

"Great Lakes Total Phosphorus Models and Loads: A Fifteen Year Update"

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Submitted to

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Introduction and Background

This report summarizes the results of updated load estimates for total phosphorous (TP), total dissolved phosphorus (TDP), nitrate, and chloride for Lakes Superior, Michigan, Huron and Ontario for the years 1994-2008. Modeling and data analysis methods were used to determine whether target loads for phosphorus established by the Great Lakes Water Quality Agreement (GLWQA, Annex 3, 1978) were being met. In addition, a mass-balance model was used to check the consistency of phosphorus loads and to estimate interlake transport for each of the lakes (Michigan, Superior, Huron and Ontario).

The objectives for this project were to:

1. Assess status of phosphorus (TP and TDP), nitrate, chloride, and hydrologic data needed for Great Lakes load estimation for the period 1994-2008.
2. Apply the experience gained from similar work on Lake Erie to the estimation of TP loads (and associated uncertainty) to Lake Michigan for the fifteen-year period. These estimates also include separate loading estimates for upper and lower Green Bay.
3. Utilize estimation procedures developed for Lake Erie to calculate loads for TDP, chloride and nitrate on the same basis as objective 2.
4. Update the TP mass balance for Lake Michigan using components of the Lesht et al. (1991) regional phosphorus model and Chapra's (2007) phosphorus budget model. Use the model to assess the estimated phosphorus loads by comparison of the model-computed versus observed *in-lake* TP concentrations.
5. Collate data from the U.S. and Canada into common formats required for computation of loads for Lakes Huron, Superior and Ontario. This task includes separate loading estimates for the North Channel, Georgian Bay and Saginaw Bay.

6. Evaluate alternative load estimation techniques that may be able to utilize the wealth of historic information to provide plausible estimates for current conditions. Use minimization of load estimation uncertainty as a criterion for this evaluation.
7. Make estimates for each component (tributary, point source and atmospheric) of total lake loading including unmonitored areas on a watershed basis. Report the load estimation uncertainty associated with each annual load to each lake.
8. Update the TP mass balance for Lakes Huron, Superior, and Ontario using components of the Lesht et al. (1991) regional phosphorus model and Chapra's (2007) phosphorus budget model. Use the model to assess the estimated phosphorus loads by comparison of the model-computed versus observed *in-lake* TP concentrations.
9. Prepare tables and graphs of results showing subtotals on an annual-average basis for each component of the regional model and source (point, nonpoint, etc.).
10. Recommend the necessary level of monitoring for each lake to continue the assessment of loading trends at a level of certainty necessary for use in models and load control programs.

Data Sources

All of the data used to estimate nutrients loads came from databases compiled by government agencies in both the United States and Canada.

Tributary sources consisted of monitored and unmonitored tributary sub-basins; point sources included direct and indirect industrial and municipal dischargers; and atmospheric sources refer to loadings from the atmosphere that fall directly on the lake surface. Point source data was retrieved from the USEPA's Permit Compliance System (PCS) and Canada's Municipal and Industrial Strategy for Abatement (MISA). The USEPA PCS system has been replaced by a new system, Integrated Computer Information System (ICIS), and some states began reporting to this new system beginning in 2006. The Wisconsin

Department of Natural Resources (WDNR) and Michigan Department of Natural Resources and Environment (DNRE) provided additional data on facilities permitted to discharge to surface waters in the basins.

Tributary streamflow and nutrient concentration data were retrieved from the U.S. Geological Survey (USGS) and Environment Canada (EC). The Minnesota Department of Natural Resources (MNDNR) provided additional flow data when none was available from USGS.

Water quality concentration data for Lake Huron were retrieved from STORET (Legacy and Modern), USGS, and the Provincial Water Quality Monitoring Network of Ontario.

Atmospheric deposition data was obtained from Environment Canada. Lake Michigan atmospheric loads were estimated using the high spatial resolution 1994-1995 loads reported by Miller et al. (2000) as part of the Lake Michigan Mass Balance (LMMB) study. No atmospheric sampling seems to have occurred since 1995 in Lake Michigan, but monthly over-lake precipitation data from the National Oceanic and Atmospheric Administration (NOAA) and chloride concentration data from the National Atmospheric Deposition Program (NADP) (USGS, 2008) sampling stations were available for the study period.

Results

Objective 1. Assess status of phosphorus (TP and TDP), nitrate, chloride, and hydrologic data needed for Great Lakes load estimation for the period 1994 to 2008.

All data needed to determine Great Lakes load estimates for the period 1994-2008 were acquired.

Hydrologic data for the lakes were obtained, however some of the Canadian data took longer to acquire.

Water-quality concentration data for the 11 Lake Michigan tributaries that were sampled as part of LMMB was successfully obtained and resulted in estimation of nutrient loads for Lake Michigan with

roughly the same ratio (1.8) of monitored to unmonitored basin area as achieved in the LMMB.

Additional sources of water quality data have been identified and were used in the refinement of loading to Green Bay.

Water-quality concentration data for Lake Huron were retrieved from STORET (Legacy and Modern), USGS, and the Provincial Water Quality Monitoring Network of Ontario. Initially, less success was achieved (compared to Lake Michigan) in obtaining consistent data from year to year to cover the major tributary basins. However, the Ontario tributary data became available online for the years 2002 to the present. Archived data covering the period 1994-2001 were requested from the Ontario Ministry of the Environment and were received in December, 2009.

All available U.S. point source data have been de-archived and processed. Some Wisconsin data that were not available in PCS, were received directly from the WDNR. Indiana data for 2007 and 2008 were not available in PCS and data for those years were provided by EPA, Region V. Canadian point source data were obtained in December, 2009 in summary form from the Ontario Ministry of the Environment. Point source data for Lake Michigan and Huron (U.S) have been quality-assured, summarized, and tabulated. See attached text files.

Objective 2. Apply the experience gained from similar work on Lake Erie to the estimation of TP loads (and associated uncertainty) to Lake Michigan for the fifteen-year period. This task includes separate loading estimates for upper and lower Green Bay.

The experience of Lake Erie has enabled estimation of TP loads for Lake Michigan including separate estimates for upper and lower Green Bay. Lake Michigan was divided into nine segments, seven segments in Green Bay (GB1-GB7) and two for Lake Michigan proper (Lake Michigan North and Lake Michigan South). All problems with missing data were resolved. See attached Excel spreadsheets titled LAKE MICHIGAN TP 1994-2008 and LAKE MICHIGAN TP 1994-2008 TRIB DETAIL TABLE. These

spreadsheets are meant to provide the level of detail that was previously available in IJC reports, such as the 1987 Appendix B (Rathke and McCrae, 1989). The 1994-2008 spreadsheet provides summary details similar to Table 3.0-3 in Rathke and McCrae (1989). The summary loads have been broken down by model segment and standard errors of estimated load have been included. The 1994-2008 TRIB DETAIL TABLE is actually an Excel file composed of 15 worksheets; one for each year. Within each year, the details of the load estimation for each tributary (organized by model segment) are included. The monitored and unmonitored area estimates, direct and indirect point sources, and atmospheric estimates by segment are all included.

Objective 3. Utilize estimation procedures developed for Lake Erie to calculate loads for TDP, chloride and nitrate on the same basis as objective 2.

Load calculations have been completed for TDP, chloride, and nitrate. These estimates have been reviewed and all problems with missing data have been resolved. See attached Excel spreadsheets titled LAKE MICHIGAN TDP 1994-2008, LAKE MICHIGAN CHLORIDE 1994-2008, and LAKE MICHIGAN NITRATE 1994-2008. See Objective 2 for a description of these tables.

Objective 4. Update the TP mass balance for Lake Michigan using components of the Lesht et al. (1991) regional phosphorus model and Chapra's (2007) phosphorus budget model. Use the model to assess the estimated phosphorus loads by comparison of the model-computed versus observed in-lake TP concentrations.

The updated mass balance with enhanced spatial resolution for Green Bay was the topic of Matthew Maccoux's master's thesis, titled, "Total Phosphorus Loads (1994-2008) and a Mass Balance Budget Model for Green Bay, Lake Michigan", and presented at the 54th Annual Conference on Great Lakes Research (IAGLR 2011) in Duluth, Minnesota at a session organized by Dolan and Chapra (Co-PIs). The total phosphorus model agreement was generally good, with the exception of a large difference in lower

Green Bay during 1999-2004. This work helped in the development of a total phosphorus TMDL for Green Bay and the Lower Fox River.

Objective 5. Collate data from U.S. and Canada into common formats required for computation of loads for Lakes Huron, Superior and Ontario. This will include separate loading estimates for the North Channel, Georgian Bay and Saginaw Bay.

An Access database was created to prepare both U.S. and Canadian tributary data for load computations. The database has been structured to allow separation of North Channel loads. Load calculations have been completed for TP, TDP, chloride, and nitrate for Lakes Huron, Superior and Ontario. Lakes Superior and Ontario were treated as one completely mixed segment whereas Lake Huron was divided into six segments, which include: North Channel, Georgian Bay, Saginaw Bay Inner, Saginaw Bay Outer, Lake Huron North and Lake Huron South.

Objective 6. Evaluate alternative load estimation techniques that may be able to utilize the wealth of historic information to provide plausible estimates for current conditions. Use minimization of load estimation uncertainty as a criterion for this evaluation.

Since most of the missing data problems have been resolved for all the lakes (Michigan, Huron, Superior and Ontario) this objective was not given priority. In general, traditional load estimation techniques were considered adequate given the availability of Great Lake data.

Objective 7. Make estimates for each component (tributary, point source and atmospheric) of total lake loading including unmonitored areas on a watershed basis. Report the load estimation uncertainty associated with each annual load to each lake.

The database referred to in Objective 5 has been structured to allow component estimates on a watershed basis. Load calculations have been completed for TP, TDP, chloride, and nitrate for Lakes

Huron, Superior and Ontario for each component including uncertainty estimates. These estimates have been reviewed and all problems with missing data have been resolved.

See attached Excel spreadsheets titled: LAKE HURON TP 1994-2008, LAKE HURON TP 1994-2008 TRIB DETAIL TABLE, LAKE HURON TDP 1994-2008, LAKE HURON TDP 1994-2008 TRIB DETAIL TABLE, LAKE HURON CHLORIDE 1994-2008, LAKE HURON CHLORIDE 1994-2008 TRIB DETAIL TABLE, LAKE HURON NITRATE 1994-2008, LAKE HURON NITRATE 1994-2008 TRIB DETAIL TABLE, LAKE SUPERIOR TP 1994-2008, LAKE SUPERIOR TP 1994-2008 TRIB DETAIL TABLE, LAKE SUPERIOR TDP 1994-2008, LAKE SUPERIOR TDP 1994-2008 TRIB DETAIL TABLE, LAKE SUPERIOR CHLORIDE 1994-2008, LAKE SUPERIOR CHLORIDE 1994-2008 TRIB DETAIL TABLE, LAKE SUPERIOR NITRATE 1994-2008, LAKE SUPERIOR NITRATE 1994-2008 TRIB DETAIL TABLE, LAKE ONTARIO TP 1994-2008, LAKE ONTARIO TP 1994-2008 TRIB DETAIL TABLE, LAKE ONTARIO TDP 1994-2008, LAKE ONTARIO TDP 1994-2008 TRIB DETAIL TABLE , LAKE ONTARIO CHLORIDE 1994-2008, LAKE ONTARIO CHLORIDE 1994-2008 TRIB DETAIL TABLE, LAKE ONTARIO NITRATE 1994-2008 and LAKE ONTARIO NITRATE 1994-2008 TRIB DETAIL TABLE.

Objective 8. Update the TP mass balance for Lakes Huron, Superior, and Ontario using components of the Lesht et al. (1991) regional phosphorus model and Chapra's (2007) phosphorus budget model. Use the model to assess the estimated phosphorus loads by comparison of the model-computed versus observed in-lake TP concentrations.

Work on the TP mass balance for Lakes Huron, Superior and Ontario have been completed. The updated mass balance with enhanced spatial resolution for Lake Huron was the topic of Heidi Schmitt Marquez's master's thesis, titled, "Nutrient Loading in the Upper Great Lakes System: Chloride and Total Phosphorus Estimates in Lakes Superior, Michigan, and Huron, 1994-2008", and presented at the 54th Annual Conference on Great Lakes Research (IAGLR 2011) in Duluth, Minnesota at a session organized by Dolan and Chapra (Co-PIs).

Simulation results for Lakes Superior and Huron generally conform to observations and indicate that these lakes have exhibited significant improvement following load reductions. However, data for Lake Ontario suggests a much greater improvement than predicted by the model.

This work was coupled with ongoing load estimation for Lake Erie and allows for better resolution of the upstream load to the Huron-Erie corridor.

Objective 9. Prepare tables and graphs of results showing subtotals on an annual-average basis for each component of the regional model and source (point, nonpoint, etc.).

Graphs and tables have been completed. For each lake (Michigan, Superior, Huron and Ontario) tables and graphs were prepared showing annual load estimates for TP, TDP, nitrate and chloride by loading source. See attached Tables and Graphs.

Objective 10. Recommend the necessary level of monitoring for each lake to continue the assessment of loading trends at a level of certainty necessary for use in models and load control programs.

Given the state of water quality monitoring in 2008, lakewide annual estimates of TP are feasible. High-quality data are still available to allow reasonable estimates of total phosphorus to the Great Lakes.

Recent concerns about lakewide changes in trophic status as well as the recurrence of local and regional water-quality problems should be ample justification for renewed monitoring efforts.

Project Outputs

1. Tables of annual TP loads with standard errors for each lake (Michigan, Huron, Ontario and Superior) as well as for the key embayments (Green Bay, Georgian Bay, Saginaw Bay) for the fifteen-year period 1994-2008.

Status: The final tables of annual TP loads for each lake (Michigan, Huron, Ontario and Superior) are attached as a spreadsheet titled LAKE MICHIGAN TP 1994-2008, LAKE HURON TP 1994-2008, LAKE ONTARIO TP 1994-2008, and LAKE SUPERIOR TP 1994-2008.

2. Tables similar to those described for Output #1 for TDP, chloride, and nitrate. The loadings in the tables described in Outputs #1 and #2 will be presented in two different ways: (1) The Summary of Estimated Atmospheric, Industrial, Municipal, and Tributary Loading to each lake comparable to Table 3.0-1 in Appendix B (Rathke and McRae, 1989); and (2) The Summary of Estimated Atmospheric, Industrial, Municipal, and Tributary Loading From Point and Nonpoint Sources to each lake comparable to Table 3.0-8 in Appendix B (Rathke and McRae, 1989). The latter table includes indirect point sources. These tables will also be consistent with those used by Chapra (1977) to display the components of loading for mass-balance modeling and will be the basis for graphs and charts displaying this information where appropriate. These tables will be in common formats for all lakes and will include Canadian data that have been converted to the same basis (units and time periods) as U.S. data.

Status: Load estimates for TDP, chloride, and nitrate have been completed for all lakes (Michigan, Huron, Superior and Ontario) and are included in this report. See attached tables.

3. Calibrated TP and Chloride model analysis of lake response to loading trends using the latest available data.

Status: Calibration is completed. The model was calibrated using chloride data due to its conservative nature and relative ease and precision of measurement. Chloride does not settle out of the water column, and thus can provide accurate information about the hydrodynamic behavior of a particular body or segment of water. A chloride mass-balance model was used to estimate turbulent eddy diffusion between model segments. Total phosphorus concentrations were then simulated based on estimated historical and measured modern loading time series. Objectives 4 and 8 were then able to be

addressed. Two masters-level students were hired and included various aspects of the calibration as the topics of their theses. The theses identified below were defended in December, 2010 and submitted in partial fulfillment of the requirements for a Master's of Science degree in Environmental Science and Policy at the University of Wisconsin – Green Bay:

Total Phosphorus Loads (1994-2008) and a Mass Balance Budget Model for Green Bay, Lake Michigan by Matthew J. Maccoux

Nutrient Loading in the Upper Great Lakes System: Chloride and Total Phosphorus Estimates in Lakes Superior, Michigan, and Huron, 1994-2008 by Heidi S. Schmitt Marquez

4. General software for evaluating the long-term trends of the contaminants addressed in this project will be delivered along with model documentation.

Status: A general model software package, GL2K, has been developed and applied to simulate historical trends of chloride and total phosphorus as a function of estimated loadings. The model is implemented as an Excel Workbook with program code written as macros with VBA (Visual Basic for Applications). This software along with supporting input files and a users manual (Chapra and Dolan 2011) are included on the CD that accompanies this document.

5. Monitoring recommendations for each lake in order to maintain a desired level of statistical certainty in load estimation.

Status: Given the state of water quality monitoring in 2008, lakewide, annual estimates of TP are feasible. High-quality data are still available to allow reasonable estimates of total phosphorus to the Great Lakes. Recent concern about lakewide changes in trophic status as well as the recurrence of local and regional water-quality problems should be ample justification for renewed monitoring efforts.

6. Two interim reports and a final technical report.

Status: The first interim report was delivered in April 2009 and the second in December 2009. This report is the final technical report

7. One or more peer-reviewed publications.

Status: Four papers have been drafted and are ready for submission to peer-reviewed journals. These draft publications include:

1. Maccoux, M.J., D.M. Dolan, and S.C. Chapra. 2011. Chloride and total phosphorus budgets for Green Bay, Lake Michigan.
2. Chapra, S.C. and D.M. Dolan. 2011. Great Lakes total phosphorus revisited: 2. Mass-balance modeling.
3. Dolan, D.M. and S.C. Chapra. 2011. Great Lakes total phosphorus revisited: 1. Loading analysis and update: 1994-2008.
4. Schmitt-Marquez, H, D.M. Dolan, and S.C. Chapra. 2011. Interlake and total loading estimates of total phosphorus and chloride in the upper Great Lakes system, 1994-2008. 2011

Several presentations on the preliminary and final results of this study have been made by co-investigators at three Annual Conferences on Great Lakes Research (IAGLR). A presentation on the preliminary results of this study was made by the co-investigators at the 52nd Annual Conference on Great Lakes Research (IAGLR 2009) at the University of Toledo on May 20th. Also, a session was included by the co-investigators at the 53rd IAGLR 2010 at the University of Toronto and at the 54th Annual Conference on Great Lakes Research (IAGLR 2011) in Duluth, Minnesota that included much of this work.

In addition, a session titled “Eutrophication Management in the Great Lakes: Past, Present and Future” is planned by the co-investigators at the 55th Annual Conference on Great Lakes Research (IAGLR 2011) in Cornwall, Ontario that will present much of this work.

Attachments

MIIN94_08loadsummary.txt: Load summary of Indiana dischargers to Lake Michigan basin

mimi94_08loadsumupdate.txt: Load summary of Michigan dischargers to Lake Michigan basin

miwi94loadsummaryfinal.txt: Load summary for Wisconsin dischargers to Lake Michigan basin

LAKE MICHIGAN TP 1994-2008.xlsx: Final TP Load Estimates for Lake Michigan

LAKE MICHIGAN TP 1994-2008 TRIB DETAIL TABLE.xlsx

LAKE MICHIGAN TDP 1994-2008.xlsx: Final TDP Load Estimates for Lake Michigan

LAKE MICHIGAN TDP 1994-2008 TRIB DETAIL TABLE.xlsx

LAKE MICHIGAN CHLORIDE 1994-2008.xlsx: Final Chloride Load Estimates for Lake Michigan

LAKE MICHIGAN CHLORIDE 1994-2008 TRIB DETAIL TABLE.xlsx

LAKE MICHIGAN NITRATE 1994-2008.xlsx: Final Nitrate Load Estimates for Lake Michigan

LAKE MICHIGAN NITRATE 1994-2008 TRIB DETAIL TABLE.xlsx

LAKE HURON TP 1994-2008.xlsx: Final TP Load Estimates for Lake Huron

LAKE HURON TP 1994-2008 TRIB DETAIL TABLE.xlsx

LAKE HURON TDP 1994-2008.xlsx: Final TDP Load Estimates for Lake Huron

LAKE HURON TDP 1994-2008 TRIB DETAIL TABLE.xlsx

LAKE HURON CHLORIDE 1994-2008.xlsx: Final Chloride Load Estimates for Lake Huron

LAKE HURON CHLORIDE 1994-2008 TRIB DETAIL TABLE.xlsx

LAKE HURON NITRATE 1994-2008.xlsx: Final Nitrate Load Estimates for Lake Huron

LAKE HURON NITRATE 1994-2008 TRIB DETAIL TABLE.xlsx

LAKE SUPERIOR TP 1994-2008.xlsx: Final TP Load Estimates for Lake Superior

LAKE SUPERIOR TP 1994-2008 TRIB DETAIL TABLE.xlsx

LAKE SUPERIOR TDP 1994-2008.xlsx: Final TDP Load Estimates for Lake Superior

LAKE SUPERIOR TDP 1994-2008 TRIB DETAIL TABLE.xlsx

LAKE SUPERIOR CHLORIDE 1994-2008.xlsx: Final Chloride Load Estimates for Lake Superior

LAKE SUPERIOR CHLORIDE 1994-2008 TRIB DETAIL TABLE.xlsx

LAKE SUPERIOR NITRATE 1994-2008.xlsx: Final Nitrate Load Estimates for Lake Superior

LAKE SUPERIOR NITRATE 1994-2008 TRIB DETAIL TABLE.xlsx

LAKE ONTARIO TP 1994-2008.xlsx: Final TP Load Estimates for Lake Ontario

LAKE ONTARIO TP 1994-2008 TRIB DETAIL TABLE.xlsx:

LAKE ONTARIO TDP 1994-2008.xlsx: Final TDP Load Estimates for Lake Ontario

LAKE ONTARIO TDP 1994-2008 TRIB DETAIL TABLE.xlsx

LAKE ONTARIO CHLORIDE 1994-2008.xlsx: Final Chloride Load Estimates for Lake Ontario

LAKE ONTARIO CHLORIDE 1994-2008 TRIB DETAIL TABLE.xlsx

LAKE ONTARIO NITRATE 1994-2008.xlsx: Final Nitrate Load Estimates for Lake Ontario

LAKE ONTARIO NITRATE 1994-2008 TRIB DETAIL TABLE.xlsx

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