRM from the 1966-1986 climate era and simulates St. Clair River flows with the current conveyance equation - Eq. (2).
- Experiment 2c) samples 10-yr sets of inputs for CGLRRM from the 1987-2005 climate era and simulates St. Clair River flows with the conveyance equation for the 1960-1977 conveyance regime - Eq. (1).

Note that the same 1000 sets of model inputs are utilized in Experiment 2a and 2c since they sample from the same climate era. This enables more 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 9) and a table of probabilities the simulated metrics exceeded the baseline stochastic metric values (Table 10).

Table 9. Average simulated stochastic change in head difference metrics (across 1000 simulations) for bootstrap experiment set 2 (conveyance regimes and climate eras varied). Each simulation length is 10 years and all simulations initialized to Jan. 1, 1996 lake levels.

Experiment #	**M_{1s} (m)** max 3-yr or 4-yr fall w ann. avg.	**M_{3s} (m)** max 3-yr to 8-yr fall w moving avg.	**M_4** (count of yrs with avg. lake fall ≤ 1990 low lake fall)	**M_5** (count of yrs with moving avg. lake fall ≤ 1991 low lake fall)
2a (1987-2005 climate, new conv. Eq. 2)	0.21	0.12	1.7	2.3
2b (1966-1986 climate, new conv. Eq. 2)	0.14	0.05	0.1	0.1
2c (1987-2005 climate, old conv. Eq. 1)	0.19	0.10	0.4	0.4

Comparing the average metrics in Table 9 shows that the change in climate era has a much larger impact (compare 2b results to 2a results) on the metrics than the change in conveyance (compare 2c results to 2a results). With the post-1977 conveyance change simulated, the average M_{3s} drop metric for the MH-Erie head difference across 1000 model simulations is calculated to be 59% lower when 1966-1986 climate era is sampled instead of the 1987-2005 climate era. This percentage is 34% when the M_{1s} drop metric is utilized. Compare these percentages to the impacts of conveyance change (experiment 2c) where simulating under the old conveyance regime only reduces the M_{1s} and M_{3s} drop metrics by 9% and 18%, respectively. Based on the averages of the metrics that are based on the magnitude of the change in fall difference (e.g. units of m), the change in climate era is more than three times as influential (59/18 and 34/9) as the post-1977 change in conveyance considering.

The impact of conveyance change using the overall averages is a rough measure and can be made more 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 drop 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 10), a more refined conveyance change impact can focus only on those pairs of simulations when the result in experiment 2c was deemed to be extreme. If the criteria for extreme behaviour is defined as one or more of the three longer term simulated metrics (M_{3s}, M_4 or M_5) are equal or more extreme than the baseline stochastic metrics, 183 pairs of simulation results are available for reassessing conveyance change impacts. Based on these pairs, the average pairwise impact of conveyance change shows that 21% (0.04 m) of M_{3s} is due to conveyance change. The range of these pairwise impacts based on the absolute magnitudes of the M_{3s} metric range are from 0.0 m (0%) to 0.11 m (34%). If the criteria for extreme behaviour is only defined with respect to the simulated M_{3s} metrics being equal or more extreme than the baseline stochastic metric, 25 pairs of simulation results are available for reassessing conveyance change impacts. Based on these pairs, the average pairwise impact of conveyance change shows that 18% (0.06 m) of M_{3s} is due to conveyance change with the range remaining the same as the range with 183 pairwise comparisons.

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

Experiment #	**Prob($M_{1s} \geq 0.27$ m)**	**Prob($M_{3s} \geq 0.31$ m)**	**Prob($M_4 \geq 5$ yrs)**	**Prob($M_5 \geq 5$ yrs)**
2a (1987-2005 climate, new conv. Eq. 2)	0.227	0.025	0.103	0.200
2b (1966-1986 climate, new conv. Eq. 2)	0.033	0.001	0.000	0.001
2c (1987-2005 climate, old conv. Eq. 1)	0.140	0.005	0.004	0.018

Table 10 also shows results consistent with Table 9 in that the impact conveyance change has on the probabilities of extreme metric values is smaller than the impact of climate era change. Furthermore, in experiment 2b, when the current conveyance regime was simulated, only 1 of 1000 alternative NBS sequences sampled from the 1966-1986 period generated simulated metric (lake level) behaviour that could be considered equal or more extreme than the baseline metrics representing the historical conditions observed from 1996-2005. What this means practically is that if the climate era from 1966-1986 persisted to present day (as represented by the moving blocks bootstrap sampling approach described previously), the climate impacts would overwhelm the conveyance change impacts and it would be extremely unlikely we would have ever observed the extreme lake fall behaviour over the past 10-15 years.

4 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 just not possible in this report. However, experiments should eventually be repeated for a variety of coefficient sets that are nearly as plausible as those in Eq. (2).
- 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 the conveyance equation that better represents the current conveyance regime (Eq. 2).
- Another issue is that the calculation of the ice and weed factors requires the measured connecting flows such that a one type of system behaviour must 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 2 (e.g. Figure 7 and Figure 8 simulated results) through the end of 2007 to see if the trend in MH-Erie lake fall difference is reasonably captured by CGLRRM. This would build even more confidence in the general findings of this report.
- Any future extensions to this analysis should utilize the late-breaking Mar 31, 2009 updates to the component NBS estimates across all the lakes such that all the model runs and experiments described above be repeated. Importantly, upon examining this new data, it seems extremely unlikely this new data will increase the estimated impact of conveyance change on the MH-Erie fall difference. On the contrary, if findings did happen to change noticeably, they are forecasted to show a reduced impact of conveyance change relative to NBS impacts. This is because relative to the previous component NBS version used in this report, the new NBS data reduces NBS to Lake MH and increases NBS to Lake Erie on average over the 1996-2005 period. In addition, it seems likely that the largest prediction CGLRRM prediction errors for the 2001-2005 will be reduced with this new NBS data. At the very least, a preliminary analysis suggests that the new component NBS data would eliminate the need for the MH NBS adjustment in Section 2.4 and in fact validates the adjustment to the MH NBS inputs for 2001-2005 in this report.
- Future modelling experiments could be designed to confirm/demonstrate that for the conveyance change that occurred between 1977-1995, the MH lake level (or MH-Erie fall difference) will not continue to drop to more extreme lows in response to this conveyance change.

5 Conclusions

The assessment of CGLRRM prediction quality under various inputs is found to be fairly reflective of measured lake levels and thus increases confidence that CGLRRM is 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 1962-1977 lake levels (and lake fall behaviour) with a lake to lake stage fall equation developed by Fay and Noorbakhsh (2004) for the 1962-1999 period.

1b) CGLRRM, based on component NBS, can reasonably replicate 1996-2000 lake levels (and lake fall behaviour) with a new lake to lake stage fall equation developed for the 1996-2006 period.

1c) Reasonably accurate CGLRRM predictions for the 2001-2005 period are not possible with component NBS data for Lake MH. Reasonable predictions are achieved when the average of component and residual NBS for Lake MH are input to the model for 2001-2005 period. Some correction to the data is warranted given an analysis of lake MH component and residual NBS data from 2001-2005 shows the level of disagreement between the two to be particularly high. The correction appears to be completely justified based on an examination of the latest NBS data available from GLERL as of Mar 31, 2009 (and thus not utilized for any of the findings in this report).

The deterministic scenario modelling analyses in Section 2 yielded the following findings:

2a) The post-1977 conveyance change on the St. Clair River was estimated to cause between 22% and 25% of three different drop in head difference metrics considered. If residual NBS is used to drive the model, these percentages are virtually unchanged and range from 21% to 22%. Other factors were responsible for 75% to 78% of the drop in head difference metrics. The metrics quantify the drop in head difference for various periods and measures for the 1996 to 2005 period.

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

The stochastic modelling analyses in Section 3 yielded the following findings:

3a) The system behaviour resulting from the actual 1996-2005 NBS time series' was fairly "unique" in comparison with the distribution of possible 10-yr NBS sequences sampled from the 1948-2005 period (1000 samples).

3b) Even with the post-1977 conveyance change, 50% of the 1000 alternative NBS sequences sampled from the 1948-2005 period would have generated a drop in head difference and/or Lake MH levels that would be unlikely to cause concerns among stakeholders.

3c) Two climate eras were defined as 1966-1986 and 1987-2005 after considering the work in Ouarda (2008) and the component NBS data across the lakes.

3d) With the post-1977 conveyance change simulated, the average drop in MH-Erie head difference across 1000 model simulations is estimated to be 59% lower when 1966-1986 climate era is sampled instead of the 1987-2005 climate era. Furthermore, only 1 of 1000 alternative NBS sequences sampled from the 1966-1986 period generated head difference behaviour that could be considered equal or more extreme than the historical conditions observed from 1996-2005.

3e) The change in climate era is more than 3 times as influential as the post-1977 change in conveyance considering their impacts on the magnitude (in m) of the drop in head difference metrics (M_{1s} and M_{3s}).

Multiple analyses were conducted to attribute some percentage of responsibility to the change in conveyance for the drop in MH-Erie lake fall difference. The various deterministic analyses yielded estimates of 21%, 22%, 23% and 25%. The various stochastic analyses yielded 9%, 18% and 21%. 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 and is more likely responsible for approximately 1/4 of the drop in head difference. 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 simulated run with adjusted NBS (see Figure 7 and Figure 8)

```
#    Complete Input Listing of CGLRRM Run at 22:46:14, 09Mar2009

 #    You should be able to reproduce the results of this run simply by using
 #    this section as an input parameter file (provided the same external
 #    time-series data files are available in the same locations, and excepting
 #    differences due to model version).
 #    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 to 2005.  MH NBS is average of rNBS & cNBS FOR 96-00, everywhere
else is c
                  Title 2: Using updated Ice Retardation, equation and initial condition
 #                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_9-5\
         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_AVG_rcNBS_96-00.prn
        Chicago Div. Data: 10m3s, constant, 9.1
 #     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\WELLANDM.txt
#    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    ........................
#    ###############################################################################
#    ###############################################################################
#    ###############################################################################
#    ###############################################################################
#    ###############################################################################
```