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Final Report:

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

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53 1 Executive Summary

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

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

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

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

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

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

- 93 1a. CGLRRM, based on component NBS, can reasonably replicate 1963-1977 lake levels
94 (and head difference behaviour) with an open water lake-to-lake stage-fall equation
95 developed by Fay and Noorbakhsh (2004) for the 1963-1999 period.
- 96 1b. CGLRRM, based on component NBS, can reasonably replicate 1996-2005 lake levels
97 (and drop in head difference) with a new open water lake-to-lake stage-fall equation
98 developed for the 1996-2006 period.
- 99 1c. The notable lake level prediction errors for the 2001-2005 period for Lake Michigan-
100 Huron cannot solely be explained by an error in the assumed lake-to-lake stage-fall
101 equation.

102 Deterministic modelling scenario analyses yielded the following findings:

- 103 2a. The post-1977 conveyance change on the St. Clair River was estimated to cause
104 between 24% and 31% of three different change in head difference metrics
105 considered. The metrics quantify the change in head difference for various periods
106 and measures from 1996 to 2005. Other factors were attributed to be the cause of
107 69% to 76% of the metrics.
- 108 2b. A steady state analysis showed that with all flow inputs in the model set to their 1948-
109 2005 average values, post-1977 conveyance change was estimated to decrease the
110 steady-state Lake Michigan-Erie head difference by 9 cm. Compare this to the
111 measured drop in head difference of 51 cm (1994 to 2007).
- 112 2c. In direct contrast to 2b, a similar type of steady state analysis showed an 18 cm drop
113 in head difference could be completely attributed to observed shifts in average
114 component NBS data. For example, relative to the average component NBS data for
115 the 1963-1995 period, the average component NBS data for the 1996-2005 period
116 decreased by 0.12 m/yr for Lake Michigan- Huron and only decreased by 0.03 m/yr
117 for Lake Erie.
- 118 2d. The Great Lakes system response time to a one-time conveyance change of the St.
119 Clair River was explicitly shown to be finite in that such a change will not cause
120 continual loss of water from Lake Michigan-Huron and thus Lake Michigan-Huron
121 levels will not continue to decrease through time. Furthermore, it was shown that so
122 long as the assumed one-time change in conveyance occurred on or before 1996, the
123 actual date of conveyance change has no impact after 2003 on the cumulative volume
124 of water lost from Lake Michigan-Huron due to conveyance change.

125 The stochastic modelling analyses yielded the following findings:

- 126 3a. The system behaviour resulting from the actual 1996-2005 NBSs was very unique or
127 extreme in comparison with the distribution of possible 10-yr NBS sequences sampled
128 from the 1963-1995 period (1000 samples).
- 129 3b. Multiple extreme but plausible 10-yr NBS sequences were used to show that
130 conveyance change on the St. Clair River controls 13% to 22% on average, to a
131 maximum of 34% of the drop in head difference.

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

136 2 Introduction

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

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

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

- 160 1) The conveyance of the St. Clair River has changed since the last dredging activities in
161 1962 and this change has occurred sometime between 1977 and 1995.
- 162 2) There are at least two different eras or periods of climate (as represented by the NBS
163 time series) that have occurred across the Great Lakes since 1948 and a change point
164 between two of these eras occurs sometime in the 1977 to 1996 period.

165
166 To be consistent with the overall study focus on the post dredging period, the data and modelling
167 conducted in this study analyzes the period after 1962. Various analyses are conducted to best
168 describe the changes in the above two factors and then determine how much each factor
169 independently contributed to the drop in head difference between Lake Michigan-Huron and
170 Lake Erie. For brevity, the remainder of the report will use the phrase "head difference" to refer
171 to the head difference between Lake Michigan-Huron and Lake Erie. Section 3 focuses first on
172 CGLRRM model development to ensure the model simulates the past measured behaviour of the
173 lakes and then performs some deterministic scenario analyses to assess the contribution of the
174 change in channel conveyance to the drop in head difference. In Section 4, the importance of
175 both factors are independently assessed with a series of stochastic modelling experiments where
176 multiple NBS time series are randomly generated using a bootstrap resampling approach.

177 3 Deterministic Modelling Analyses

178
179 CGLRRM is a hydrologic routing model of the Great Lakes and is comprised of continuity
180 equations for each lake, solved using a second-order finite-difference technique (Quinn, 1978)
181 with a numerical time step of one hour. It uses as inputs time series of NBS and any diversions,
182 as well as initial outflows and lake levels, for each lake. The model calculates discharge from
183 each lake from an open-water lake-to-lake stage-fall-discharge equation with regression-based
184 coefficients. In the winter, flows in the connecting channels are naturally reduced by the
185 presence of ice. CGLRRM does not explicitly simulate the ice retardation process and instead
186 this phenomenon must be described by a time series of ice retardation rates (e.g. reduction in
187 connecting channel flow in m^3/s) for each channel. Caldwell (2008) provides a detailed
188 description of the ice retardation approach in CGLRRM and assesses the long term impacts of
189 apparent roughness factors, which include ice retardation on lake levels. Inputs for CGLRRM in
190 all analyses in this report are provided on a monthly time step (except for Niagara River ice
191 retardation rates which were available at a quarter monthly time step). In the deterministic
192 analyses in this section of the report, CGLRRM simulates the levels of Lakes Michigan-Huron
193 (considered to be a single lake for hydraulic purposes), St. Clair and Erie and uses as input the
194 estimated flows of the St. Marys River (coordinated monthly averages). The Chicago and
195 Welland Canal diversions are also inputs to the model (coordinated monthly averages).

196
197 Outputs of CGLRRM include monthly mean lake levels, beginning-of-month levels, and monthly
198 flow rates for the connecting channels. In this report, the simulated average monthly lake levels
199 are the focus and thus compared to the measured coordinated monthly average lake levels. Given
200 that other St. Clair River Task Team projects are focused on revising the historical coordinated
201 Detroit and St. Clair river flows, CGLRRM predictions of these flows were not assessed and
202 instead the simulated system outflows from Lake Erie (Welland Canal + Niagara River) are
203 compared to the coordinated Lake Erie outflows.

204
205 The deterministic model analyses conducted in this section are focused on developing the most
206 representative CGLRRM model of the midlakes as possible for the recent past (1996-2005). In
207 addition, a second representative CGLRRM model of the 1962-1977 period is also identified.
208 Although these two periods are assumed to exhibit a different conveyance regime, within each of
209 these periods the conveyance of the St. Clair River was assumed to be constant. The
210 representative 1996-2005 CGLRRM model will then form the basis for the deterministic (Section
211 3.3) and stochastic scenario analyses (Section 4). Demonstrating the model is representative
212 essentially means simulating past time periods to check the model can approximately simulate
213 the observed Lake Michigan-Huron, Lake Erie and Lake St. Clair water levels over time.

214
215 The most critical input to CGLRRM is the temporally varying net basin supply (NBS) for each
216 lake. The two methods for estimating NBS are referred to as component and residual.
217 Component NBS is net inflow to a lake and is calculated as $NBS = \text{over-lake precipitation} +$
218 $\text{runoff into the lake} - \text{over-lake evaporation}$. Residual NBS is calculated from other components
219 in the water balance equation (connecting channel flows, diversions and changes in storage over
220 the NBS time step) and can be useful because these quantities are more reliably measured in
221 comparison to the quantities in the component NBS estimate. See chapter 6.1.2 in IUGLS (2009)
222 for a more complete description of residual and component NBS estimation methods. Because

223 residual NBS estimates are derived from measured lake levels (beginning of month levels), using
224 the model with historical residual NBS values as inputs and then evaluating model predictions
225 against measured lake levels (average monthly or annual lake levels) is not a robust test of model
226 performance. Therefore, this report focuses as much as possible on using component rather than
227 residual NBS values for driving the model.
228

229 The focus of this study on the 1996-2005 period is based on a few considerations. Firstly,
230 component NBS data is only available through the end of 2005. Secondly, the quantitative
231 description of the current conveyance regime as described in Section 3.1 is based on a 1996
232 through 2006 data analysis. These considerations yield a simulation period of 1996-2005. In
233 addition to these two considerations, there appears to be little trend in the head difference from
234 1963-1995 and as of 1995, the head difference is within a few centimetres of the 1963-1995
235 average.
236

237 **3.1 St Clair River lake-to-lake stage-fall-discharge equations**

238
239 The conveyance of the St. Clair River is represented in CGLRRM by a lake-to-lake stage-fall
240 equation for open-water between Lake Michigan-Huron and Lake St. Clair. Prior to this study,
241 the equation for St. Clair River flow was taken to be Eq. (1) from Fay and Noorbakhsh (2004):
242

$$243 \quad Q=82.2((MH+SC)/2-166.98)^{1.87}(MH-SC)^{0.36} \quad (1)$$

244
245 where Q is the average monthly St. Clair River flow (m³/s), MH is the average monthly lake-
246 wide average level for Lake Michigan-Huron (m) and SC is the average monthly lake-wide
247 average level for Lake St. Clair (m).
248

249 The model is simulated with Eq. (1) along with the alternative component NBS (lake and land
250 precipitation) estimates from the Great Lakes Environmental Research Laboratory (GLERL).
251 Both of these simulated time series are compared to measured (coordinated) average monthly
252 lake levels for the 1963-2005 period in Figure 1. GLERL NBS data is described in Hunter and
253 Croley (1993) and the data used in these analyses are the updates as of Mar. 31, 2009 to
254 component NBS. The lake precipitation derived component NBS is based on the precipitation of
255 near lake rain gauges while land precipitation derived component NBS includes more inland rain
256 gauges. See Hunter and Croley (1993) for further details.
257

258 Considering the entire simulation period, Figure 1 shows that lake precipitation derived
259 component NBS is a slightly better predictor of lake levels for all three lakes. As such, all
260 remaining analyses will utilize lake precipitation derived component NBS. Comparing simulated
261 (LakePcp) lake levels to measured levels, it is also clear that between 1963 and 1977 the model
262 predictions are relatively accurate for all three lakes. However, after 1977, the model predictions
263 begin to diverge from the measured lake levels. On Lake Michigan-Huron, this divergence
264 grows with time and is very pronounced in the mid 1990s (average monthly prediction error is
265 0.28 m between 1994-1997) and even more so after 2002 (average monthly prediction error is
266 0.31 m between 2003-2005).
267

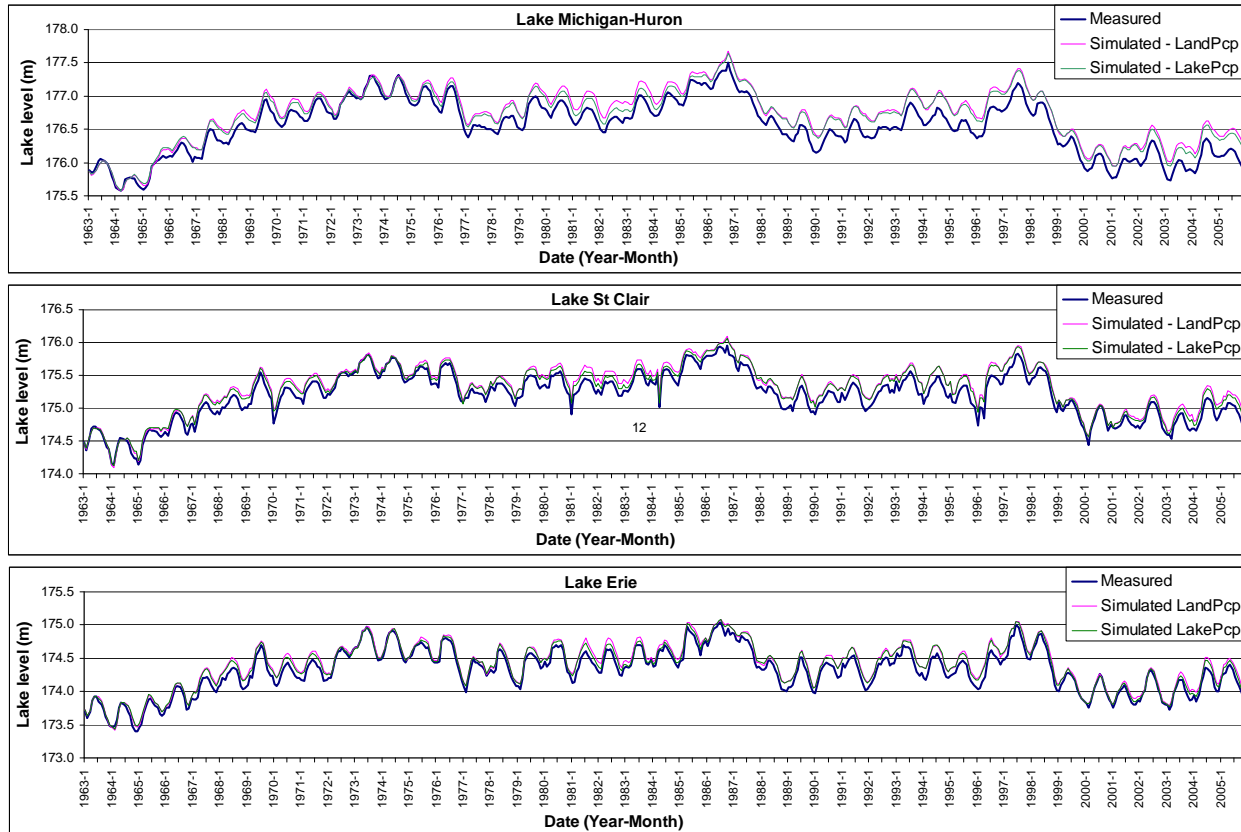


Figure 1. Comparison of measured (coordinated) and simulated average monthly lake levels for the middle Great Lakes from 1960 to 2005 using Equation (1) for St. Clair River flows.

268
 269
 270
 271
 272 Two potential causes (out of many) for the disagreement between model simulated and measured
 273 lake levels are 1) errors in the component NBS estimates and 2) changing St. Clair River channel
 274 conveyance over time. If errors in NBS were the main culprit and these errors were present for
 275 the entire time period, one would expect model prediction errors to be more prevalent than they
 276 are in the 1963-1977 period. Other studies in the St. Clair River TWG are finding that some
 277 channel conveyance change has occurred since 1977. Therefore, the CGLRRM improvement
 278 efforts in this study recognize a channel conveyance change has likely occurred after 1977 and as
 279 such focus on evaluating a revised lake-to-lake stage-fall equation to represent the current
 280 conveyance regime in the St. Clair River.

281
 282 A revised lake-to-lake stage-fall-discharge equation (see Eq. (2) below) relating the flow of the St
 283 Clair River to levels of Lakes Michigan-Huron and St. Clair was developed by David Fay of
 284 Environment Canada based on recent 1996-2006 Acoustic Doppler Current Profiler (ADCP) flow
 285 measurements. This was a multi-step process. First, a set of stage-fall-discharge equations were
 286 developed for 8 reaches between gauge locations on the St. Clair River using a dataset of about
 287 230 streamflow and water level measurements made between 1996 and 2006. These 8 stage-fall-
 288 discharge equations were then used to produce a set of monthly mean flows for the St. Clair
 289 River using monthly mean stages from 1962 to 2007 for the ice-free period (May – November).
 290 These monthly mean St. Clair River open-water flow estimates, along with monthly mean lake-
 291 wide average levels of Lakes Michigan-Huron and St. Clair, were then used to develop a lake-to-
 292 lake stage- discharge equation reflective of the recent conveyance capacity of the St. Clair River.

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

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

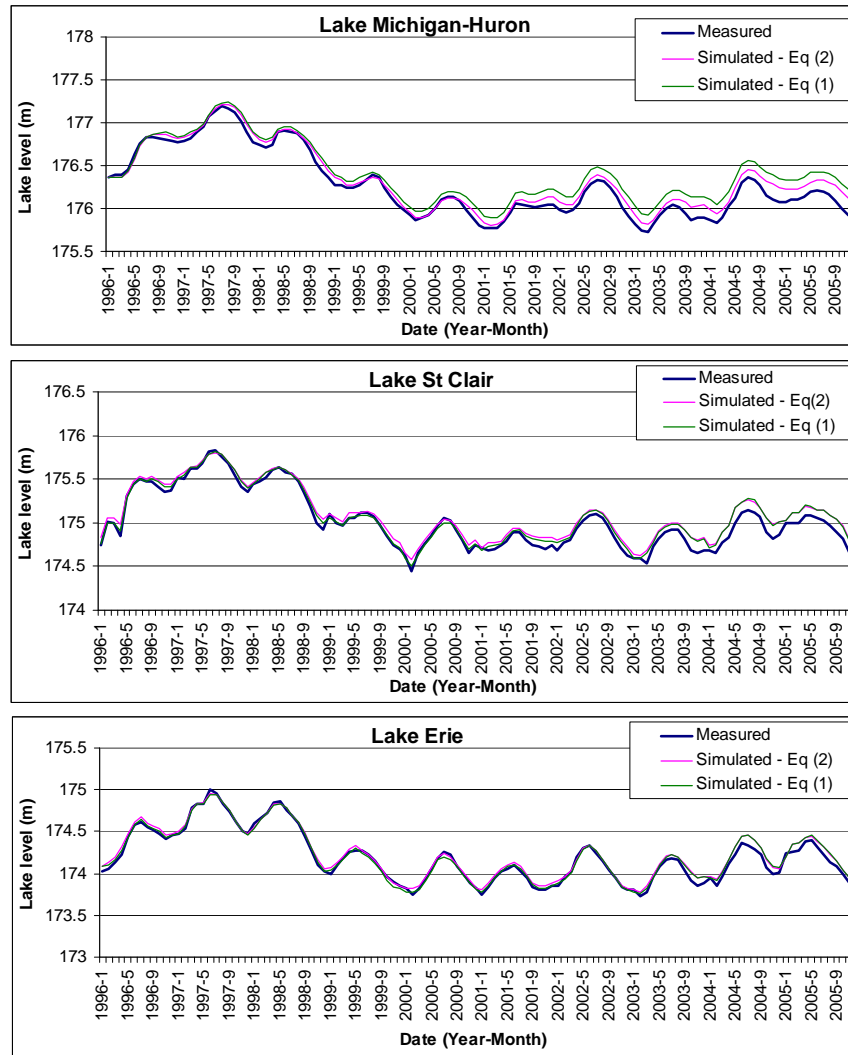
302 where Q is the average monthly St. Clair River flow (m³/s), MH is the average monthly lake-
303 wide average level for Lake Michigan-Huron (m) and SC is the average monthly lake-wide
304 average level for Lake St. Clair (m). The procedure for developing Equation (2) is described in
305 more detail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

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

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

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

338 demonstrates that changing to Equation (2) greatly reduces the cumulative under-prediction of
 339 Lake Erie outflows (by approximately 50%).
 340



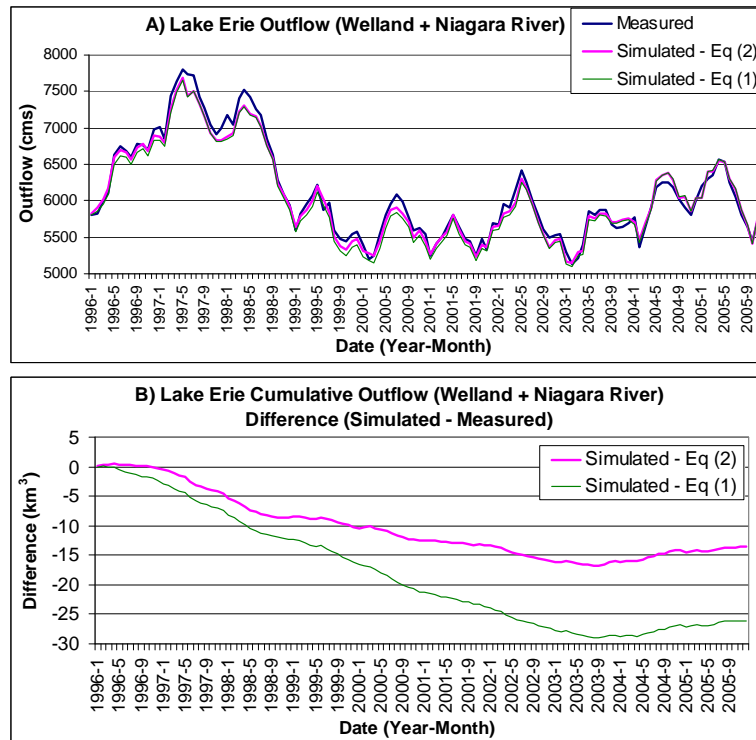
341
 342 Figure 2. Comparison of measured (coordinated) and simulated average monthly lake levels for
 343 the middle Great Lakes from 1996 to 2005 using Equation 2 for St. Clair River flows.
 344

345 When the simulation errors for the 2001-2005 period in Figure 2 and Figure 3b are both
 346 considered, it is apparent that the slowly diverging simulated Lake Michigan-Huron levels
 347 (relative to measured data) result from more than just an imperfect lake-to-lake stage-fall-
 348 discharge equation. Consider that by the end of 2005, all three lakes are simulated to store too
 349 much water (nearly 25 km^3 in total, 23.5 km^3 of which is in Lake Michigan-Huron). Figure 2
 350 shows that the vast majority of this excess water accumulated in the three lakes between 2001-
 351 2005. If the only significant cause of Lake Michigan-Huron level over-predictions was that
 352 Equation (2) under-estimated the St. Clair River conveyance for the 2001-2005 period, and thus
 353 excess water remained in Lake Michigan-Huron, the cumulative volume of water leaving the
 354 system (draining from Lake Erie) for the same period should be under-estimated. The relatively
 355 flat line from 2001 to 2005 for Equation (2) in Figure 3b shows that this in fact does not occur
 356 and instead, the simulated cumulative outflow under-predicts the measured data by only 1 km^3

357 (compared to nearly 25 km³ of excess water stored in the three lakes). Therefore, the over-
 358 predicted Lake Michigan-Huron levels for the 2001-2005 period cannot be solely attributed to
 359 Equation (2) under-estimating the conveyance of the St. Clair River.

360
 361 Overall, the CGLRRM model with Equation (2) is deemed to replicate measured 1996-2005 lake
 362 levels with sufficient accuracy to assume that Equation (2) represents a reasonable approximation
 363 of the current conveyance regime on the St. Clair River. It is not clear when the change to this
 364 current conveyance regime took place. However, the accuracy of the CGLRRM model
 365 predictions with Equation (1) over the 1963-1977 period is sufficient to assume that Equation (1)
 366 represents a reasonable approximation of the previous conveyance regime on the St. Clair River.
 367 Therefore, the CGLRRM model with Equation (1) or Equation (2) forms the basis for all of the
 368 following scenario analyses that are modelled.

369
 370 The CGLRRM input file for simulating 1996-2005 with Equation (2) is provided in Appendix 1.
 371

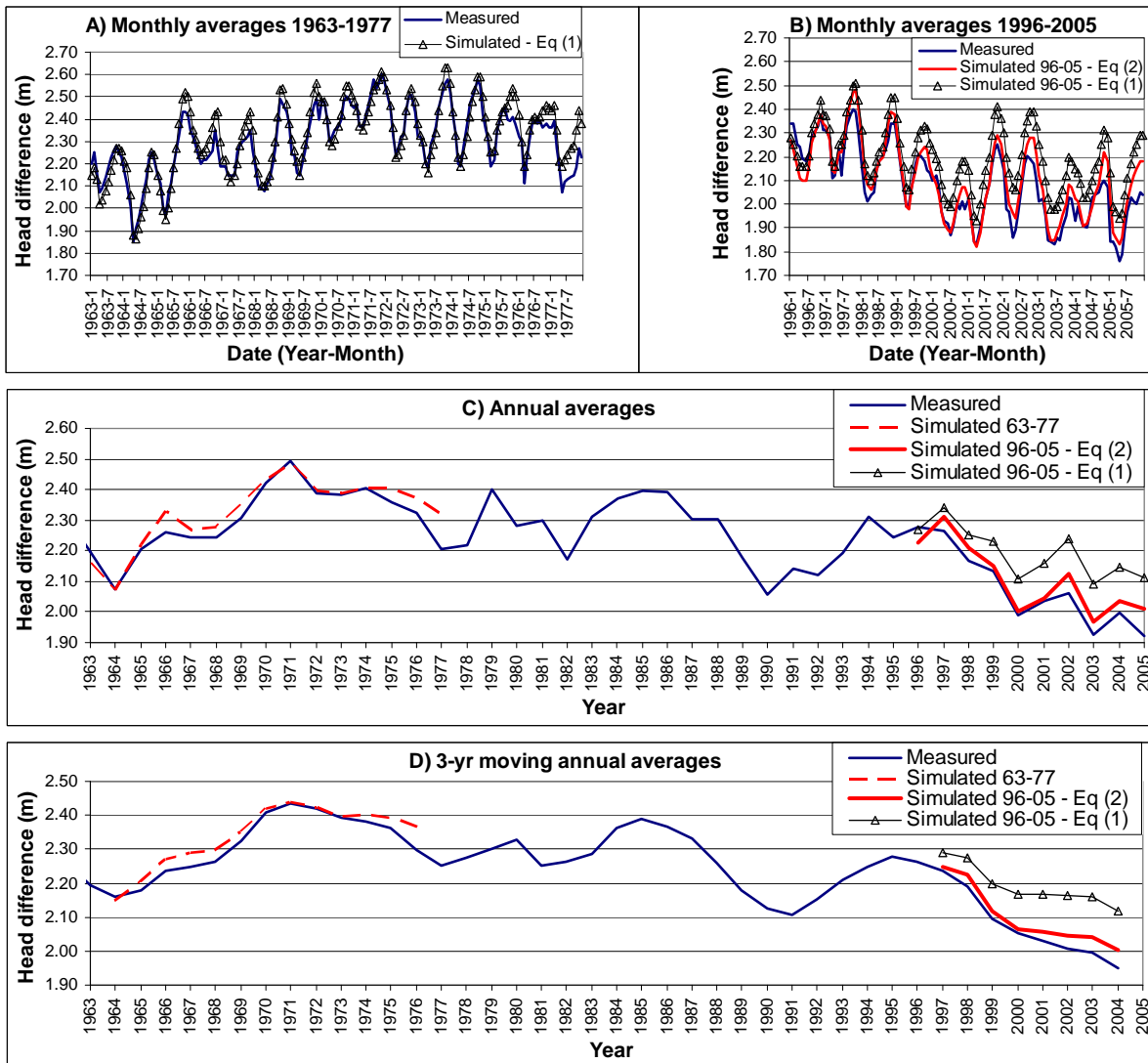


372
 373 Figure 3. Comparison of measured and simulated Lake Erie outflows from 1996 to 2005 using
 374 Equation (2) for St. Clair River flows.
 375

376 **3.2 Metrics for quantifying the drop in head difference between Lake**
 377 **Michigan-Huron and Lake Erie**

378
 379 Prior to comparing the above two CGLRRM models with Equations (1) and (2) and making
 380 inferences regarding causes of the change in head difference between Lake Michigan-Huron and
 381 Lake Erie, it is necessary to consider the metrics that can be used to describe the change in head
 382 difference. Therefore, Figure 4 shows the measured head differences over time for various time

383 steps. Figure 4 also shows the simulated head differences for Equation (1) and (2). A
 384 comparison of the accuracy of simulated head differences between Equations (1) and (2) in
 385 panels B, C, and D of Figure 4 reiterates the previous finding that Equation (1) does not
 386 accurately represent the current conveyance regime of the St. Clair River. More importantly, all
 387 four panels of Figure 4 demonstrate that the models assumed to approximate the two conveyance
 388 regimes on the St. Clair River also generally approximate the trend through time of the measured
 389 change in head differences for the various time steps. The recent (1996-2005) large drop in head
 390 difference over time is most apparent when the measured 3-yr moving annual averages are
 391 considered (Figure 4D). In fact, the trend downwards of the 3-yr moving annual average
 392 continues into 2006 when 2006 and 2007 average annual lake level data are considered (not
 393 shown in plot below).
 394



395
 396 Figure 4. Simulated and measured head difference between Lake Michigan-Huron and Lake Erie
 397 for various time steps (monthly average lake levels, annual average lake levels, 3-year moving
 398 annual average lake levels). Measured head differences based on coordinated average monthly
 399 lake levels. The simulated 63-77 result with Eq. (1) represents pre-conveyance change, while the
 400 simulated 96-05 result with Eq. (2) represents post conveyance change.

401 Note that CGLRRM results are not evaluated between 1977 and 1996 because it is unclear when
 402 the change in St. Clair channel conveyance occurred and whether it was a relatively sudden or
 403 gradual change. For the purposes of the analyses in this report, determining exactly when the
 404 conveyance change occurred is not important. What is important is the accurate description of
 405 the two conveyance regimes: 1963-1977 and then 1996-2005.
 406

407 Table 1 and Table 2 below depict a variety of potential head difference metrics for the measured
 408 and simulated lake levels. The numbers in these tables are based directly on the various time
 409 series in Figure 4.
 410

411 Table 1. Listing of potential measured and simulated metrics for assessing change in head
 412 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

- 413 a) Current conveyance regime CGLRRM model developed for 1996 through 2006 St. Clair River flow data
 414 and as such was not applied before 1996.
 415 b) Component NBS estimates for 2006-2008 not available at the time this report was completed.
 416

417 Table 1 shows that for the changes in measured head difference of greatest interest to the IJC and
 418 Great Lakes stakeholders (e.g. the drop between 1994-2007 of 0.51 m) is not replicated by
 419 CGLRRM as the model is not currently simulating this time period. Considering the time period
 420 being simulated in the model currently (1996-2005), the model does not accurately simulate the
 421 observed 1996-2005 change in head difference (under-predicts by 0.14 m or 39%). This error is
 422 in large part due to the under-predicted head difference for 1996 that can be seen in Figure 4C.
 423 Instead, if only the 1997-2005 period is considered, the simulated head difference trend closely
 424 tracks the measured head difference trend (coefficient of determination or $R^2 = 0.95$) and the
 425 simulated change in head difference for the period is only under-predicted by 0.05 m or 14%.
 426

427 Three regression-based metrics are shown in the last three rows of Table 1 and are utilized here
 428 because other projects and documents in the overall IUGLS study have summarized the drop in
 429 head difference on the basis of the change in head difference predicted by a linear regression line
 430 through a set of head differences over time. For example, the 1963-2007 regression line change
 431 in measured head difference is calculated based on a linear regression equation developed using
 432 the annual average measured head differences from 1963 to 2007 (head differences calculated
 433 from coordinated average monthly lake levels) with the year as the independent variable. The
 434 value of 0.34 m in row 4 of Table 1 is then calculated as the regression equation prediction for
 435 the year 1963 minus the regression equation prediction for the year 2007. Of the three time
 436 periods considered for regression-based metrics in Table 1, only the 1996-2005 regression-based

437 metric can be computed for the CGLRRM simulated head differences over time. The model
 438 under-predicts the measured 1996-2005 regression-based metric by 0.07 m (or 21%).
 439

440 Table 2 shows similar results to Table 1 except it is based on 3-yr moving annual averages. The
 441 3-yr moving average is utilized because it acts to smooth the time series of head differences and
 442 thus make the trends more apparent. This is an alternative to taking a regression-based approach
 443 for smoothing out the change in head over time. As such, no regression-based metrics are
 444 considered for the 3-yr moving average head differences. The model under-predicts the
 445 measured 1997-2004 change in head difference in Table 2 by 0.04 m (or 15%).
 446

447 Table 2. Listing of potential measured and simulated metrics for assessing change in head
 448 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

449 a) Component NBS estimates for 2006-2008 not yet available.
 450

451 **3.2.1 Baseline model metrics for quantifying the drop in head difference** 452 **between Lake Michigan-Huron and Lake Erie**

453
 454 This section summarizes the set of selected metrics (a subset of the potential metrics listed in
 455 Table 1 and Table 2) that will be used as a baseline in which further modelling scenarios and
 456 experiments in later sections will be compared to. Establishing baseline simulated metrics are
 457 critical to determining the relative contribution of conveyance change and changes in climate
 458 (NBS) to the head difference of Lake Michigan-Huron and Lake Erie. By using simulated
 459 metrics as a baseline, the impact of each of the above two factors can be isolated. This is because
 460 factor impacts can be assessed by comparing model simulations with a factor changed (to
 461 generate a new value of the metric) relative to the baseline simulated metric. In contrast, if a
 462 measured metric value was selected as a baseline, the difference between model simulations with
 463 a factor changed relative to the baseline measured metric would be due to a combination of the
 464 factor and model error (i.e. if the model does not exactly simulate the baseline measured metric).
 465

466 Table 3 below summarizes the metrics selected, their short names that will be used throughout
 467 the rest of the report and the corresponding baseline simulated values. Metric selection is largely
 468 determined based on the availability of a simulated metric. The metric values in Table 3 are
 469 based directly on the various simulated time series in Figure 4. Although the simulated metrics
 470 do not perfectly match the measured metrics, the simulated metrics are all within 14%-21% of the
 471 measured metrics as discussed in the previous section.
 472
 473
 474
 475
 476

477 Table 3. Selected baseline simulated metrics that approximate the change in head difference
 478 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

479 a) 1997 selected over 1996 as initial year because the difference between simulated M_{1 ann} is much closer to
 480 measured M_{1 ann}.
 481

482 3.3 Analysis of Conveyance Change Impact on Head Difference

483 3.3.1 Scenario analysis for 1996-2005 period

484
 485 This section assesses what the model predicted drop in head difference would be if the
 486 conveyance regime for the 1963-1977 period, as described by Eq. (1) for the St Clair River flow,
 487 persisted from 1996 through 2005. In other words, the analysis attempts to predict what would
 488 have happened if there was no change in St Clair River conveyance (and thus Eq. (1) still
 489 applied). Therefore, this analysis simply compares the head differences simulated with Equation
 490 (1) and Equation (2) that are shown in Figure 4.
 491

492 Results comparing the impact of conveyance are presented in Table 4 for each of the three
 493 metrics. The change from the baseline simulated change in head differences measures the
 494 impact of conveyance change on the St Clair River (as represented by the lake-to-lake stage-fall
 495 equation in CGLRRM). The last column in Table 4 shows that conveyance is responsible for
 496 between 24-31% of that change. All other factors taken together, such as change in climate and
 497 differential glacial isostatic rebound (GIA), have a more controlling influence on this change in
 498 head difference.
 499

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

Metric	<u>BASELINE</u> 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)

502 a) Attribution % column is calculated with more precision in head differences than appears in previous
 503 columns.
 504

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

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

510
 511 It is also important to note the direct impact the conveyance change (as simulated in CGLRRM)
 512 has on Lake Michigan-Huron levels. On average, Lake Michigan-Huron levels between 1996-
 513 2005 would be 7 cm higher if no conveyance change in the St. Clair River had occurred between
 514 1977-1995 (e.g. Equation 1 still accurately described St. Clair River conveyance). The largest
 515 impact of conveyance in terms of the annual average Lake Michigan-Huron level, is a difference
 516 in 2005 of 11 cm.

517

518 3.3.2 Scenario Analysis of Steady-State Lake Levels

519

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

525

526 The scenario analysis in Section 3.3.1 was repeated with all model inputs set to constant (steady-
 527 state) values starting Jan. 1, 1996. The constant values of CGLRRM inputs (NBS, ice and weed
 528 retardation factors, diversions, etc.) were set at the average monthly values of the 1948-2005
 529 period and the model was simulated for 50 years, again starting with Jan 1, 1996 lake levels.
 530 Results are presented in Table 5 below. First, it is clear that approximate steady-state conditions
 531 were reached after 10 yrs. After 15 years, lake levels reach steady-state to two decimal places of
 532 precision (model output files only written with two decimal places of precision) as they are equal
 533 to the simulated lake levels after 50 years. At steady-state, a comparison of the head differences
 534 between using Eq. (1), the old 1963-1977 conveyance regime, and Eq. (2), the new 1996-2006
 535 conveyance regime, shows that the change to the new conveyance regime induced a 9 cm
 536 decrease in the head difference. This steady-state change in head difference is only 18% of the
 537 1994-2007 measured drop in head difference (51 cm) between Lakes Michigan-Huron and Erie.
 538

539

540 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

541

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

542

543 Another reason to carry out the steady-state analysis is to look at how much water is lost from
 544 Lake Michigan-Huron as a result of conveyance change. An increase in St. Clair River

545 conveyance causes water to drain at an increased rate from Lake Michigan-Huron. However, this
546 increased flow of water is not permanent. The results of the steady state model demonstrate this
547 explicitly.

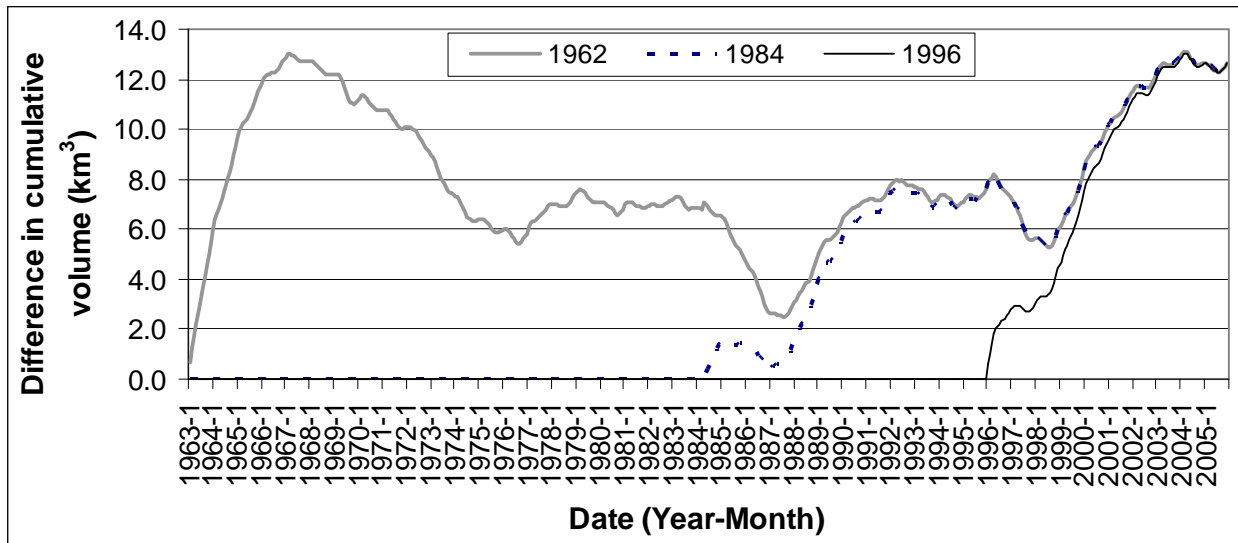
548
549 For example, the steady state net inflows to Lake Michigan-Huron in both steady-state
550 simulations (with and without conveyance change) summarized in Table 5 are the same and are
551 equal to all inflows (St. Marys + NBS = 5570 m³/s) minus all outflows before the St. Clair River
552 (Chicago diversion = 91 m³/s). All net inflows thus equal 5479 m³/s. Simulation results for no
553 conveyance change with Eq (1) show the system is at steady-state after about 14 years and the
554 steady-state St. Clair River flow is also 5479 m³/s. Of course, to reach steady-state levels on
555 Lake Michigan-Huron, the net lake inflows must equal the lake outflow into the St. Clair River.
556 After about 14 years, simulation results with a conveyance change using Eq (2) show the exact
557 same result: net lake inflows = the lake outflow into the St. Clair River = 5479 m³/s. This very
558 clearly demonstrates that with steady-state inputs, if conveyance is not continually increasing on
559 the St. Clair River, water is not continually lost from the lake. Instead, a one-time conveyance
560 change causes temporary increases in outflows for a period of only 14 years. Although it is not
561 quite as straightforward to demonstrate, the concept is exactly the same for non-steady-state
562 inputs such that the full impacts of a one-time conveyance change will eventually be realized and
563 at that point Lake Michigan-Huron will no longer be losing water due to conveyance change.
564

565 **3.3.3 Scenario Analysis to evaluate time to full impacts of conveyance** 566 **change**

567
568 The purpose of this analysis is to evaluate the length of time required for the full impacts of a
569 one-time conveyance change to be realized under the true dynamic, rather than steady-state, set
570 of CGLRRM inputs taken to best represent the historical conditions across the Upper Great
571 Lakes. The full impacts of any conveyance change are those that result in the long term. Impacts
572 in this analysis are measured in terms of simulated St. Clair River flows.

573
574 Three pairs of model runs were evaluated in this experiment. The first pair of model runs
575 involved simulating lake levels from 1963 to 2005 with Equation (1) to represent no conveyance
576 change and then with Equation (2) to represent conveyance change occurring at the start of 1963.
577 Each model run was initialized to Jan 1, 1963 coordinated lake levels. The second pair of model
578 runs involved simulating lake levels from May 1984 to 2005 with Equation (1) to represent no
579 conveyance change and then with Equation (2) to represent conveyance change occurring at the
580 start of May, 1984. Each model run in this second pairing was initialized to May 1, 1984
581 coordinated lake levels. The May 1, 1984 date was selected because the date of a major St. Clair
582 River ice jam was April, 1984 and as such represents a potential point in time where a sudden
583 conveyance change did occur. Note however, that the analysis is hypothetical and not meant to
584 suggest that the ice jam was 100% responsible for the change to the current conveyance regime
585 on the St. Clair River. The last pair of model runs involved simulating lake levels from 1996 to
586 2005 with Equation (1) to represent no conveyance change and then with Equation (2) to
587 represent conveyance change occurring at the start of Jan. 1996. Note that these model runs were
588 already conducted in previous analyses.
589

590 For each pair of model runs the cumulative increase in St. Clair River flow (in km³) due to
 591 conveyance change was then computed over the time period simulated. These three cumulative
 592 increases over time are shown in Figure 5 and results clearly demonstrate that the date of a one-
 593 time conveyance change happening on or before Jan. 1996 has no impact after 2002 on the total
 594 volume of water lost from Lake Michigan-Huron. All three pairs of simulations in Figure 5
 595 converge to the same cumulative increase in St. Clair River flow. Analyzing lake levels rather
 596 than St. Clair River flows would yield the same findings.
 597



598
 599 Figure 5. Cumulative increase in simulated St. Clair River flow due to a one-time conveyance
 600 change (Equation (2) instead of Equation (1) for flow St. Clair River flows) occurring on
 601 different dates.
 602

603 Overall, the results demonstrate that even in non-steady-state conditions, after some initial period
 604 of time passes since the last conveyance change, increasing the length of time since the
 605 conveyance change has no impact on the total volume of water lost (increase in St. Clair River
 606 flow) due to the conveyance change. Assuming Equation (2) represents the conveyance change,
 607 so long as the change occurred on or before 1996, the full impacts of conveyance change on the
 608 St. Clair River flows and Lake Michigan-Huron level have been realized by approximately 2003.
 609

610 **3.4 Analysis of Observed NBS Change Impact on the Steady-State** 611 **Head Difference**

612
 613 The purpose of this analysis is to focus on NBS rather than changing the conveyance regime.
 614 One very simple way to delineate two NBS regimes is to assume that there was a change in
 615 regimes at the start of the major decline in head difference (see measured data in Figure 4C or
 616 Figure 4D) in 1996. Thus, consistent with the previous analyses, the 1996-2005 period is
 617 analyzed separately. The 1996-2005 NBS data can then be compared to the 1963 (post-dredging)
 618 to 1995 NBS data. Component NBS data are analyzed for each of these periods and compared
 619 below in Table 6 where the NBS data are expressed as the average m/yr added to each lake
 620 (coordinated lake areas used to convert from m³/s).

621
 622 Results in Table 6 show that after 1995, NBS has declined on both lakes but more importantly
 623 show that NBS has declined much more quickly on Lake Michigan-Huron than it has for Lake
 624 Erie. If these NBS declines reflect the change in relative total supplies of each lake (e.g. Net
 625 Total Supplies), then the resulting response of the system would have to be a decrease in the head
 626 difference between the lakes since Lake Michigan-Huron depth would be decreasing faster than
 627 Lake Erie depths. The magnitude of such a decrease in relation to the observed decrease in head
 628 difference since 1996 is not clear. Actual NTS estimates are not considered here because they
 629 require connecting channel flow estimates which would confound the analysis by including the
 630 system response the St. Clair River conveyance change.
 631

632 Table 6. Lake Michigan-Huron and Lake Erie component NBS averages for different time
 633 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

634 a) Difference row is calculated with more precision in NBS than appears in upper rows.
 635

636 3.4.1 Scenario Analysis Comparing Steady-State Lake Levels due to 1963- 637 1995 average NBS and 1996-2005 average NBS

638
 639 A series of modelling experiments were designed to assess the steady-state response of the lakes
 640 to average component NBS values for different time periods independent of channel conveyance
 641 change. For these experiments, CGLRRM is simulated with Equation (1) which represents the
 642 St. Clair River with no change in conveyance. The first experiment simulated the lake level
 643 response to 50 years of steady-state inputs based on the average inputs for the 1963-1995 period
 644 (summarized in Table 7). The model was initialized to Jan 1, 1996 as in previous modelling
 645 analyses. The resulting simulated steady-state lake levels and head difference are given in Table
 646 8. The second modelling experiment initialized all lake levels to the steady-state levels that
 647 resulted from the first experiment and then simulated the lake level response over 50 years of
 648 steady-state inputs based on the average inputs for the 1996-2005 period (summarized in Table
 649 7). Simulation results for this second experiment are also given in Table 8.
 650

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

660
661

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

CGLRRM Input	1963-1995 average (m³/s)	1996-2005 average (m³/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

662
663
664
665

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

666
667

668 4 Stochastic Modelling Analyses

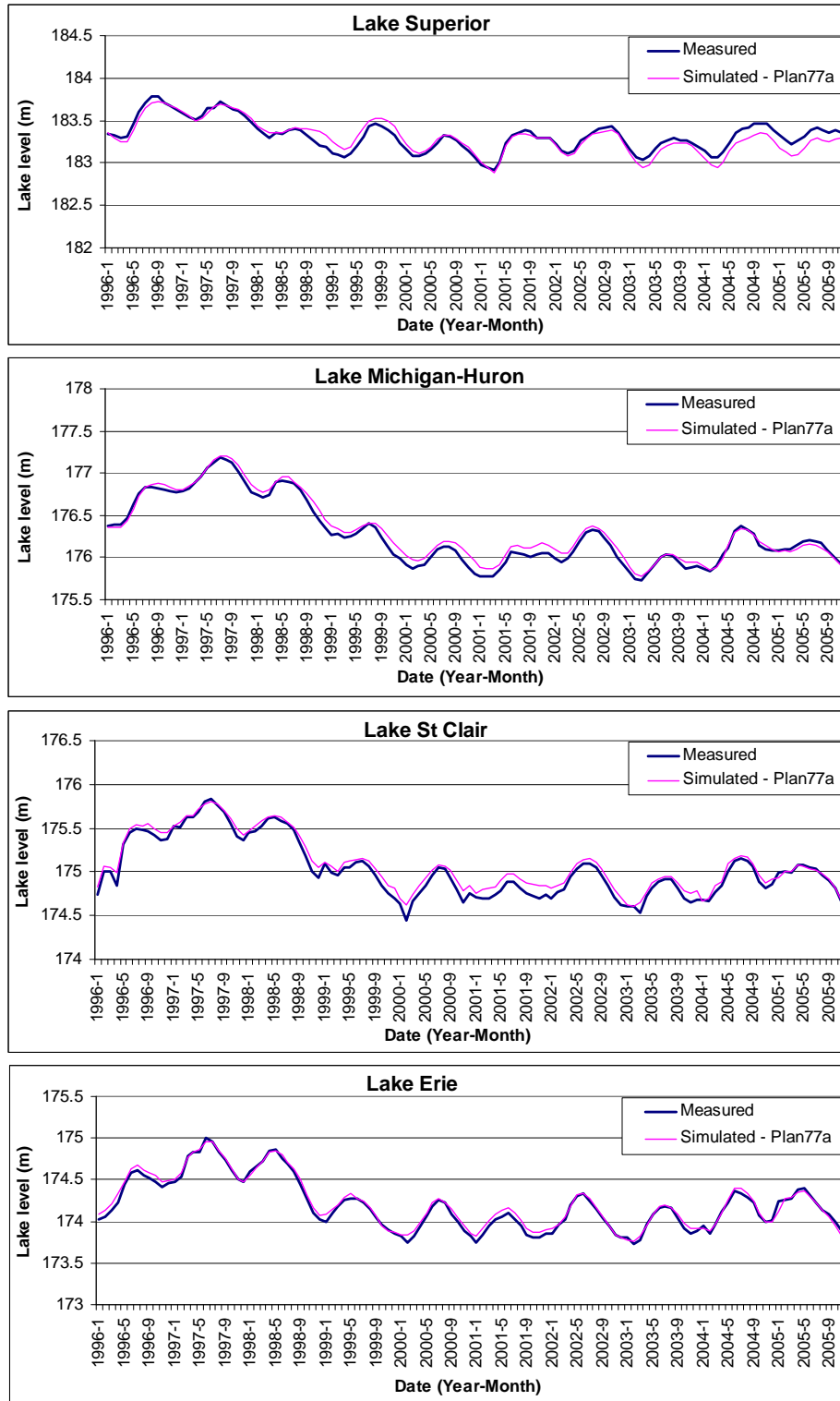
669 4.1 Model Input Changes for Stochastic Analyses

670
671 The analyses conducted in Section 4 are designed to assess the distribution of the drop in head
672 difference metrics that would be observed under randomly sampled alternative time series of
673 NBS inputs. As per the Hydroclimate Uncertainty peer review comments, bootstrap experiments
674 (rather than simple Monte Carlo sampling) are conducted to generate the alternative NBS time
675 series. Monte Carlo sampling is problematic here because it would require developing complex
676 time series models that respect the temporal and spatial correlation structure among all inputs .
677 Note that the analyses here are not designed to assess the impact of the uncertainty of historical
678 component NBS estimates (the GLERL estimates of component NBS used in Section 3 are
679 assumed correct). Instead, the analyses here are designed to evaluate the distribution head
680 difference metrics that result from the observed variability in NBS over time. The analyses
681 conducted differ by varying the sampling strategy and/or another factor in the model and these
682 differences are described clearly at the beginning of each subsection below.

683
684 Prior to running CGLRRM under alternative NBS time series, it was necessary to change two of
685 the model simulation settings relative to the inputs used to define the baseline metrics calculated
686 in Table 3. These changes are as follows:

- 687 1. As per a recommendation and data provided by Yin Fan at Environment Canada
688 (Personal communication), Welland Canal diversions are assumed not to respond to Lake
689 Erie water levels and are thus fixed at the 12 monthly average values. To ensure the
690 monthly averages are representative for the simulation time period (1996-2005), the
691 average monthly flows for this period are used as model input.
- 692 2. Similar to 1 above, Chicago diversions are assumed not to respond to Lake Michigan-
693 Huron levels. As such, the average Chicago diversion rate for the 1996-2005 period of 83
694 m³/s was input to CGLRRM as the constant diversion rate for all stochastic experiments.
- 695 3. Lake Superior levels are simulated and the flow of the St Marys River is the result of Plan
696 1977A regulation strategy that is encoded in the regulation portion of CGLRRM. In other
697 words, CGLRRM is capable of simulating the regulation strategy that determines the
698 monthly flows of the St. Marys River into Lake Michigan-Huron. The initial Lake
699 Superior level is set to the coordinated measured level for Jan 1, 1996 and the previous
700 month's St. Marys River flow is set to the Dec. 1995 average monthly flow estimate.

701
702 Changes 1-3 above were evaluated for their impact on the simulated metrics for the 1996-2005
703 period by implementing the two changes above and then running the model under all the same
704 inputs determined to be representative of the 1996-2005 period (i.e. Equation (2) for St. Clair
705 River flows). Lake level simulations are compared with historical lake levels, including Lake
706 Superior, in Figure 6 below. The results in Figure 6 demonstrate that changes 1 and 2 do not
707 inhibit the model from simulating the variation in time of Michigan-Huron and Erie lake levels.
708 Instead, all lake levels, including Lake Superior, are now simulated quite well relative to the
709 measured lake levels. In fact, simulated lake levels for Lakes Michigan-Huron, St. Clair and Erie
710 now appear slightly closer to their measured lake levels later in the simulation in comparison to
711 simulations without changes 1-3 (see previous results for Equation (2) in Figure 2).



712
 713 Figure 6. Comparison of measured (coordinated) and simulated average monthly lake levels for
 714 Lakes Superior, Michigan-Huron, St. Clair and Erie. The Plan 77a designation is used to indicate
 715 that both model changes 1-3 as described in Section 4.1 were implemented. These simulated lake
 716 levels are used to calculate updated head difference metrics in Table 9.
 717

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 ($M_{1 \text{ ann}}$, $M_{2 \text{ reg}}$ and $M_{3 \text{ 3yr}}$) 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 $M_{1 \text{ ann}}$, $M_{2 \text{ reg}}$ and $M_{3 \text{ 3yr}}$ (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.

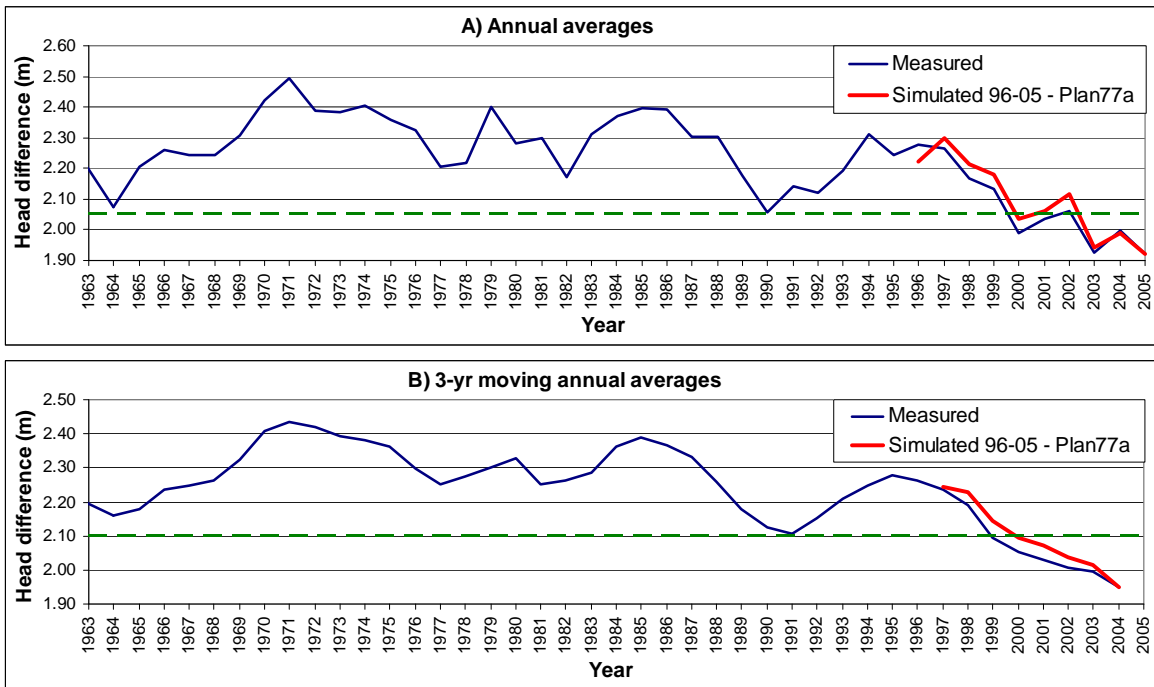
Table 9. Measured and updated (for stochastic experiments) baseline simulated metrics for assessing change in head difference across different periods based on annual average lake levels.

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
$M_{1 \text{ ann}}$	1997 ^a -2005	Based on annual average head differences	0.35	0.37 (0.30) ^b
$M_{2 \text{ reg}}$	1996 - 2005	Calculated from linear regression of annual average head difference vs. year	0.35	0.35 (0.28) ^b
$M_{3 \text{ 3yr}}$	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 $M_{1 \text{ ann}}$ is much closer to measured $M_{1 \text{ ann}}$.

b) Brackets contain previous metric value for deterministic analyses as presented in Table 3.

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



757 Figure 7. Illustration and rationale for additional head difference metrics (M_4 and M_5). The
 758 dashed lines are the lows in the measured data for the 1960-1995 period.
 759
 760

761 4.3 Bootstrap sampling description and data analysis

762
 763 In order to randomly sample alternative time series for NBS and the ice and weed retardation
 764 factors, a moving blocks bootstrap approach was selected. The moving blocks bootstrap is an
 765 approach for resampling from a univariate time series of data (pg. 101, Efron and Tibshirani,
 766 1993) and is simply a way of resampling (by reordering) plausible alternative sets of time series.
 767 Being able to sample alternative time series enables the repeated sampling of some statistics of
 768 interest (in this case, the metrics for change in head difference over the 1996-2005 period) that
 769 are calculated as a function of sampled time series. This repeated sampling of the statistics

770 enables the estimation of the probability distribution of the statistic (Vogel and Shallcross, 1996).
771 The basic idea is to select an appropriate block length (number of time steps) and consider all
772 contiguous blocks of time of this length (e.g. N blocks) as the population of blocks from the
773 original time series that can be resampled. Alternative time series are then created by repeatedly
774 sampling at random, with replacement, one of the N blocks and then concatenating the blocks
775 together until a time series of the desired length has been generated.

776
777 Vogel and Shallcross (1996) note that the moving blocks bootstrap can be easily extended to
778 multivariate time series. In this application, the entire set of upper Great Lakes NBS time series
779 (Lakes Superior, Michigan-Huron, St. Clair and Erie) as well as the ice and weed factor
780 retardation factor time series (for the St. Clair, Detroit and Niagara Rivers) are bootstrapped
781 together. This means that sampling a block length of three years for example, would take the
782 same three-year period from all seven time series. In this way, the moving blocks bootstrap is
783 powerful because it automatically preserves the spatial correlation structure of the NBS (and ice
784 and weed factors) across the four upper Great Lakes.

785
786 The original time series to be resampled are defined to be the 1948-2005 period since this is the
787 period of time for which component NBS data are available. The block length, L , of the
788 bootstrap should be selected large enough such that data more than L time steps apart will be
789 nearly independent but the autocorrelations present in the original time series less than L time
790 steps apart are retained (pg. 102, Efron and Tibshirani, 1993). Since this study is focused on a
791 multivariate data set, the block length determination considers the cross correlations in addition
792 to the autocorrelations.

793
794 In this analysis, block lengths less than 12 months in length were not considered. Blocks lengths
795 are measured in units of years (12 consecutive months) and so the monthly data need to be first
796 assessed for which month to define the start of each block length unit. The month-to-month
797 correlation coefficients for all seven time series were computed and showed that the only pair of
798 consecutive months where all seven time series have a statistically insignificant correlation
799 coefficient (at the 5% significance level) is March and April. The lack of correlation between
800 March and April NBS makes hydrological sense because this coincides with the beginning of the
801 snowmelt/ice-free period for the Great Lakes basin. The switch from winter climate conditions to
802 spring melt conditions should generate NBS that are not correlated since baseflow type flow
803 conditions at the end of winter are not good predictors of the spring time snowmelt induced flood
804 magnitudes. Therefore, the monthly time series data are aggregated to annual average data
805 (weighted by days in each month) based on a year from April 1 – Mar 31.

806
807 The next analysis was to determine the appropriate block lengths based on an autocorrelation and
808 then cross correlation analysis to assess the annually averaged (with year defined Apr-Mar) time
809 series. Both of these correlation analyses only focused on the four NBS time series as they are
810 one to more than two orders of magnitude larger than the ice and weed retardation factors (which
811 average around $10 \text{ m}^3/\text{s}$) on an annual basis. Lag-1, lag-2 and lag-3 autocorrelations and cross
812 correlations were computed to assess the validity of blocks lengths up to three years in length.
813 Block lengths more than three years were considered too long given that the length of the time
814 series to be constructed by the moving blocks bootstrap is 10 years in length. None of the lag-1
815 through lag-3 autocorrelations for the four NBS time series were statistically significant at the 5%

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

823

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

829

830 **4.4 Bootstrap experiment set 1**

831

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

839

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

846

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

# of bootstrap samples in Experiment	$M_{1 \text{ ann}}$ (m) max of all 3-, 4-, ..., and 10-yr decreases in ann. avg. head difference	$M_{2 \text{ reg}}$ (m) decrease in head difference from 1996 to 2005 by linear regression	$M_{3 \text{ 3yr}}$ (m) max of all 3-, 4-, ..., and 8-yr decreases in 3yr moving. avg. head difference	M_4 # yrs with avg. head difference \leq 1990 extreme	M_5 # yrs with 3yr moving avg. head difference \leq 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

850

851 Since the average values metric values in Table 10 are notably smaller or less extreme than the
 852 baseline metrics in Table 9, it can be concluded that the actual head difference behaviour was
 853 somewhat extreme (more than average). Note that the negative average values for $M_{2 \text{ reg}}$ means

854 that on average, the regression line slope is positive such that a regression line measure of change
855 in head would suggest increasing rather than decreasing head differences over time. The fact the
856 average regression line metric is negative indicates that the regression line metric is a relatively
857 poor metric for this type of analysis where the head difference variations of concern can occur
858 over a shorter period than what is included in the regression. As such, the all results for the
859 regression metrics should be given less weight than the results for the $M_{1\text{ ann}}$ and $M_{3\text{ 3yr}}$ metrics.

860
861 Overall, average metric values are imperfect measures for quantifying how extreme the baseline
862 system behaviour is. Instead, the stochastic results were also analyzed to estimate the
863 probabilities that equal or more extreme stochastic simulated metrics relative to the baseline
864 metric values derived in Section 4.2 are sampled. For example, for the $M_{3\text{ 3yr}}$ metric, only 74 of
865 1000 simulations (from experiment with 1000 samples) generated a metric value that was equal
866 to or larger than the baseline of 0.293 m. As such, the probability that any sampled 10-yr set of
867 input time series yielded an equal or more extreme value of 0.293 m for $M_{3\text{ 3yr}}$, denoted $\Pr(M_{3\text{ 3yr}} \geq 0.293)$,
868 is $74/1000 = 0.074$. These probabilities calculated for all five metrics ($M_{1\text{ ann}}$, $M_{2\text{ reg}}$, $M_{3\text{ 3yr}}$,
869 M_4 , and M_5) using the 1000 sample size experiment are 0.148, 0.034, 0.074, 0.141 and 0.143,
870 respectively. Given the range of probabilities is between 0.03 to 0.15, it is clear the system
871 behaviour resulting from the actual 1996-2005 NBS time series was fairly unique.

872

873 **4.5 Bootstrap experiment set 2**

874
875 In this set of experiments, the independent impacts of both the NBS (climate) and the conveyance
876 change are both controlled so that their relative importance could be assessed. The conveyance
877 change for the St. Clair River is already assumed to be completely described by changing the
878 equation for St. Clair River flow from Eq. (1) to Eq. (2). The NBS influence in these
879 experiments is defined to be the 1996-2005 period of NBS values on the basis of results in Table
880 6 which show average Lake Michigan-Huron NBS values from the 1996-2005 period are notably
881 smaller than average Lake Michigan-Huron NBS values from the 1963-1995 period. Therefore,
882 the influence of the 1996-2005 NBS data can be removed by bootstrap sampling from past years
883 not including this period (sampling from years before 1996 only).

884

885 In order to focus on the past NBS conditions observed since the last significant dredging of the
886 St. Clair River (1962), the bootstrap sampling period for all experiments in this section begins in
887 1963. Three bootstrap sampling experiments were conducted and are described as follows:

888 • Experiment 2a) samples 10-yr sets of input time series for CGLRRM from the 1963-2005
889 period and simulates St. Clair River flows with the current conveyance equation - Eq. (2).
890 This experiment then forms a baseline from which the impacts of conveyance and NBS
891 can be assessed by comparing with the two following experiments.

892 • Experiment 2b) samples 10-yr sets of input time series for CGLRRM from the 1963-1995
893 period and simulates St. Clair River flows with the current conveyance equation - Eq. (2).
894 Thus, experiment 2b is the exact same as experiment 2a except that the 1996-2005 period
895 is not sampled from and thus isolates the impact of 1996-2005 NBS data.

896 • Experiment 2c) samples 10-yr sets of inputs for CGLRRM from the 1963-2005 period
897 and simulates St. Clair River flows with the conveyance equation for the 1960-1977
898 conveyance regime - Eq. (1). Thus, experiment 2c is the exact same as experiment 2a

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

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

904
 905 The results of experiment set 2 are summarized the same way as experiment set 1 results using a
 906 table of average metric values for each of the three experiments (Table 11) and also table of
 907 probabilities of equal or more extreme stochastic simulated metrics relative to the baseline metric
 908 values (Table 12).

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

Experiment #	$M_{1 \text{ ann}} \text{ (m)}$ max of all 3-, 4-, ..., and 10-yr decreases in ann. avg. head difference	$M_{2 \text{ reg}} \text{ (m)}$ decrease in head difference from 1996 to 2005 by linear regression	$M_{3 \text{ 3yr}} \text{ (m)}$ max of all 3-, 4-, ..., and 8-yr decreases in 3yr moving. avg. head difference	M_4 # yrs with avg. head difference \leq 1990 extreme	M_5 # yrs with 3yr moving avg. head difference \leq 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

914
 915 Comparing the average metrics in Table 11 shows that the change in NBS sampling period (not
 916 sampling from 1996-2005) has a slightly larger impact (compare 2b results to 2a results) on the
 917 $M_{1 \text{ ann}}$, $M_{2 \text{ reg}}$ and $M_{3 \text{ 3yr}}$ metrics than the change in conveyance (compare 2c results to 2a results).
 918 The count metrics in Table 11 respond slightly more to the change in conveyance than they do
 919 the change in NBS sampling period. The probabilities in Table 12 show similar relative results
 920 between 2b and 2c. The very small probabilities (all less than 0.065) in Table 12 for experiments
 921 2a and 2b, both of which simulate the conveyance change with Eq. (2), demonstrate even more
 922 than the previous results in section 4.4 that the sequence of actual climate or NBS for the 1996-
 923 2005 period was very unique. For example, only 5 of 1000 (0.005) sets of 10-yr input time series
 924 sampled from the 1963-1995 period yielded more extreme $M_{3 \text{ 3yr}}$ metric values than the baseline
 925 simulated results for the actual input time series observed from 1996-2005.

926
 927 The impact of conveyance change in terms of a percentage of the baseline metric values can be
 928 made precise based on the correlated sampling approach between experiments 2a and 2c (same
 929 1000 input data sets are used). This allows a pairwise comparison of the change in head
 930 difference metrics between experiments 2a and 2c. In addition, since the majority of simulation
 931 results showed lake level behaviours that were not at all extreme (for example see probabilities in
 932 Table 12), this more refined conveyance change impact is focused only on those pairs of
 933 simulations when the result in experiment 2a was deemed to be extreme. The criteria for extreme

934 behaviour for a given metric is defined as previously: when the simulated metric value is equal or
 935 exceeding the baseline metric value.

936
 937 Table 12. Probabilities that the simulated metric value is equal or more extreme than the
 938 baseline metric value for bootstrap experiment set 2 (conveyance regimes and NBS sampling
 939 periods varied). Each simulation length is 10 years and all simulations initialized to Jan. 1, 1996
 940 lake levels.

Experiment #	$\Pr(M_{1 \text{ ann}} \geq 0.373)$	$\Pr(M_{2 \text{ reg}} \geq 0.348)$	$\Pr(M_{3 \text{ 3yr}} \geq 0.293)$	$\Pr(M_4 \geq 4)$	$\Pr(M_5 \geq 5)$
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

941
 942 Considering $M_{1 \text{ ann}}$, 55 extreme behaviours were observed in experiment 2a. Conveyance change
 943 (comparing 55 pairs from experiments 2c with 2a) controlled an average of 13% (0.05 m) of the
 944 $M_{1 \text{ ann}}$ metric value (up to a maximum of 24% or 0.10 m). Considering $M_{2 \text{ reg}}$, 8 extreme
 945 behaviours were observed in experiment 2a. Conveyance change (comparing 8 pairs from
 946 experiments 2c with 2a) controlled an average of 22% (0.09 m) of the $M_{2 \text{ reg}}$ metric value (up to a
 947 maximum of 34% or 0.12 m). Considering $M_{3 \text{ 3yr}}$, 23 extreme behaviours were observed in
 948 experiment 2a. Conveyance change (comparing 23 pairs from experiments 2c with 2a) controlled
 949 an average of 17% (0.06 m) of the $M_{3 \text{ 3yr}}$ metric value (up to a maximum of 30% or 0.09 m).
 950 These results demonstrate that the conveyance change impacts across a range of extreme but
 951 plausible NBS inputs are fairly consistent with conveyance change controlling 13% to 22% on
 952 average, to a maximum of 34% of the decrease in head difference. These values are also quite
 953 consistent with the deterministic attribution percentages (24% to 31%) calculated in Table 4 on
 954 the basis of the actual 1996-2005 climate (NBS) inputs. As such, it seems unlikely that the
 955 observed or actual 1996-2005 NBS data functioned to temporarily mask the overall conveyance
 956 change impact on the upper Great Lakes.

957

958 5 Discussion

959
 960 Every modelling exercise has limitations and problems of some degree that should be
 961 acknowledged. These acknowledgements provide the basis for continued model improvement in
 962 the future. The most important limitations noted throughout the previous sections include the
 963 following:

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

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- 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.

988 **6 Conclusions**

989

990 CGLRRM prediction quality of historical measured lake levels was high and CGLRRM was

991 deemed to be an adequate tool for making inferences regarding the relative importance of

992 conveyance change and changes to the climate (NBS). Specific findings regarding model quality

993 are as follows:

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- 995
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- 999
- 1000
- 1001
- 1002
- 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.

1003 Deterministic modelling scenario analyses yielded the following findings:

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- 1010
- 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

1011 steady-state Lake Michigan-Erie head difference by 9 cm. Compare this to the
1012 measured drop in head difference of 51 cm (1994 to 2007).
1013 2c. In direct contrast to 2b, a similar type of steady state analysis showed an 18 cm drop
1014 in head difference could be completely attributed to observed shifts in average
1015 component NBS data. For example, relative to the average component NBS data for
1016 the 1963-1995 period, the average component NBS data for the 1996-2005 period
1017 decreased by 0.12 m/yr for Lake Michigan- Huron and only decreased by 0.03 m/yr
1018 for Lake Erie.
1019 2d. The Great Lakes system response time to a one-time conveyance change of the St.
1020 Clair River was explicitly shown to be finite in that such a change will not cause
1021 continual loss of water from Lake Michigan-Huron and thus Lake Michigan-Huron
1022 levels will not continue to decrease through time. Furthermore, it was shown that so
1023 long as the assumed one-time change in conveyance occurred on or before 1996, the
1024 actual date of conveyance change has no impact after 2003 on the cumulative volume
1025 of water lost from Lake Michigan-Huron due to conveyance change.

1026 The stochastic modelling analyses yielded the following findings:

1027 3a. The system behaviour resulting from the actual 1996-2005 NBSs was very unique or
1028 extreme in comparison with the distribution of possible 10-yr NBS sequences sampled
1029 from the 1963-1995 period (1000 samples).
1030 3b. Multiple extreme but plausible 10-yr NBS sequences were used to show that
1031 conveyance change on the St. Clair River controls 13% to 22% on average, to a
1032 maximum of 34% of the drop in head difference.

1033 Multiple analyses were conducted to attribute some percentage of responsibility to the change in
1034 conveyance for the drop in head difference between Lake Michigan-Huron and Lake Erie. The
1035 various deterministic analyses yielded estimates of 24%, 30% and 31%. The various stochastic
1036 analyses yielded average estimates of 13%, 17% and 22%. In the most extreme stochastic
1037 simulation, a value of 34% was calculated. Considering all these percentages, the post-1977
1038 conveyance change on the St. Clair River is estimated to cause no more than 1/3 of the drop in
1039 head difference for the 1996-2005 period. Other factors (such as climate via NBS variability)
1040 control the substantial majority of the drop in head difference that was observed for the 1996-
1041 2005 period.
1042

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1082 **APPENDIX 1 – Input file for CGLRRM simulation with Equation (2) in Figure 3.**

```

1083
1084 # CGLRRM version 1.40 modified & compiled with gfortran 4.2 on 02Dec2008 by Travis Dahl
1085
1086 # ..... System Settings .....
1087     Message Database: C:\run_CLGRRM\messbase.txt
1088     Only One Open:           F
1089     Modeler Name: Bryan Tolson
1090
1091 # ..... Job Titles .....
1092     Title 1: 1996-2005 run. Supplemental Superior flows.
1093     Title 2: Using updated Ice Retardation, NEW *** 2009 St Clair equation
1094 #     Title 3: (not used)
1095
1096     Lakes To Solve For:      MCE
1097
1098 # ..... Simulation Period .....
1099     Start Date:      1996, 1, 1
1100     End Date:        2005, 12, 31
1101     Month Length:    actual
1102
1103 # ..... Output File Characteristics .....
1104     Output Directory: C:\run_CLGRRM\out\
1105     Output Extension: .out
1106
1107 # ..... Misc Levels of Debugging Output .....
1108
1109     General Verbosity:      3
1110     TS Data Verbosity:     3
1111     Check Verbosity:       3
1112
1113 # ..... General Rounding .....
1114     Flow Round:            -99
1115     Level Round:           -99
1116     BOM Round:             -99
1117
1118 # ..... Lake Superior not modeled .....
1119
1120 # ..... Middle Lakes Settings .....
1121
1122     Midlake Verbosity:     3
1123     Routing Title: Quarter-Monthly Routing through Middle Lakes Using Monthly Supplies
1124     MidLake Time Step:    qmonthly
1125     MidLake Inc.:         Hourly
1126     MidLake Solution:     iterative
1127
1128 # ..... Lakes Michigan-Huron data .....
1129
1130     MHu Output Files:      M
1131     St. C. Riv Eqn: 1450.92000, 171.00000, 0.78472, 0.38388, 0.50000, 0.000
1132     MHu Start Level:      176.3600000 M
1133     MHu Area/Elev:        117470753820.000 M2
1134     St. M. Riv. Flow Data: C:\run_CLGRRM\supflowm.dat
1135     MHu NBS Data: C:\run_CLGRRM\MH_comp1_nbsm_48_05.prn
1136     Chicago Div. Data: C:\run_CLGRRM\Diversion_Chicago.dat

```

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1137 # MHu Other Div. Data: (not used)
1138 # MHu Con. Use Data: (not used)
1139 # MHu. Other Sup. Data: (not used)
1140 # Mic Con. Use Data: (not used)
1141 # Mic Other Div. Data: (not used)
1142 # Mic. Other Sup. Data: (not used)
1143 # Hur. Con. Use Data: (not used)
1144 # Hur. Other Div. Data: (not used)
1145 # Hur. Other Sup. Data: (not used)
1146 # MHu EOP Level Data: (not used)
1147 St. C. Riv. Retr. Data: C:\run_CLGRRM\stc_ice_1900_2006.dbf
1148 # St. C. Riv. Ice Data: (not used)
1149 # St. C. Riv. Ice Data: (not used)
1150
1151 # ..... Lake St. Clair data .....
1152
1153 St. C. Output Files: M
1154 Det. Riv Eqn: 26.20000, 164.95000, 2.33000, 0.36000, 1.00000, 0.000
1155 St. C. Start Level: 174.8200000 M
1156 St. C. Area/Elev: 1122901542.000 M2
1157 # St. C. Riv. Flow Data: (not used)
1158 St. C. NBS Data: C:\run_CLGRRM\SC_comp1_nbsm_48_05.prn
1159 # St. C. Con. Use Data: (not used)
1160 # St. C. Other Div. Data: (not used)
1161 # St. C. Other Sup. Data: (not used)
1162 # St. C. EOP Level Data: (not used)
1163 # Det. Riv. Ice Data: (not used)
1164 # Det. Riv. Weed Data: (not used)
1165 Det. Riv. Retr. Data: C:\run_CLGRRM\det_ice_1900_2006.dbf
1166
1167 # ..... Lake Erie data .....
1168
1169 Eri. Output Files: M
1170 Write Erie Outflow: T
1171 Nia. Riv Eqn: 558.30000, 169.86000, 1.60000, 0.00000, 1.00000, 0.000
1172 Eri. Start Level: 174.0600000 M
1173 Eri. Area/Elev: 25692618420.000 M2
1174 # Det. Riv. Flow Data: (not used)
1175 Eri. NBS Data: C:\run_CLGRRM\ER_comp1_nbsm_48_05.prn
1176 # Eri. Other Sup. Data: (not used)
1177 # Eri. Con. Use Data: (not used)
1178 Welland Canal Data: C:\run_CLGRRM\Diversion_Welland.dat
1179 # Eri. Other Div. Data: (not used)
1180 # Eri. EOP Level Data: (not used)
1181 # CGIP Avg. Level Data: (not used)
1182 Nia. Riv. Retr. Data: C:\run_CLGRRM\nia_ice_1900_2006.dbf
1183 # Nia. Riv. Ice Data: (not used)
1184 # Nia. Riv. Weed Data: (not used)
1185
1186 # ..... Lake Ontario not modeled .....

```