March 25, 2010

Dr. J.W. Kamphuis
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Subject: Review of the Modelling of Falling Water Levels on Lake Michigan-Huron

Dear Dr. Kamphuis,

Thank you for sharing your review with us. As you point out, your review is of a cursory nature and you have not been able to read and digest all the relevant information or drill down into the pertinent facts and details. You also note how complex the system is throughout your review and the multidisciplinary knowledge that is required to address and understand the complexities involved in this Study.

As an academic, you understand the importance of scientific rigour, objectivity and the need to incorporate scientific uncertainty in any decision-making process. Unlike the Bialkowski and Baird reports, the International Upper Great Lakes Study had a large binational, multidisciplinary team comprised of more than 100 scientists and engineers collaborating to address the numerous issues that you have raised in your review. The Study was designed to tackle those issues and many more that were analyzed from multiple perspectives, employing a broad range of techniques to deal comprehensively and transparently with scientific uncertainty.

The Study was reviewed internally and externally by experts from both countries with extensive knowledge of the Great Lakes system. Throughout the Study the work also underwent a major independent peer review that was managed by the International Joint Commission (IJC) with the American Society of Civil Engineers and Canadian Water Resources Association.

We would like to highlight the following comment from your report: "A complete detailed review of this work requires intimate knowledge of the data and all the tools used. I do not have this detailed knowledge and therefore these comments are based on general knowledge and experience." We therefore find it surprising that you unquestioningly accept the approach and findings of the Bialkowski and Baird reports that have not undergone this degree of intensive scientific scrutiny, while on the other hand are prepared to make broad statements regarding the Study's approach and findings.

As you are aware, we did an internal review of Baird's comments on our modelling work and tried to reconcile the differences between our modelling results and theirs, but to no avail. You may not be aware, however, that the Study did a major review of the Bialkowski report and identified many significant issues with his approach and conclusions. We also asked a renowned expert (Dr. Frank Quinn) with more than 40 years of experience working in the field of Great Lakes hydroclimatology to provide his independent assessment. Dr. Quinn's review points out many flaws in the Bialkowski work and confirms our concerns with this assessment. We have attached both of these reviews so that you can appreciate the issues raised regarding this work.

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You have raised a number of points in your review which we have addressed in the accompanying attachment. For most of these issues, the information was either available in the main report or in the 34 supporting scientific reports, which were available on our website www.iugls.org.

The Study's mandate was to look at post-1962 dredging and that was the focus of our work. The governments did not ask us to review the impacts of all the dredging and sand and gravel activities even though you feel that this should have been within the scope of our Study.

Another very important issue is the lack and quality of the historical data, in particular bathymetric data, prior to 2000. The Study spent considerable effort mining data, cleaning up data sets and understanding the uncertainty associated with this information. We feel that we have provided a comprehensive assessment based on the data and information available. Further study, as you point out will not provide any further insights into changes in the hydraulic regime prior to 2000 due to these data limitations. Post-2000, we have more confidence in our findings because they are based on more comprehensive data and information.

We share your concerns that decisions on regulating the Great Lakes need to be based on sound science. This is our goal as an independent, binational, scientific advisory Board. The IJC is currently holding public consultations to determine the public's opinion on the Study's recommendations. The IJC will then assess all the information and make their recommendations to the two governments, who are ultimately responsible for making a decision on a course of action.

Respectfully,

Ted R. Yuzyk
Canadian Co-Chair

Eugene Z. Stakhiv
U.S. Co-Chair

cc: Murray Clamen, Secretary, Canadian Section, IJC
Chuck Lawson, Secretary, U.S. Section, IJC

Conclusions from Dr. J.W. Kamphuis Review entitled, "Modelling of Falling Water Levels on Lake Michigan-Huron":

1 The problem of falling water levels in Lake Michigan-Huron is complex and urgent. It is complex because of the technical complexity of the hydraulic/ sedimentary system, and because of the huge social and environmental cost involved in making the wrong decisions. It is urgent because of the lead times involved (decades) in planning and implementing any solutions and changes.

Both the IJC and the IUGLS are well aware of the complexity of the Great Lakes system. That is why the IJC has undertaken a series of very thorough studies each time the Great Lakes have approached recorded extremes of lake levels. We do not necessarily agree, however, that the situation is urgent, as lake levels have rebounded but remain below historic norms, and a progressive series of regulation adjustments have compensated, to some extent, for the accumulation of human interventions in the system. The recent decline (1998-2006) in lake levels is not unique, and is the combination of multiple factors: climate, conveyance change and GIA.

We have seen a similar decline in Lake Michigan-Huron water levels in the past, notably in 1929, for a 10-year period (see Figure 1). The lakes have rebounded after these periods of low water levels, but we realize that the issue of climate change needs to now be addressed in our analysis.

We understand the long lead timelines and that is why the Study engaged Ralph Pentland to investigate the institutional framework for implementing any physical works as the Study moves ahead with possible mitigative options due to a changing climate. We also contracted Baird & Associates to look at possible structures. The Study will continue to look at the need for mitigative structures as highlighted by the second recommendation.

2 Much good, state-of-the-art work has been done to gain a technical understanding of the problem. Because of uncertainties in the data, the data quality and the way it is used, because of uncertainties in the models used and in the interpretation of the model results, there are some differences between the conclusions reached in the various studies. Additional work is needed to understand these differences and come to a commonly acceptable resolution of the technical aspects before any further decisions can be made. A full understanding of the technical aspects of this problem is the critical path to responsible decisions.

The Study recognized the importance of factors noted in the above conclusion. The overall Study strategy was very carefully considered, debated amongst a score of top scientists engaged by the Study, and externally peer-reviewed. This was a rigorous process, which Dr. Kamphuis does not acknowledge in his review of the Baird and Bialkowski reports. Individual projects were designed to properly reflect the importance of numerous technical factors, and to explicitly quantify the uncertainty in the data, measurements and in the models. At times the Study relied on efforts of other IJC studies as well. The independent peer reviewers were satisfied with the breadth and depth of the analyses. As noted in the results from a variety of hydroclimatic, hydraulic and sediment modelling and analysis of water levels, hydroclimatic variables in Chapters 5 and 7, the Study demonstrated the range of various contributing factors in quantifying the conveyance change and the state of Lake Michigan-Huron water levels.

3 The central question in these studies must be: What part of the rapid decrease in water level difference between Lake Erie and Lake Michigan-Huron is man-made?

That was the central question of the IUGLS, but it also recognized the complementary part of the question i.e., what part of the declines in lake levels and head difference were caused by other natural factors. The science questions that were the focus of the IUGLS drew out of the Study directive from the IJC. These set up a series of scientific questions, captured at the beginning of each of the four chapters (4 to 7), which were debated at length by the Study and presented at the two sets of public meetings in 2008 and 2009. The Study had a more global mandate than noted in this conclusion; the science questions were designed to not only quantify the contributing factors but also attribute the multiple sources and causality of these changes.

4 Until now it has been assumed that flow out of Lake Michigan-Huron is controlled by the St Clair River. This assumption must be justified and may need further investigation.

The IUGLS did not make any assumptions regarding control points when it began its investigations, but both the Baird report and the Bialkowski review did, and neither justified their assumptions adequately. The issue of flow control was carefully considered by the various technical working groups and modelling teams of the IUGLS, as they investigated the question of whether the flow was section controlled or reach controlled. The Study scientists concluded that Lakes Michigan-Huron, St. Clair and Erie are one connected system with no single section controlling the outflow. The above noted postulation was investigated through a number of studies and IUGLS believes no further investigation in this area is required.

5 The assumption that Lake St Clair is a water storage reservoir, rather than a control for flow out of Lake Michigan-Huron must also be justified and may also need further investigation.

Again, Dr. Kamphuis has not familiarized himself with the extensive processes and considerable details that the IUGLS went through to arrive at its conclusions. The Study formulated a coherent and detailed strategy, relying on an examination of different existing models and research teams to investigate a variety of hypotheses and postulations. The Study consulted with the Canadian Hydraulic Centre of the National Research Council and invested in developing a system model from Lake Huron to the outlet of Lake Erie. The results documented in the reports on the IUGLS website are a testimonial of the breadth of investigations. This model also documented the connectivity of Lake Erie and Lake Michigan-Huron. It showed that Lake Erie exerts a backwater effect of approximately 40% on Lake Michigan-Huron water levels. This factor effectively shows that there are no unique sections of flow control.

6 Baird (2004) and Bialkowski (2009) both identify (using different methodology) that a gradual increase in conveyance between Lake Michigan-Huron and Lake Erie is needed to simulate the water level changes between these lakes correctly.

The IUGLS examined a variety of hypotheses, including a gradual increase in conveyance. The reality is that the physical data, and other associated lines of evidence suggest an episodic change in conveyance sometime in the mid-1980's – most likely associated with the record high lake levels of 1986. The Study demonstrated that retracing of the historic water levels by adjusting conveyance is a trial and error approach and the same results can also be obtained by a variety of other assumptions. It is a simple case of more equations than unknowns and a variety of combinations can yield the same answer.

Further, the Study employed all techniques that were peer reviewed either through the IJC's independent peer review process or of the open models employed that appeared in peer reviewed journals, accepted by the peers or have been in practice for a number of years.

7 Establishing a true cause and effect relationship between dredging and such gradual conveyance increase would require large mobile bed models. It is not clear that such modelling is feasible, given the large uncertainties involved in such modelling. It is also not clear that the results from such modelling would yield a major improvement. Therefore full mobile bed model study is not recommended.

Dr. Kamphuis did not read the studies and the strategy on the Study website, or he would have realized that the IUGLS did indeed undertake the very studies that he suggested. The Study did invest in developing and implementing 2- and 3-D mobile bed models with special routines to simulate the erodibility and armouring of the bed and computation of shear stress. All these studies have conclusively shown that the shear stresses are relatively low and not able to erode bed, especially in the upper section of the river where no dredging ever took place.

Theoretically, a sound mobile bed model should be able to start in an earlier bathymetry era; in the Study case this is 1971 and should be able to recreate 2007 bathymetry after running the model for a period of 36 years. The challenge is the nature of bed material and its distribution throughout the river reach in 1971, calibration data from 1971 and bed properties, etc. In absence of such pertinent information, the Study opted to look at the erodibility of the bed to confirm or refute the hypotheses of ongoing erosion. The Study found no evidence to support that there is ongoing erosion.

8 The only solution that does not call for a gradual increase in conveyance is the IUGLSB small element solution. As such, it is the only solution that is consistent with the assumptions for the fixed bed, small element modelling technique used. But is this approach correct?

Dr. Kamphuis suggests a potential solution, but then appears to question his own proposal. The IUGLS undertook a very thorough examination of all the possible approaches to analyzing and modelling the hydraulic characteristics of the St. Clair River. Dr. Kamphuis suggests that somehow the IUGLS approached the problem of model selection in an arbitrary manner. The reality is that every issue that Dr. Kamphuis has raised was thoroughly considered by the IUGLS scientists and engineers and the independent peer review group. Multiple hydraulic models were employed by IUGLS to provide a more comprehensive assessment of conveyance change and quantify a range of water level decline due to the increase in the conveyance capacity. The Study proposed this approach to the Independent Peer Reviewers, who approved this strategy, followed up with the review of the sub-products and agreed with the synthesis of the results. The Study believes that this is a good approach.

9 In view of:

- the large uncertainties in the calculation of the compensating factors (climate change and isostatic rebound),
- the likelihood that the bottom of the connecting channels is erodible, in spite of the extensive discussions presented in the IUGLSB report,
- questions about the strict applicability of the models and assumptions used,

the IUGLSB work needs further careful review and verification before it could be considered a valid answer to the problem.

The Independent Peer Review Group were presented the Study strategy that encompassed all of these conditions, followed up with the science conducted by the scientists and engineers who have collectively hundreds of years of experience in the Great Lakes modelling, data collection and analysis. The results and reports were discussed in open forums attended by the members of the Public Interest Advisory Group appointed by the IJC; all this information has been on the Study website for the last nine months. The work and products of the Study have seen both internal and external peer review. An open and transparent process was followed by the Study.

10 The IUGLSB solution is also only consistent at two specific instances in time – 1963 and 2000. It says nothing about the time in between. More work would need to be done to ascertain if a gradual increase in conveyance is needed also in this IUGLSB solution to produce the gradual decrease in water level difference between Lakes Michigan-Huron and Erie, between 1963 and 2000. As it stands, the interval between 1963 and 2000 can be filled in arbitrarily by sudden or gradual change in conveyance, which is not a satisfactory analysis of what occurred.

From the beginning, the Study recognized that the data gap between 1971 (surrogating for 1963) and 2007 was the critical challenging aspect of the Study. That data gap was the primary reason and largest source of uncertainty, so that the Study undertook a strategy of addressing the conveyance issue from a variety of approaches – some of which were purposefully overlapping or even redundant. The Study wanted to be confident that it could explain the changes in conveyance from a variety of perspectives. These all pointed towards some conveyance change in mid-1980s. This period included the historic record ice jam in 1984, followed by record high water levels starting in late 1985 and continued to 1987 and culminated with the severe drought and one of the steepest declines in head differences between Lake Michigan-Huron and Lake Erie. At this time a number of water level gauges showed departures from traditional (water level) differences and a return to “normal” after 1988-89. The Study inference of conveyance change in the river was not arbitrary but backed with rigorous analyses. One has to acknowledge for a large dynamic system as the Great Lakes, an episode can easily last several years.

11 The large bathymetry differences between the IUGLSB and Baird models, and their effect on conveyance change and water level change should be further investigated before the conclusions by Bruxer and Thompson (2010), that the bathymetry differences have little influence on the final results are proven. The differences between the Baird and Bialkowski results on the one hand and the IUGLSB results on the other hand must be understood before any of the results are credible.

Dr. Kamphuis does not refer to the Study's extensive review of Mr Bialkowski's work. Had he read that work, many of the issues raised by Dr. Kamphuis might well have been addressed. Mr. Bialkowski has not carried out any differential analysis of the 2007 and 1971 bathymetry of his own to be considered in this forum. There were differences in how bathymetry data are mapped on to the modelling grid, assumptions at the shorelines, etc. Depending on what assumptions were used (e.g., shoreline, boundary conditions, etc.) the Study got different answers in terms of simulated water levels and flows for any given year, but so long as the assumptions were kept the same between years, the difference in conveyance observed approached the same answer. The Study tried to be very clear in outlining the assumptions made and the limitations that result in the analysis. This was discussed in the technical detail in the Study response to the Baird review.

12 All three reports add to the understanding of a very complex dynamic system with very large time lags. The basic truth about the system is that the system has existed as a dynamically balanced system for a very long time, so there must have been a major force that upset this equilibrium.

The Baird report did help to provide some understanding of processes and changes in the St. Clair River. It certainly helped identify the issues which the IUGLS has been able to look at in a more comprehensive and thorough manner. As noted in Point 1 of this response, the Great Lakes have seen similar declines in the past, in 1929 and again in early 1960s. In addition, the Study believes the hydrology of 1929 event was even more severe than the one we had experienced. The lakes bounced back to its natural equilibrium without any external modifications to the system and recorded high lakes levels and a period of high water supplies and water level from mid-1960s to 1990s. The Study has identified and quantified the factors that have affected the recent low water levels.

13 Bialkowski (2009) has made a very good attempt to understand the gradual increase in conveyance needed in the system to produce the measured water level changes. He was also able to relate the changes in conveyance to the latest dredging. This work should be followed up with further study.

The Study reviewed Bialkowski's report in detail using both Study experts and an external expert. Both reviews identified major issues with the work starting with the basic assumption that all model, data and measurement uncertainties lay in the bathymetry and none in the Net Basin Supply estimates.

14 Bialkowski (2009) has also made a good attempt to understand the impact of climate change on the system. This work also needs to be followed up with further study and should be included in any future climate change discussions.

The IUGLS has developed the Climate Change projects and work that needs to be carried out which has been endorsed by the Independent Peer Review Group. The Study also consults with experts in Climate Change on a routine basis and has the services of two IPCC Nobel Prize laureates on the Study Board helping to guide this work.

15 Bialkowski (2009) has introduced a thoughtful discussion on flow control to manage water levels. Serious investigation of any flow control opportunities between Lake Michigan-Huron and Lake Erie must begin as soon as possible:

- because of the lead times involved in design, approval and implementation of flow control structures,
- because the approvals process will be very lengthy, since stakeholders with very differing ideas will all be present at the table,
- because the designs deal with flow control to prevent gradually lowering water levels over large areas, rather than the more common prevention of flooding.

The Study contracted two reports (Baird and Pentland) that discuss these concepts and ideas.

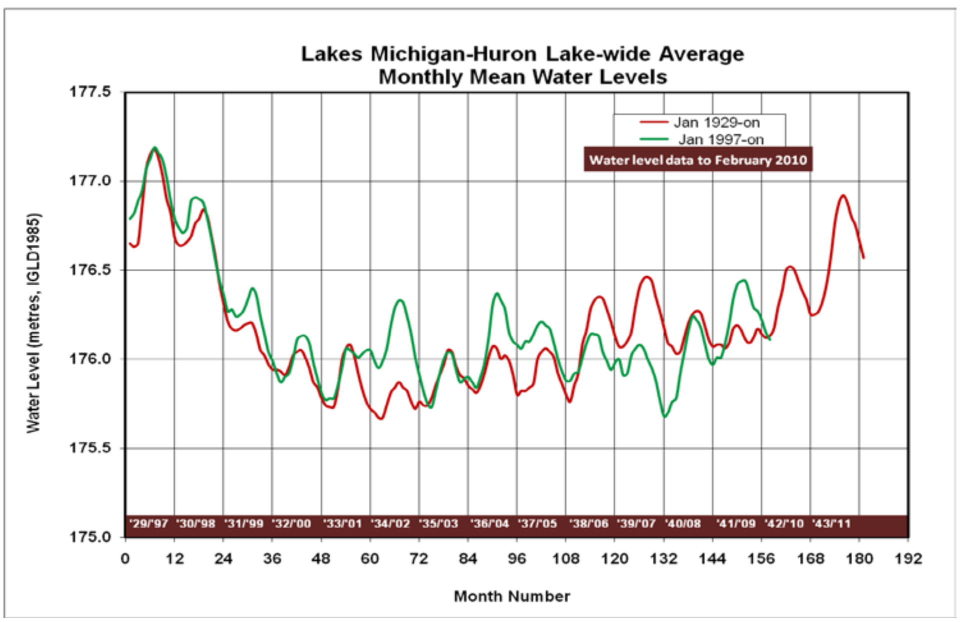

Figure 1- History in water levels repeated from 1929 era compared to the recent period

Review of the Modelling of Falling Water Levels on Lake Michigan-Huron
by
J. W. Kamphuis

1. Introduction

This review was written in response to a request by Georgian Bay Forever on 7 Dec, 2009. The request was to review a report written by Bialkowski in August 2009 entitled: "Rationalizing the International Upper Great Lakes Study St. Clair River 1 May, 2009 Draft Report Claims and Recommendations".

In the process it was necessary to familiarize myself with the physical (hydraulics and sediment transport) system of the middle Great Lakes and with four other reports, the IUGLSB (2009) final study report on the Upper Great Lakes water levels, the two connected studies by Baird (2004, 2009) and Bruxer and Thompson's (2010) comments on Baird (2009).

A complete, detailed review of this work requires intimate knowledge of the data and all of the tools used. I do not have this detailed knowledge and therefore these comments are based on general knowledge and experience. This review can not focus on the details of the calculations and the results (which depend very much on interpretation of the input data and model results, and facility with the modelling tools), The focus of this review is on "Was it done correctly?"; "How can the results be improved?", and "What can be done to understand and reconcile the different results?"

2. The Central Question

Because the Great Lakes system has essentially existed in its present dynamically balanced state for thousands of years, because the present decrease in water level appears to have no precedent in recorded data, and because the system has been subjected over the last century to interventions by man (such as water diversions, flow regulation, dredging and sand mining) the immediate implication would be that man must have had something to do with the decreasing water levels in Lake Michigan-Huron.

Therefore, the central question with respect to the decreasing lake levels, posed implicitly in these studies is: "What part of the decrease in the water level difference between Lake Erie and Lake Michigan-Huron is the result of man-made influences (through flow regulation, dredging and sand mining)?"

Since water motion is the easy part of these studies (compared to sediment movement), the influence on lake levels of flow regulation and diversion of water is relatively well understood and can be effectively evaluated. But the sediment motion (armouring, erosion and deposition changing channel cross sections) is much more difficult to study and evaluate; the uncertainties are much greater. Therefore the impacts of dredging and sand mining downstream of Lake Michigan-Huron are much more difficult to assess than, for example, the impacts of flow regulation into and out of the lakes, such as changing inflow from Lake Superior or outflow to the Mississippi drainage basin.

3. Concept of Basins with Connecting Channels

All studies begin with the premise that Lake Michigan-Huron is one component of a dynamic system, consisting of:

- Three water bodies - Lake Michigan-Huron, Lake St Clair and Lake Erie.
- Two connecting channels – the St Clair River and the Detroit River.
- The various inflows and outflows of the system.

The system is complicated by its size, which causes large time lags in the system and makes both computation and interpretation of the results difficult.

Within this concept of three basins connected by two channels, there has been much focus in the reports on “control sections” in the St Clair River. But it is not clear that the control sections (the cross sections that control the flow out of Lake Michigan-Huron) are in the St Clair River. Control could be exercised anywhere in the combination of the St Clair River, Lake St Clair and perhaps the Detroit River.

A key question to be addressed is: Is Lake St Clair simply a water storage reservoir, like the other two lakes in the system, or does it have some controlling influence on the flow out of Lake Michigan-Huron, and hence on the water level difference?” With its 30 km long 8.5 m deep dredged channel through a very shallow, weedy lake it is certainly a candidate to function as a flow control, a control that was substantially altered through historical dredging projects. At the same time, Lake St Clair is not comparable as a water storage basin to the other two basins: Lake Michigan-Huron and Lake Erie. Lake St Clair has only 4% of the surface area of Lake Erie and hence 4% of the storage capacity of Lake Erie. It has less than 1% of the surface area of Lake Michigan-Huron. Therefore, rather than a simple water storage basin, comparable in function to the other two basins, Lakes Michigan-Huron and Erie, it seems likely that Lake St Clair also functions as a wide, shallow flow section in the long connecting channel between Lake Michigan-Huron and Lake Erie, consisting of the combination of the St Clair River, Lake St Clair and the Detroit River. This open question should be answered in order to better understand the erosion/accretion processes.

The IUGLSB studies were based on fixed bed modelling of only the St Clair River. Therefore IUGLSB implicitly assumed that the St Clair River is the crucial flow control. This may be quite correct, but no clear justification was given for this choice, nor was any modelling done or quoted to show that Lake St Clair does not have flow control properties.

Baird in a review of IUGLSB's work expands on the IUGLSB fixed bed model by including part of Lake Huron to simulate the fluid velocities and head losses at the entrance into the St Clair River. This approach is more correct in that it would generate a truer boundary condition in Lake Huron, a condition that would be only minimally affected by the changes in the system downstream. However, Bruxer and Thompson (2010) state that their modelling, subsequent to the Baird study, indicates that this change in upstream boundary of the model does not introduce much change in their results. They observe: "… extension of the model boundary into Lake Huron would not likely provide additional insight in terms of conveyance changes over time since we would have to use the same bathymetry data for Lake Huron for each model year." The Baird model may be more correct, but without a history of the changing bathymetry in lower Lake Huron and the St Clair River entrance, the change in boundary will not make much difference on the end results. There appears to be more morphology data for the Lower Lake Huron - St Clair River entrance. Perhaps not of the same quality as the other data, but it should be studied, since it could shed additional light on the conveyance changes introduced below.

Baird's model, in spite of the changed boundary condition, still identifies the St Clair River and its entrance as the control section of the system. Both these models, therefore, implicitly assume that the concept of three basins connected by two channels is valid and that flow control resides in the St Clair River. The analysis in Baird (2004), Fig 2.5 would lend support to this concept. Discussions about where morphology change has taken place also seem to indicate that the St Clair River is the flow control.

Nevertheless, to obtain further insight into the hydraulic/sediment transport system, the concept of 2 basins (Lake Michigan-Huron and Lake Erie) and one long connecting channel (St Clair River + Lake St Clair + Detroit River), in which Lake St Clair functions as part of the flow control out of Lake Michigan-Huron should be more thoroughly investigated. At the same time, the use of the 3 basin/2 channel conceptual model should be better justified. Reading through the material certainly points to the need to justify the assumption that Lake St Clair is a water level control reservoir, rather than a flow control channel.

This change in concept from 3 basins to 2 basins has major implications about the central issue of gradual conveyance changes discussed later on and for the numerical models that IUGLSB and Baird used.

4. Dredging Impact

The man-made impacts from dredging and sand mining were identified in Section 2 as a major concern in this study. It is unfortunate that no one (at least in my readings) has tried to study in detail the effects of the massive dredging operation in 1933-36, the deepening of the 6 m (20 ft) deep navigation channel to a 7.6 m (25 ft) deep channel, or even the smaller dredging operation in 1960 – 1962, the further deepening of the channel to 8.25 m (27 ft) Seaway depth, in order to obtain a better understanding of dredging impact on this system.

A cursory look at water level records for Lake Michigan-Huron shows that after both major dredging incidents the Lake Michigan-Huron water levels rose for several years subsequent to dredging. So from the water levels themselves, there does not appear to be a direct causal relationship between dredging and Lake Michigan-Huron water levels.

The water level records clearly indicate, however, that dredging does not introduce sudden, instantaneous drops in water levels. Any decrease in water level difference between Lakes Michigan-Huron and Erie is gradual. This, by inference, can only mean that dredging and sand mining has resulted in gradual erosion in the flow control sections.

Baird (2004) separates man-made from natural impacts and produces a graph of the water level differences between Lakes Erie and Michigan-Huron resulting from man-made interference with the system (Baird, 2004; Fig 6.2). This water level drop is then plotted over incidences of dredging and sand mining in Baird, Fig. 6.3. Although Baird (2004), Fig 6.3 points to a possible relation between dredging, sand mining and water levels, cause and effect are not clearly identified.

Any cause and effect study on dredging and sand mining would need to simulate both the cause (dredging and sand mining volumes) and the effect (impacts). For that, it would be necessary to model sediment transport (mobile bed channel models instead of fixed bed channels). Such models are much more complicated than the fixed bed modelling used, and the interpretation of the model results would be much more difficult and more easily disputed, given the limitations of this type of modelling and the uncertainties in the input data.

The available bathymetry measurements consist of cross section soundings in 1954 and 1971, a single sideband survey in 2000 and multiband surveys in 2007, 2008. With only such limited historical bathymetry data available at very irregular intervals, of varying quality, of varying density of coverage, and with limited and incomplete sediment transport and dredging data, it is doubtful that mobile bed modelling would produce better end results.

5. Review of the Small Element Modelling

The simplest method to understand this system is a numerical model that connects basins with channels, as described in Section 3. This involves very few integral equations - simplified summations of the various complex processes taking place in the lakes and the channels.

There are more “sophisticated” methods that can simulate the processes in greater detail. Such methods split the problem into thousands of little sub-problems that are easier to formulate (closer to the real physics involved). This method leads to very large sets of interconnected equations to be solved simultaneously, requiring advanced numerical analysis techniques and large, efficient computational capability.

The usual approach to solving water/sediment transport problems is the method that uses small, connected elements, simply because it is thought to be superior by virtue of its closer simulation of the interacting physical processes involved. Particularly when, as is the case here, such sophisticated modelling is readily available and has already been applied to the particular problem or to similar problems, this methodology will be the method of choice.

5.1 IUGLSB (2009)

IUGLSB (2009) opted for the small element approach. It applied small element modelling technology and used several different varieties of such models. IUGLSB recognized that there are many uncertainties in the results of such models, introduced by uncertain bathymetric and sediment transport input data and by inaccurate representation of the physical processes in these numerical models. To obtain some estimate of model uncertainty and to obtain several competing estimates of the answers, IUGLSB resorted to repetitive and redundant modelling. IUGLSB used various versions of 1D, 2D and 3D models and ran these models for an identical bathymetry in each model. Then they ran similar sets of tests for other bathymetries and compared all the results. This methodology was successful in producing good indications of the uncertainties in the model results and of the range of results.

All the small element models used by IUGLSB were “fixed bed” models; the bathymetry of the model is completely defined by input bathymetry data; the model physical processes do not alter this bathymetry during model runs. This is as opposed to “mobile bed” models in which the model changes the model bathymetry during the model run.

In a fixed bed model, the change in water level difference between Lakes Michigan-Huron and Erie is computed as a function of the changed input bathymetry over time. This computed change was then compared to observed water level changes.

IUGLSB found that between 1963 and 2006 the difference in water levels between Lake Huron and Lake Erie decreased by 23 cm (based on the long term trend line fitted to the measured water level difference data from 1860 to 2007) – IUGLSB, Fig 8.1. The IUGLSB model results showed that 7 – 14 cm can be attributed to the changes in the measured bathymetry[1]. The difference between the model result (7-14 cm) and the results derived from water level record (23 cm) was attributed by IUGLSB to natural variations – changes in climate patterns and isostatic adjustment of the earth’s crust.

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[1] The 7-14 cm refers to water level drop from 1971. But in the summary diagram (IUGLSB, Fig. 8.5) it is directly compared to the 23 cm between 1963 and 2006. There are several such liberties with dates in both the IUGLSB and Baird reports. For the sake of presenting a clear argument here, these differences are ignored, simply assuming the authors knew what they were doing. The numbers are used as presented in the reports, in order to demonstrate the problem of closure between the calculated and measured water level drop.

IUGLSB's analysis is consistent with the assumptions of a fixed bed model. That is, the fixed bed analysis plus natural changes (climate change and isostatic adjustment) could completely account for the observed water level changes and no additional erosion is needed to explain the observed water level changes. IUGLSB goes to some length to justify the fixed bed assumption with sediment transport calculations and observations, and introduces possible further "natural" causes for water level fluctuations such as incidences of ice jamming and weed growth.

IUGLSB gives a clear and unequivocal answer to the crucial question posed in Sections 2 and 4 about the influence of man-made changes on the water level change. Their answer is that all water level change can be explained by the measured bathymetry plus natural phenomena plus uncertainties in the computations. By inference this means that man-made impacts, other than those contained in the measured bathymetries must be small (of the order of the errors in the numerical computations).

As a result of the uncertainties and the natural causes, IUGLSB recommends a wait and see solution to the problem of the falling water levels in Lake Michigan-Huron. This decision is rather surprising in the absence of any study about the impact of the falling water levels. A poorly explained drop of 23 cm since 1963 (or 80 cm since 1860) should have triggered some discussion and study of the impacts and some preliminary investigation about what can be done.

5.2 Baird (2004)

Baird (2004) in a review of the IUGLSB modelling opted for one of the 2D small element modelling technologies that had already been applied to the study area by IUGLSB (the RMSA model). But the two applications of essentially the same modelling technology yielded two quite different sets of results. Baird found that only 4 cm of decrease in water level difference between Lakes Huron and Erie could be attributed directly to dredging. Baird also found that water level changes due to climate change and isostatic adjustment are small. As a result, Baird can only explain the difference between 4 cm drop from dredging and the recorded 23 cm drop in water level difference by attributing this difference to additional erosion of the river bed. Such river bed erosion can only be *inferred* from fixed bed modelling; it does not model erosion/accretion, therefore erosion cannot be a conclusion from the modelling. This erosion, therefore, means that the fixed bed modelling tool is inadequate for the problem.

Because the observed water level changes are gradual, Baird postulated that the (inferred) river bed erosion must be gradual. Baird then further introduced evidence and several possible explanations for such river bed erosion, including some large episodic changes in cross-section noted in the measured bathymetries.

Baird's answer to the central question posed in Sections 2 and 4 is that the decrease in water level difference between Lakes Michigan-Huron and Erie can not be explained by measured bathymetry plus natural phenomena; there must be additional erosion in the system.

5.3 Comparison

IUGLSB assumed a fixed bed model, a model that cannot predict erosion/accretion and they find that other natural causes of water level change, such as climate change and isostatic adjustment, appear to be able to explain the difference between the non-eroding model results and the measured water level changes. Baird finds that the fixed bed model results plus natural changes can not account for the observed water level drop and they infer that some additional erosion is occurring.

The difference between the IUGLSB and Baird solutions is, therefore, not just in the details. Their results, obtained by essentially the same modelling technology and the same databases, give opposing answers to the crucial research question.

The IUGLSB solution is consistent with the fixed bed modelling assumptions. The Baird solution needs to infer slow, gradual erosion (slow, gradual increase in conveyance over time) in addition to the conveyance change that resulted from the measured bathymetry change. This outcome cannot be simulated by the fixed bed modelling procedure. As a consequence the fixed bed model may be an incorrect formulation and a (much) more complex methodology - a mobile bed (erodible) model - would be needed to compute such morphological changes correctly. This possibility and its feasibility are discussed below.

What is this mysterious gradual erosion? In the absence of other causes, the only possible explanation for any additional erosion would be that it represents a time-delayed adjustment to earlier, man-made interference with the system (such as dredging, sand mining, etc.).

5.4 How to Progress?

IUGLSB in its report went to some length to show that there is little or no active sediment transport in the St Clair system, but there do appear to be substantial changes to the measured river bottom bathymetries over time. IUGLSB attempted to explain these changes, but additional analysis of the sediment transport processes in the St Clair River is needed in order to provide a convincing explanation for these sediment features and their movement.

Baird's solution indicates that fixed bed modelling is insufficient to derive the desired results. Since mobile bed modelling on the scale that would be needed and to provide the accuracies required is probably not possible, we are left with two conflicting sets of results from models that are possibly not appropriate for this problem and there will be no way to prove from the fixed bed small element models which of the interpretations of the problem and which of the model results are correct.

The differences in the results are not surprising because of the substantial uncertainties contained in the computations, resulting from uncertain input data (such as the bathymetry, impact of climate change and isostatic adjustment, use of long term average water level differences trend), numerical errors, differing interpretations of how to introduce and formulate certain elements, different interpretations of the results, etc.

As an example of differences in interpretation, there are large differences in the way IUGLSB (2009) and Baird (2009) interpreted depths in the bathymetry data gaps, particularly near the shore. Baird finds with their interpretation of bathymetry that a water level drop of 23 cm occurs between 1971 and 2000 due to the bathymetry change indicated by the 1971 and 2000 surveys. IUGLSB, using the same model and the same data, but with different interpretation find a drop of 16 cm between 1971 and 2000. And Bruxer and Thompson (2010) state in response to the Baird analysis that no matter what bathymetry they introduced in the IUGLSB calculations, the final results of their many model runs all seem to approach the same answer. That does not make much sense and it is probably the result of working with fixed-bed flow models with large uncertainty. A resolution of the differences that are strictly a result of different interpretation of the same data can only be achieved by further study.

To sort out all the differences between the IUGLSB (2009) and Baird (2004, 2009) results would require some additional detailed study of the parameters, the processes and the models involved. It would also involve some additional modelling, particularly of the sensitivities of the computations to changes in various input conditions and to process adjustments, but also of the sediment transport processes.

But importantly, completion of this project will need ingenious people, who are able to develop a clear understanding and vision of the complete problem, while at the same time being familiar with all the details.[2] This project is much larger than its parts and will only be successful if the different "products" produced in various areas of expertise can be integrated into a coherent whole.

In addition to the fact that the fixed bed small element models may not be appropriate, any investigation of Lake St Clair as a flow channel, rather than a reservoir would require substantial changes to the IUGLSB (2009) and Baird (2004, 2009) model studies; the model boundaries for the calculations would need to be extended to include all of Lake St Clair and possibly the Detroit River and its outflow into Lake Erie. In the end, such extended fixed bed models would still only give indications of any increases in conveyance, but these results may permit greater understanding about the inferred gradual channel erosion.

Finally, modelling bed erosion and sediment transport in mobile bed models would add a whole new dimension to the studies. Since at this time, it is not clear whether this

[2] This statement is not a criticism. I make it because of the difficulty I myself have, grasping the overall and the details of this project.

approach would be possible or even feasible, or that it would yield better results, it is recommended not to proceed along this path.

From the reports and correspondence provided, it appears that IUGLSB considers that the study phase of this work is drawing to a close. This would be unfortunate, because some more work definitely needs to be done to justify and substantiate the assumptions and the interpretations of the input data and the output results made in both the IUGLSB and the Baird work. Clearly, resolution between the various model results can not be brought about by stopping the studies with each side trying to justify uncertain results. Much work has been done to date, much good insight has been gained, but some further work is required, based on the gains already made, to arrive at some resolution of the differences between the solutions and at some technically sound answers that are generally acceptable. It would be a pity not to take advantage of all the work done to date, in order to arrive at a firm resolution. The additional knowledge would essentially come at marginal cost, since the costly groundwork has been done.

Finally, the consequences of incorrect decisions, based on faulty technical information are too large to be contemplated.

6. Connected Basins Modelling

The fixed bed small element solutions were shown to provide uncertain result about erosion/accretion. They were also incapable of calculating conveyance change resulting from gradual, sustained erosion processes. Such conveyance changes could only be inferred from the model results, because they were necessary to explain observed water level change. Yet, understanding such time-related change in conveyance is very important and apparently the relatively simple connected basins approach can be used to find some further answers.

Baird (2004) uses the simplest possible basin system - a simple inflow/outflow model of Lake Erie to determine any changes in conveyance that can be attributed to man-made changes in flow in the connector channel between Lakes Huron and Erie (the combination of the St Clair River, Lake St Clair and the Detroit River) – Baird (2004), Ch 6 and Fig 6.1. The inflow into Lake Erie through this connector channel is then translated into a head difference between Lakes Huron and Erie needed to drive this discharge (Fig 6.2). Seasonal and weather related changes in head are excluded from Fig 6.2 and therefore the head difference in Fig 6.2 is indicative of the impact of man-made changes. The timing of the changes in head difference was compared with known dredging and sand mining events, showing some possible relationship (Fig 6.3). This is valuable additional information, not available directly from the small element modelling results.

Bialkowski (2009) uses control theory, a sophisticated methodology for process control to approach the problem of conveyance change. In Bialkowski's own words, this is a simple application of the technology:

"By this standard "Midlakes" with its 3 differential equations and 3 algebraic equations is tiny. Also, considering that the fluid being simulated is water (as opposed to exotic non-Newtonian fluids, such as slurries) the technical complexity is very low."

The Bialkowski (2009) control theory approach is refreshing (for the coastal engineering community) and this solution essentially amounts to a sophisticated, numerical, connected basins solution (3 basins, 2 connecting channels). The advantage of Bialkowski's particular approach is the availability of a set of tools, including the numerical integration technique (RK4) and the Kalman filter technique. Bialkowski's results throw a different light on the search for change of conveyance with time. Since the preferred small element, fixed bed modelling cannot calculate (but only infer) gradual change in conveyance, this type of integral analysis becomes a very important contribution to the understanding of the problem.

7. Bialkowski (2009)

The Bialkowski (2009) analysis first presents water levels for Lakes Michigan-Huron, St Clair and Erie calculated for a constant, average value of conveyance. These calculations are then compared to measured water levels in Bialkowski (2009), Fig 7. The calculated and measured water levels diverge and the difference is greatest for the record with the largest deviations. Part of this divergence could be because the problem is formulated as an initial value problem, in which the solution is carried forward in small time steps, starting at 1948. Each result at the next time interval is completely a function of (known and/or estimated) values at the previous time. This means any errors in the method of calculation (for example, due to truncation of numbers in the computer) accumulate in time and produce a divergence with time.

The question is: How much of the total deviation in Fig. 7 actually represents a change in the hydraulic characteristics of the system, and how much is error resulting from the numerical method used. Bialkowski (2009) contains no discussion of truncation errors, etc, but when asked about this, a subsequent communication - Bialkowski (2010) - shows that the error is quite small and that the deviations in Fig 7 are essentially the result of changes in channel conveyance.

Bialkowski subsequently replaces the constant conveyance of Fig 7 with an "appropriate" conveyance at each time interval to bring about agreement between calculated and measured water levels. Bialkowski (2009), Fig 18 shows the result – an almost perfect match between calculated and observed water levels. The "appropriate" conveyance values for each time increment were determined using an iterative Kalman filter technique. Since Figs. 7 and 18 include all the inputs/outputs to the lakes and therefore include any changes in net basin supply, Fig. 18 is the result of only conveyance change, the elusive quantity that could only be inferred from the small element fixed bed models.

This conveyance variation over time, needed to produce the water level match in Fig 18 is plotted in Fig 19. This figure shows a lot of noise in the solution. The noise begins in 1958 and must be related to a sudden disturbance of the equilibrium of the system at that time. The time corresponds to the date of the latest major dredging. Subsequent to 1958, there is a persistent gradual increase in conveyance of 11 %. This analysis indicates that a gradual increase in conveyance is needed to explain the water levels and that it is the result of a sudden impact (dredging) to the system. The analysis corroborates Baird's (2004) inference that additional gradual erosion is taking place. The work provides some numerical values for the conveyance history of the system. The Bialkowski (2009) analysis can probably be improved with some further development, but the initial results are enlightening and very useful additions to the information provided by the small element models.

8. Further Comments on Bialkowski (2009)

This section comments on some details of Bialkowski's work, in response to the request by Georgian Bay Forever.

Re Objective 1: The calculations are for quasi-steady states. But the system is dynamic and contains large time lags. The sediment system takes a long time to adjust to changes. Therefore, the water levels declined by 61 cm indeed, but it is not correct to use instantaneous water levels, such as the 1971 high or the 1990 low to determine conveyance change in a dynamic system with large time lags. On the other hand, the long-term average trend of 23 cm (IUGLSB, 2009) does not incorporate any system change and may be too low for this calculation.

Re Objective 2: This work looks reasonable, but this figure may also contain some time lag effect from the previous consistent increase in water levels after 1950.

Re Objective 4: This work corroborates that a gradual increase in conveyance in the connecting channels is needed to explain the gradual drop in lake level difference between Lakes Huron and Erie, as postulated by Baird (2004). It manages to quantify that a gradual conveyance change of 9.5% applied between 1971 and 2000 produces a decrease in lake level difference of 24 cm and very closely corroborates the 10% and 23 cm claimed by Baird (2004). Such a conveyance change can only be inferred from the more sophisticated small element fixed bed models.

Re Figure 19: The overriding question to be answered somewhere in all reports is: Why does the St Clair River conveyance appear to increase gradually over 50 years? I can think of no explanation other than that it must be a time-lagged adjustment to the dredging of 1958-62 (and 1933-36?), possibly with some positive feedbacks. In particular, I suspect that the dredging increased the conveyance through Lake St Clair, which results in higher flows in the St Clair River that could be the cause of subsequent gradual erosion in the St Clair River. In summary, Fig 19 is great evidence of a gradual conveyance increase, but an adequate physical reasoning for the gradual conveyance increase in St Clair River is still needed.

Re Ongoing Erosion: Erosion could indeed be ongoing. There are several more-or-less horizontal sections and some long adverse slopes in:

- the Lake Michigan-Huron water level record
- the water level difference record between Lakes Michigan-Huron and Erie,
- Baird (2004, Fig 6.2) representing water level difference between the lakes due to man-made intervention
- the conveyance increase in Fig. 19

Therefore the post 2000 water levels are not unique and they can hardly be interpreted as a significant long-term trend toward water level stabilization.

Re Erosion in the upper reaches of the St Clair River*:* This must be somehow be related to the earlier dredging either in the St Clair River or further downstream. Increased flow because of dredging should be capable to increase erosion upstream. It is true, as stated by the IUGLSB report, that the river is armoured and erosion is difficult, but sediment transport is always a delicate balance between the disturbing shear stresses and the sediment resistance to motion. It is very unlikely that no sediment motion takes place, unless the bottom of the St Clair River was formed during historic cataclysmic flows. Therefore gradual erosion of the St Clair River is likely when flow is increased through downstream dredging.

Re Objective 7: This is very useful work. The Kalman filtering appears to be a useful tool in the all important identification of conveyance change.

Bialkowski's interpretations of the details in the Kalman-generated curve (e.g. Fig. 24) are probably valid. More explanation of the interpretation of Fig. 24 would be helpful. The statement on p 52:

"An inescapable conclusion, however, from Figure 24 is that whatever did in fact happen, it was triggered in 1958 during the dredging for the 27-foot channel Therefore the cause of the erosion and subsequent conveyance increase experienced by St Clair River was not natural but man-made, specifically the construction of the St. Lawrence Seaway".

is probably correct, but could also use some further justification.

Re Climate Change: The climate change related work is good and is helpful and should certainly be included in any future discussions about the influence of climate change on water levels.

Re Flow Control: The discussion on flow control and structures is also informative and timely. It should be added that implementation of any control structures is first of all going to take many years to discuss, plan, design, determine cost, and be approved. But, secondly, the major obstacle to flow control structures to mitigate low water levels is that our (world wide) focus is on flood control[3]. It will still be some time before large scale low water control reaches the radar screen. Compare the lack of local and international concern about Lakes Chad and Baikal with the open concern about New Orleans, Bangladesh or the Netherlands, for example. Drought and low water environments somehow appear to be less urgent than floods. That is because floods instantly kill many people and cause incredible damage (they are classified as disasters), while the cost of drought and low water seems only to involve benign economic and social costs that pale in comparison to floods. It will still be a long time until the world wakes up to the real cost of low water and lack of water and to the fact that drought and low water are disasters of possibly greater magnitude than flood disasters.

9. Conclusions

1 The problem of falling water levels in Lake Michigan-Huron is complex and urgent. It is complex because of the technical complexity of the hydraulic/ sedimentary system, and because of the huge social and environmental cost involved in making the wrong decisions. It is urgent because of the lead times involved (decades) in planning and implementing any solutions and changes.
2 Much good, state-of-the-art work has been done to gain a technical understanding of the problem. Because of uncertainties in the data, the data quality and the way it is used, because of uncertainties in the models used and in the interpretation of the model results, there are some differences between the conclusions reached in the various studies. Additional work is needed to understand these differences and come to a commonly acceptable resolution of the technical aspects before any further decisions can be made. A full understanding of the technical aspects of this problem is the critical path to responsible decisions.
3 The central question in these studies must be: What part of the rapid decrease in water level difference between Lake Erie and Lake Michigan-Huron is man-made?
4 Until now it has been assumed that flow out of Lake Michigan-Huron is controlled by the St Clair River. This assumption must be justified and may need further investigation.
5 The assumption that Lake St Clair is a water storage reservoir, rather than a control for flow out of Lake Michigan-Huron must also be justified and may also need further investigation.
6 Baird (2004) and Bialkowski (2009) both identify (using different methodology) that a gradual increase in conveyance between Lake Michigan-Huron and Lake Erie is needed to simulate the water level changes between these lakes correctly.
7 Establishing a true cause and effect relationship between dredging and such gradual conveyance increase would require large mobile bed models. It is not clear that such modelling is feasible, given the large uncertainties involved in such modelling. It is also not clear that the results from such modelling would yield a major improvement. Therefore full mobile bed model study is not recommended.
8 The only solution that does not call for a gradual increase in conveyance is the IUGLSB small element solution. As such, it is the only solution that is consistent with

[3] Low flows are being controlled on a small scale, but not on a large scale such as the Great Lakes

the assumptions for the fixed bed, small element modelling technique used. But is this approach correct?

9 In view of:
   - the large uncertainties in the calculation of the compensating factors (climate change and isostatic rebound),
   - the likelihood that the bottom of the connecting channels is erodible, in spite of the extensive discussions presented in the IUGLSB report,
   - questions about the strict applicability of the models and assumptions used,

   the IUGLSB work needs further careful review and verification before it could be considered a valid answer to the problem.

10 The IUGLSB solution is also only consistent at two specific instances in time - 1963[4] and 2000. It says nothing about the time in between. More work would need to be done to ascertain if a gradual increase in conveyance is needed also in this IUGLSB solution to produce the gradual decrease in water level difference between Lakes Michigan-Huron and Erie, between 1963 and 2000. As it stands, the interval between 1963 and 2000 can be filled in arbitrarily by sudden or gradual change in conveyance, which is not a satisfactory analysis of what occurred.

11 The large bathymetry differences between the IUGLSB and Baird models, and their effect on conveyance change and water level change should be further investigated before the conclusions by Bruxer and Thompson (2010), that the bathymetry differences have little influence on the final results are proven.

12 The differences between the Baird and Bialkowski results on the one hand and the IUGLSB results on the other hand must be understood before any of the results are credible.

13 All three reports add to the understanding of a very complex dynamic system with very large time lags. The basic truth about the system is that the system has existed as a dynamically balanced system for a very long time, so there must have been a major force that upset this equilibrium.

14 Bialkowski (2009) has made a very good attempt to understand the gradual increase in conveyance needed in the system to produce the measured water level changes. He was also able to relate the changes in conveyance to the latest dredging. This work should be followed up with further study.

15 Bialkowski (2009) has also made a good attempt to understand the impact of climate change on the system. This work also needs to be followed up with further study and should be included in any future climate change discussions.

16 Bialkowski (2009) has introduced a thoughtful discussion on flow control to manage water levels. Serious investigation of any flow control opportunities between Lake Michigan-Huron and Lake Erie must begin as soon as possible:
   - because of the lead times involved in design, approval and implementation of flow control structures,
   - because the approvals process will be very lengthy, since stakeholders with very differing ideas will all be present at the table,
   - because the designs deal with flow control to prevent gradually lowering water levels over large areas, rather than the more common prevention of flooding.

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[4] Or 1971, see Footnote 1

10. References

Baird (2004) "Regime Change (Man-Made Intervention) and Ongoing Erosion in the St Clair River and impacts on Lake Michigan-Huron Lake Levels"
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