# EXAMINATION OF THE STATUS OF THE GOALS OF ANNEX 3 OF THE GREAT LAKES WATER QUALITY AGREEMENT

*by*

**Members of the Annex 3 Technical Sub-group of the RWG D**
Joseph V. DePinto (U.S. co-chair), David Lam (Canadian co-chair), Martin Auer, Noel Burns, Stephen Chapra, Murray Charlton, David Dolan, Russ Kreis, Todd Howell, Don Scavia
with assistance from
David Rockwell (U.S. co-chair of RWG D), Eric van Bochove (Canadian co-chair of RWG D)
Tom Looby (RWG D secretary)

## Introduction and Background

One of the great successes of the Great Lakes science and management community since the signing of the Great Lakes Water Quality Agreement has been the control of eutrophication in the lakes through the reduction of phosphorus loadings in accordance with model-derived target phosphorus loads for each lake and major embayment. With the signing of the Great Lakes Water Quality Agreement in 1972 and its revision in 1978, the governments of the U.S. and Canada implemented a program of P load reduction that was unprecedented in any region of the world. A description of this program and its success can be found in DePinto et al. 1986.

A great deal of research and modeling led to the preparation and implementation of Annex 3 ("Control of Phosphorus") of the Agreement, but perhaps the most pivotal analysis was the work of Task Group III (1978) (the full TG III report is presented in Appendix A). This group coordinated the application of a suite of Great Lakes eutrophication models in order to gain a consensus on the loadings of phosphorus to each of the lakes that would be necessary to achieve water quality objectives for those lakes.

The process of establishing the target P loads in Annex 3 first involved first the establishment of goals of phosphorus control. These goals are stated in section 1 of Annex 3 (IJC 1978):

(a) Restoration of year-round aerobic conditions in the bottom waters of the Central Basin of Lake Erie;

(b) Substantial reduction in the present levels of algal biomass to a level below that of a nuisance condition in Lake Erie;

(c) Reduction in present levels of algal biomass to below that of a nuisance condition in Lake Ontario including the International Section of the St. Lawrence River;

(d) Maintenance of the oligotrophic state and relative algal biomass of Lakes Superior and Huron;

(e) Substantial elimination of algal nuisance growths in Lake Michigan to restore it to oligotrophic state; and

(f) The elimination of algal nuisance in bays and in other areas wherever they occur.

Water quality objectives were then established in order to meet these goals. A description of the process that determined the objectives is presented in Thomas, et al. (1980). The objectives that were established are presented in Table 1. Then a technical Task Group was constituted and

**Table 1. Water Quality Objectives used to establish target phosphorus loads for eutrophication control in the Great Lakes.**

| Lake Basin | Chlor *a* (ug/L) | TP (ug/L) | Trophic State |
|---|---|---|---|
| Superior | 1.3 | 5 | Oligotrophic |
| Michigan | 1.8 | 7 | Oligotrophic |
| Huron | 1.3 | 5 | Oligotrophic |
| Saginaw Bay | 3.6 | 15 | Mesotrophic |
| Western Erie | 3.6 | 15 | Mesotrophic |
| Central Erie | 2.6 | 10 | Oligomesotrophic |
| Eastern Erie | 2.6 | 10 | Oligomesotrophic |
| Ontario | 2.6 | 10 | Oligomesotrophic |

charged with applying a suite of eutrophication models of varying complexity to quantitative determine the phosphorus loading to each lake that would achieve those objectives. The Task Group III report (1978) fully documented this analysis and confirmed the establishment of the target phosphorus loads that appear in Annex 3 and in Table 2 below.

In response to these recommendations, the Great Lakes community made significant reductions

**Table 2. Total phosphorus target loads to Great Lakes compared with the baseline load estimates for 1976. Starred (*) target loads could not be met by point source reductions alone; additional nonpoint source controls were required.**

| Basin | 1976 TP Load (mta) | Target TP Load (mta) |
|---|---|---|
| Lake Superior | 3600 | 3400 |
| Lake Michigan | 6700 | 5600 |
| Main Lake Huron | 3000 | 2800 |
| Georgian Bay (LH) | 630 | 600 |
| North Channel (LH) | 550 | 520 |
| Saginaw Bay (LH) | 870 | 440 |
| Lake Erie | 20000 | 11000* |
| Lake Ontario | 11000 | 7000* |

in TP loads to Lake Michigan and the lower Great Lakes. For Lake Erie, for example, the major load reductions were achieved through phosphate detergent bans and municipal point source controls, which were largely achieved in the Lake Erie basin by the early 1980s. Because point source controls were not sufficient to achieve the target loads, best management practices were implemented on agricultural lands within the basin, and Lake Erie first achieved its target P load in 1981 (DePinto, et al. 1986). Response to P load reductions was rapid, profound, and close to those predicted by DiToro and Connolly (1980). A post-audit of their eutrophication model indicated it predicted concentrations of P, chlorophyll *a*, and central basin hypolimnion dissolved oxygen quite well (DiToro et al. 1987). Bierman and Dolan (1986) also successfully post-audited their model for Saginaw Bay. However, after the 1980s very little model analysis was done on the Great Lakes, and with the exception of Lake Erie, TP load measurement stopped in 1991.

In the process of reviewing Annex 3 of the GLWQA, a technical sub-group of the Nutrients Review Work Group (RWG D) was formed to revisit the technical basis for the development of Annex 3 and essential post-audit its success to the extent possible through the decade of the 1990's and beyond where possible.

## Charge to the Sub-group

Through internal discussions and interaction with the Nutrients Review Work Group co-chairs of, David Rockwell and Eric van Bochove, the Technical Sub-group formulated a set of three fundamental questions to help frame their analysis of Annex 3:

***Question 1- Have we achieved the target Phosphorus (P) loads in all of the Great Lakes?***

***Question 2- Have we achieved the water quality objectives in all of the Great Lakes?***

***Question 3- Can we define the quantitative relationships between P loads and lake conditions with existing models? Are the models still valid on a whole lake basis or have ecosystem changes to the P- chlorophyll relationship occurred such that new or updated models need to be run?***

It should be recognized that the time and resource constraints of the overall Agreement review process, have made it impossible to undertake a rigorous and thorough analysis of these charge questions (especially question 3). However, in an attempt to inform this review we have summarized the information gathered and analysis conducted in this report.

## Question 1: Target Phosphorus Loads Achieved?

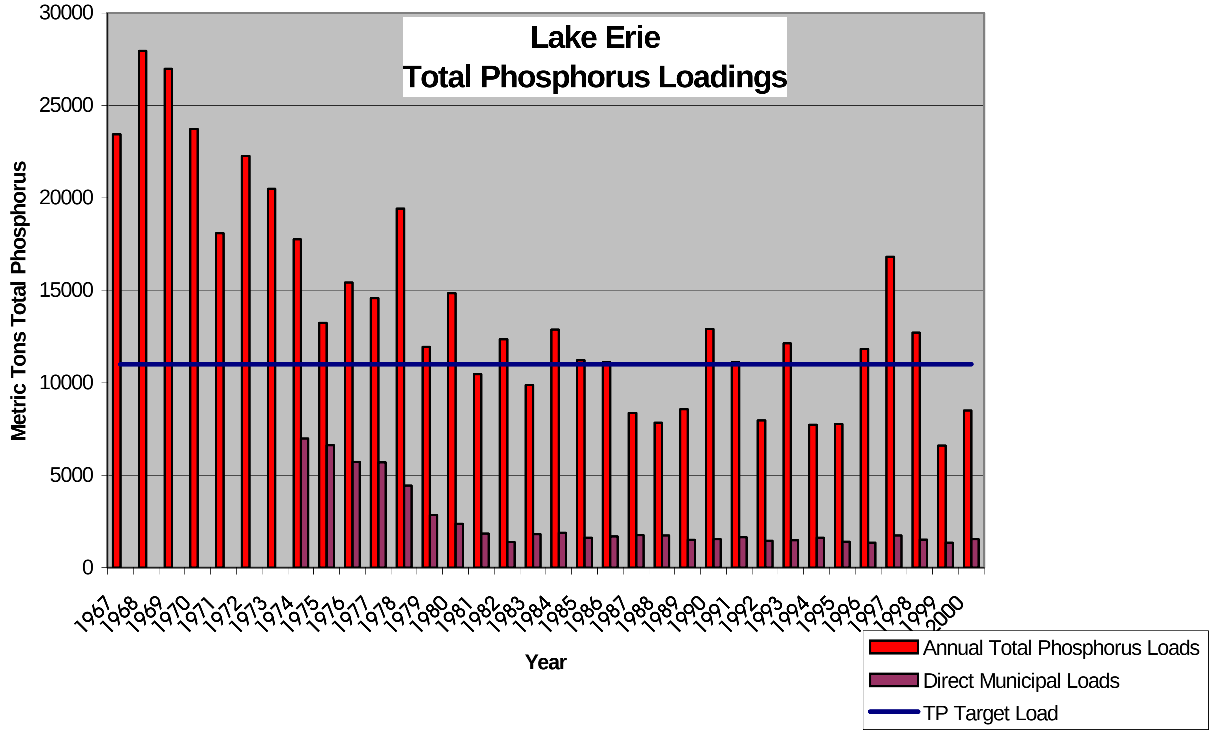
This question asks for an audit of the status of TP loads to the lakes relative to their target loads. We are especially interested in the frequency and extent to which TP loads have met the targets through the 1990s and into the 2000s. Unfortunately, with the exception of Lake Erie, loading data for the lakes has not been collected or compiled in any coordinated fashion since 1991. Therefore, addressing this question can be incomplete at best. Nevertheless, we have used available loading data to make the following assessments:

- TP loading estimates for Lake Superior exist for 1974 – 1991. Lake Superior was occasionally above its target load of 3400 metric tonnes per year (mta) prior the 1981, probably due to lack of state detergent bans up to that point. However, after 1981, there were no reported loads above the target, so it appears that Lake Superior has consistently met its target load since that point.

- TP loading estimates for Lake Huron exist for 1974 – 1991. Lake Huron load was occasionally above its target of 4360 mta through 1985. However, after 1985, there were no reported loads above the target. Based on this information, it appears that the target load has been met for Lake Huron. Some recent Michigan Department of Environment Quality load estimates for Saginaw Bay, an embayment of Lake Huron with an extremely large contributing drainage basin, indicate that this system is not meeting its target load of 440 mta. The MDEQ estimates are 614, 513, 227, 724 mta for 2001 – 2004, respectively. The load is almost directly proportional to the annual mean flow in the Saginaw River, suggesting that variation in precipitation and associated nonpoint source loads from the watershed are responsible for the exceedances of the target load.
- Like the above, TP loading estimates for Lake Ontario exist for 1974 – 1991. Lake Ontario first achieved its target load of 7000 mta in 1983, dropping from values above 20,000 mta prior to the mid-1970s. Since 1983, the Lake Ontario TP load has exceeded its target value five times – in 1984, 1986, 1987, 1990, and 1991. These excursions suggest that Lake Ontario has not been consistently meeting its target load (at least through 1991). Furthermore, it seems that the years when the Lake Ontario target is exceeded align with those years that have a high load to Lake Erie (over its target load).
- Lake Michigan has a record similar to the above three lakes (1974-1991). However, it has been supplemented by results from the Lake Michigan Mass Balance Study (LMMB) in 1994 and 1995. After 1980, there were no reported loads above the target of 5600 MTA. Based on this information, it appears that the target load has been met for Lake Michigan.
- Lake Erie has a continuous P load record from 1967 through 2002. Monitoring data exist for 2003 to the present and estimates will continue to be made despite gaps in the data. After an exponential drop in TP load, due largely to sewage treatment plants coming into compliance with a 1 mg/L effluent standard, the target load of 11000 MTA was first achieved in 1981 (Figure 1). During the period 1982 – 2002, the target has been achieved roughly half the time. A breakdown of the load categories indicates that variability in the load occurs as a result of hydrology during a given year, with loads exceeding the target occurring in years with relatively high precipitation and runoff. Recent data (2003 – 2005) suggest that current loads are at or just under the target. Based on this information, it appears that the target load has not been met consistently for Lake Erie.

In summary, a definitive answer to Question #1 is not possible due to the lack of load estimates in the last 15 years. Even if target loads on a lakewide basis are being met, it seems likely that nearshore areas and embayments may be may be experiencing excess P loading and the resulting degradation in trophic status. As TMDLs and other local and regional loading targets are developed, the relevant historical record should be examined and updated where necessary.

**Figure 1. Total Phosphorus loads to Lake Erie from 1967 – 2001. Estimated direct municipal loads are also presented for the period of record (1974 – 2001).**



## Question 2: Water Quality Objectives Achieved?

This question deals with an assessment of how Great Lakes data compare in total phosphorus, summer chlorophyll *a* and Secchi depth compare to the objectives stated in Table 1 above.

**Total Phosphorus**

Data for spring total phosphorus concentration was obtained from two primary sources:

- Environment Canada. Mean spring TP concentrations were obtained from Environment Canada for the following parts of the system: Lake Superior, Lake Huron, Georgian Bay, Lake Ontario and the three basins of Lake Erie. These data provided estimates for the period from 1970 through 2005.
- U.S. EPA. Individual grab measurements collected during April were provided by EPA for Lake Superior, Lake Michigan, Lake Huron, Lake Ontario, and the three basins of Lake Erie. These data were collected for the period from 1983 through 1991 and from 1996 through 2004. Note that several of the lakes had missing years; in particular, several had no data from 1992 through 1995. These data were edited to exclude all (1) flagged values, (2) zero values, and (3) nearshore values. The remaining measurements were then averaged to obtain a mean spring value for each available year.

In addition, the Lake Michigan data was supplemented by values reported by Scavia et al. (1986).

### Upper Lakes

As summarized in Figure , the open waters of the Upper Great Lakes as well as Georgian Bay appear to be currently below their respective TP goals. In fact, all areas appear to be at or approaching an oligotrophic state.

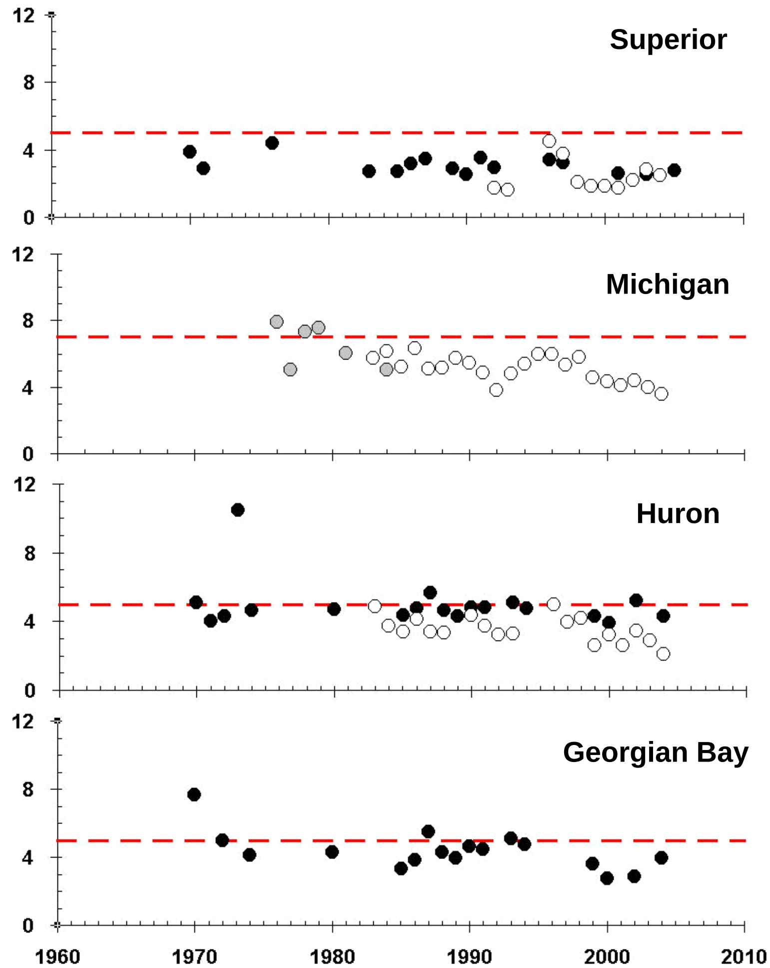



**Figure 2 Mean spring TP concentrations (μgP/L) for the offshore waters of the Upper Great Lakes and Georgian Bay. The filled and open circles represent Canadian and U.S. data, respectively. The grey circles for Lake Michigan are taken from Scavia et al. (1986). Dashed lines represent the target water quality objectives.**

A trend is not apparent in Lakes Superior, Huron and Georgian Bay. This may in part be due to the fact that they were never severely degraded during the late 1960's and early 1970's. In contrast, the levels in Lake Michigan appear to have been reduced from about 7-8 in the mid-1970's to current values of about 4 μgP/L.

## Lake Erie

As summarized in Figure , although the Lake Erie data exhibits much more scatter, a downward trend also appears to have occurred in each of its three basins. However, in contrast to the Upper Lakes, levels have not yet dropped below the water-quality goals. In particular, the Western Basin still appears to be eutrophic with regard to its total phosphorus level.

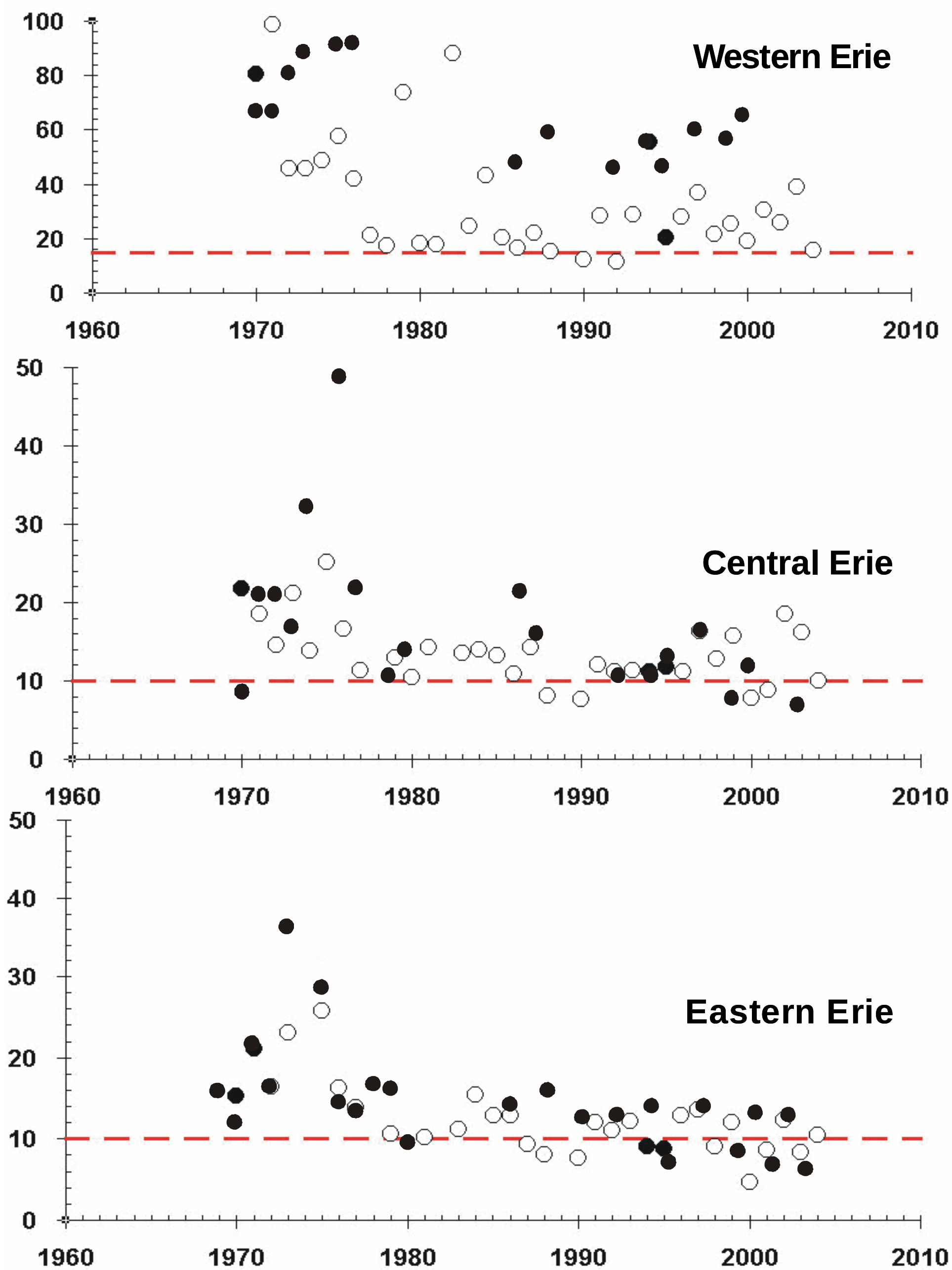



**Figure 3 Mean spring TP concentrations (µgP/L) for the offshore waters of the three basins of Lake Erie. The filled and open circles represent Canadian and U.S. data, respectively. Dashed lines represent the target water quality objectives.**

## Lake Ontario

Of all the lakes, the most clear evidence of recovery is exhibited by Lake Ontario. As summarized in Figure , its total phosphorus concentration has dropped from levels in the 20-30 µgP/L range down to solidly oligotrophic concentrations well below its 10 µgP/L goal.

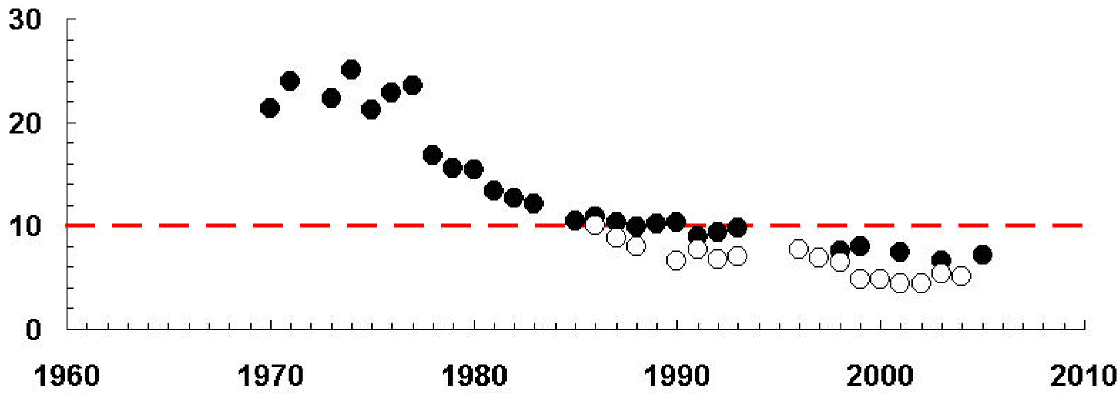



**Figure 4 Mean spring TP concentrations (μgP/L) for the offshore waters of Lake Ontario. The filled and open circles represent Canadian and U.S. data, respectively. The dashed line represents the target water quality objective.**

Inspection of the data for Lakes Superior, Huron and Ontario suggests that the U.S. data is systematically lower than the Canadian measurements. It should be determined whether this bias is real or merely an artifact of the differing approaches used to censor and average the data.

## Summer Chlorophyll a

Data for summer chlorophyll *a* concentration was obtained from two primary sources:

- Environment Canada. Individual grab measurements collected during June, July and August were provided by EC for Lake Superior, Lake Huron, Georgian Bay and Lake Ontario. This data was collected for the period from 1973 through 2004. Note that several of the lakes had missing years; in particular, several had no data for the mid-1990's. These data were edited to include only offshore epilimnetic values. These data were then averaged to obtain a mean summer value for each available year.
- U.S. EPA. Individual grab measurements collected during August were provided by EPA for Lake Superior, Lake Michigan, Lake Huron, the three basins of Lake Erie and Lake Ontario. As with the TP data, values were provided for the period from 1983 through 1991 and from 1996 through 2004 with several of the lakes having missing years. These data were edited to exclude all (1) flagged values, (2) zero values, (3) nearshore values and hypolimnetic readings. The remaining measurements were then averaged to obtain a mean summer value for each available year.

### Upper Lakes

As summarized in Figure , the open waters of the Upper Great Lakes as well as Georgian Bay appear to be currently below their respective chlorophyll *a* goals. All areas appear to be solidly oligotrophic or ultraoligotrophic. Note that in contrast to TP, there seems to be no evidence of a trend in Lake Michigan chlorophyll. This may in part be due to the absence of data prior to 1983.

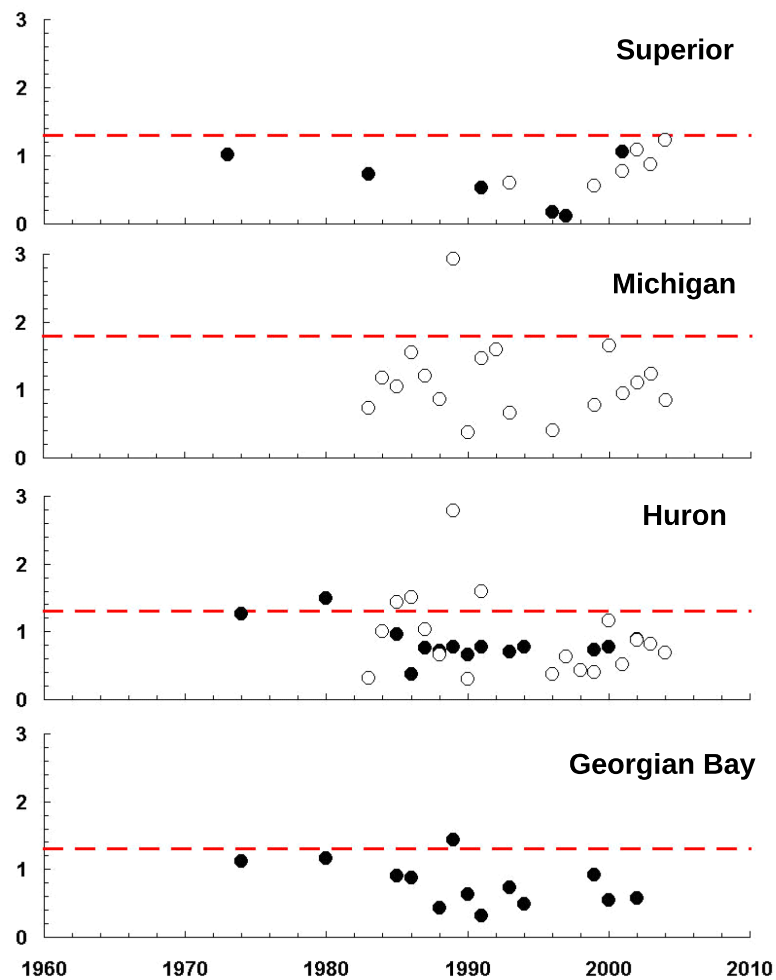



**Figure 5 Mean summer chlorophyll a concentrations (μg/L) for the offshore waters of the Upper Great Lakes and Georgian Bay. The filled and open circles represent Canadian and U.S. data, respectively.**

## Lake Erie

As summarized in Figure , although the Lake Erie data exhibit much more variability, a downward trend appears to have occurred in each of its three basins. However, in contrast to the Upper Lakes, levels have not yet dropped significantly below the water-quality goals. In particular, the Western Basin still appears to be eutrophic. In addition, the data suggest that levels may be increasing in recent years.

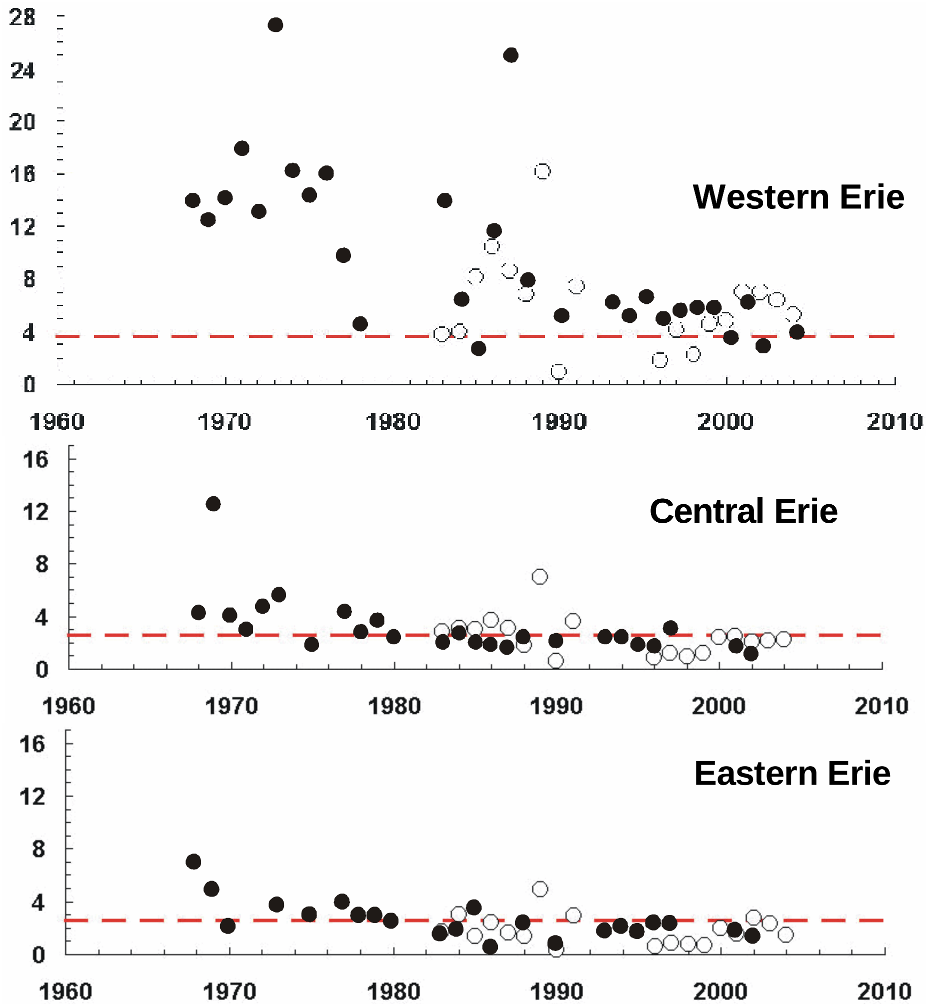



**Figure 6 Summer chlorophyll a concentrations (μg/L) for the offshore waters of the three basins of Lake Erie. The filled and open circles represent Canadian data for June, July, and August and U.S. August data, respectively. Dashed lines represent the target water quality objectives.**

## Lake Ontario

Of all the lakes, the clearest evidence of recovery again is exhibited by Lake Ontario. As summarized in Figure , its chlorophyll *a* concentration has dropped from levels in the 4-6 μgP/L range down to the 2-4 μgP/L level. However, note that whereas the TP levels have dropped well below the water-quality objective, the chlorophyll values are hovering at the goal. Hence, it appears that the chlorophyll reductions are not commensurate with the decreases in phosphorus.

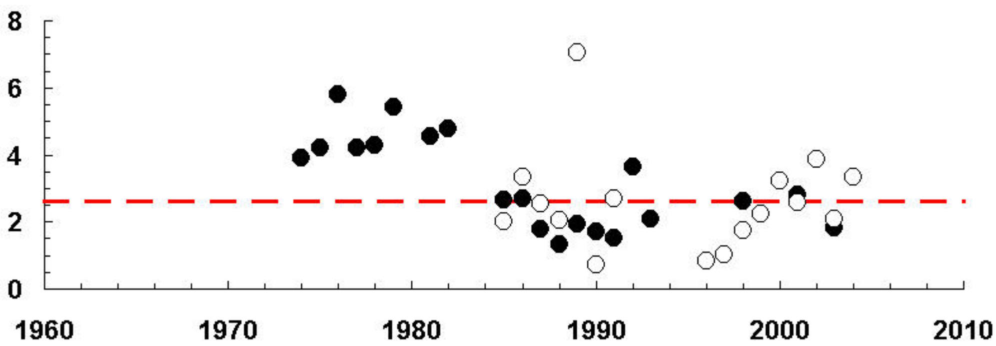



**Figure 7 Mean summer chlorophyll a concentrations (µg/L) for the offshore waters of Lake Ontario. The filled and open circles represent Canadian and U.S. data, respectively.**

It is interesting to note that all lakes exhibit inordinately high values for 1989. It should be determined whether the 1989 outliers are real or merely an artifact of the censoring and averaging process.

## Question 3: Validity of Historical Models

As indicated in the Task Group III modeling report, a number of models were used and compared in developing a recommendation for target P loads for each lake and embayment. Time and resources did not permitted our technical sub-group to evaluate each model that was used. However, we have made current assessments with three models, each of which provides some useful information about the current status of the lakes relative to the goals of Annex 3. Their findings are presented in the subsections below.

### <u>Chapra Total Phosphorus Model for the Great Lakes</u>

#### Background

Thirty years ago, a total phosphorus model was developed to assess the impact of population and land use trends on Great Lakes eutrophication (Chapra 1997). Since the model was developed to simulate long-term trends, average annual values were simulated and within-year variability ignored. On such a time scale, the lakes were treated as completely-mixed systems with the exception of Lake Erie, which was divided into its three subbasins. As depicted in Figure , the model simulated loadings based on demographic variables such as population and land use. These loads were then input to a phosphorus budget model that represented a mass balance around each lake. The budget model accounts for transport between lakes as well as in-lake losses and yielded predictions of in-lake total phosphorus concentration as a function of time.

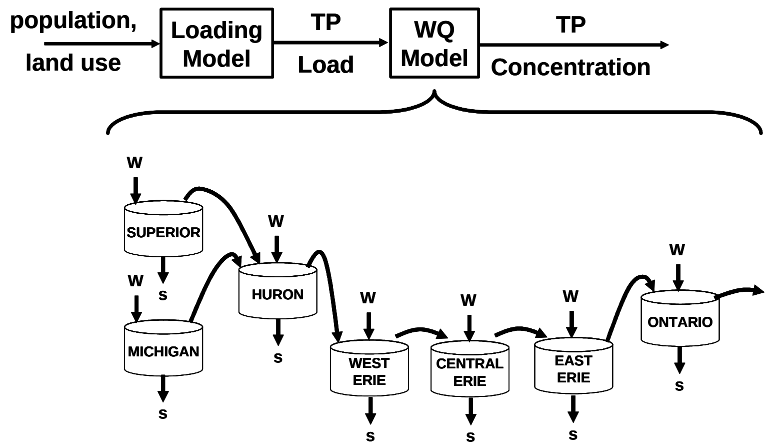



**Figure 8 Schematic of a long-term, total phosphorus model for the Great Lakes (Chapra 1977).**

The model was subsequently refined in two ways. First, as shown in Figure , major embayments were incorporated for Lake Michigan (Lower and Upper Green Bay) and Lake Huron (Saginaw and Georgian Bays) as described in Chapra and Robertson (1977), Chapra (1979), and Chapra and Sonzogni (1979). Second, Great Lakes-specific empirical correlations were developed to compute chlorophyll *a* as a function of total phosphorus concentration and Secchi depth as a function of chlorophyll *a* concentration (Chapra and Dobson 1981). The framework was then used, along with several other models, to establish phosphorus loading targets for the Great Lakes Water Quality Agreement (Chapra, 1980a, Bierman 1980, IJC 1980).


**Figure 9 Revised segmentation of Great Lakes total phosphorus model (Chapra and Robertson 1977, Chapra and Sonzogni 1979).**

In 1980, an initial assessment (Chapra 1980b) of the model’s predictive ability was made for Lake Ontario where reductions in detergent phosphorus by New York State and the Province of Ontario had induced a downward trend in the lake’s total phosphorus concentration. As in Figure 10, the results of that assessment were promising.

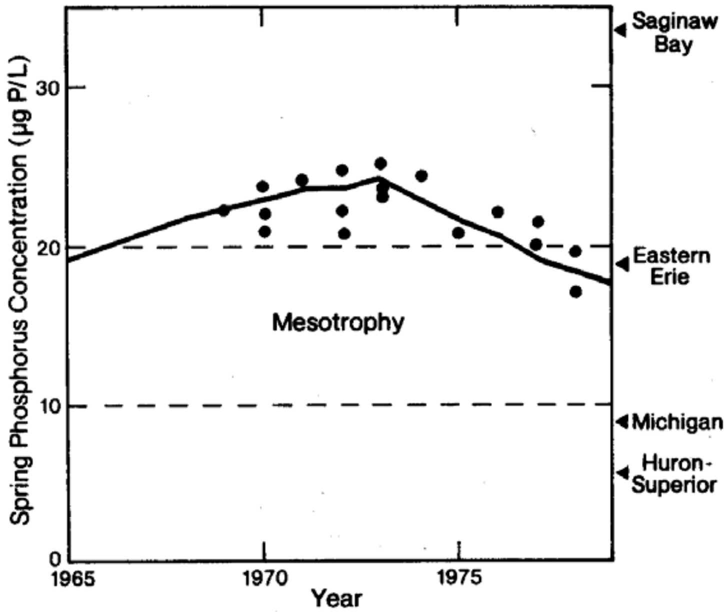



**Figure 10 Comparison of model predictions with data for total phosphorus concentration in Lake Ontario (Chapra 1980b).**

The present paper describes a more complete assessment by comparing model predictions with data collected over the past thirty years. The primary motivation is to assess whether the model adequately simulates the water-quality improvements that have occurred over this period.

## Model Development

### *Loadings*

The current model employs direct measurements of total phosphorus loadings wherever possible. Loadings have been determined for the three basins of Lake Erie from 1976 through 2001. For the other lakes, estimates are available on a whole-lake basis from the 1974 through 1991. The whole-lake values have been disaggregated based on population and drainage areas in order to estimate the bay loadings for Lakes Michigan and Huron.

For the period prior to 1970, historical total phosphorus loadings were computed based on population and land-use trends in the same fashion as originally reported by Chapra (1977). Minor adjustments were made to these trends (< 5%) so that they intersected the direct measurements in the early 1970's.

An exponential decay model was used to extrapolate loadings for the recent periods where data are unavailable. The model was assumed to apply to the loads for each lake over the period from the mid-1970's to the last year of measured data. The rates of decrease, which are listed in Table , range from 2.17% for Eastern Lake Erie to 5.19% for Lake Superior. The resulting model was then used to determine loading estimates for the subsequent years.

**Table 3 Rates of decrease of loadings in the period from the mid-1970s through the most recent year that data was collected (2001 for Lake Erie and 1991 for all other lakes)**

| Lake | Rate (%/yr) |
|---|---|
| Superior | 5.19% |
| Michigan | 4.93% |
| Huron | 2.68% |
| West Erie | 4.20% |
| Central Erie | 3.93% |
| East Erie | 2.17% |
| Ontario | 3.35% |

The exponential model fits the loading trends relatively well. Figure 11 shows the results for the three basins of Erie along with the total loading. The plot suggests that the loads for all basins have decreased at a consistent rate over the quarter century depicted. In addition, the trend does not appear to be leveling off. Both these results are somewhat surprising. One would have expected that the loads would have dropped precipitously during the 1970s and 1980's due to the installation of phosphorus treatment at basin wastewater treatment plants and the introduction of low phosphate detergents. It is not clear why the loadings have continued to decrease at about the same rate after 1990.

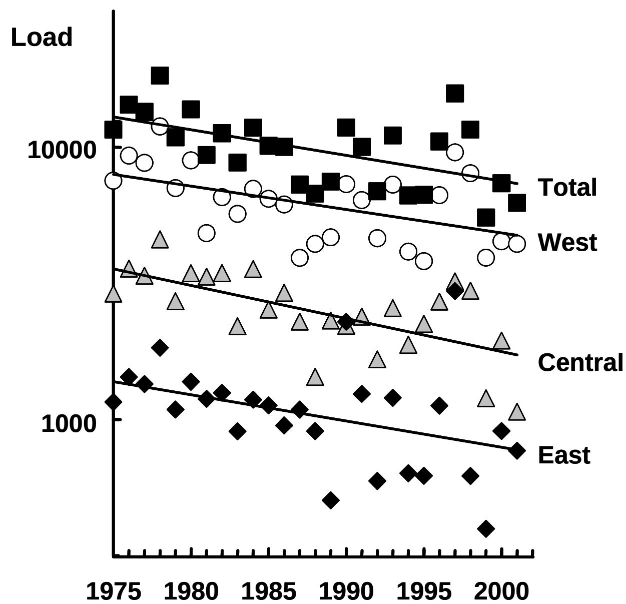



**Figure 11. Semi-log plot of Lake Erie loadings versus year as compiled by Dolan.**

## Budget Model

With the exception of the apparent settling velocity, all model parameters are identical to those used by Chapra and Sonzogni (1979). A constant settling velocity was determined for each lake so that the total phosphorus predictions matched observations in the early 1970's.

## Simulation Results

### Upper Lakes

Simulation results for total phosphorus concentrations for the upper Great Lakes are depicted in Figure . Note that the results for Lakes Michigan and Huron are for the main lakes excluding the bays. All lakes exhibit reduced TP concentrations following load reductions since the mid-1970’s. It is clear that all three lakes are now solidly oligotrophic if not ultraoligotrophic. Although the model generally follows the data trend, the latter exhibits considerable variability, which causes some individual observations to exceed the water-quality goal in Lake Huron. In addition, the model predictions for both Michigan and Huron are generally lower than the observations. This is reinforced by Figure 13, which shows the simulation results along with data for chlorophyll *a*. All three lakes exhibit concentrations less than 1 μg/L with observations approaching levels of the type observed in ultraoligotrophic systems such as Lake Tahoe.

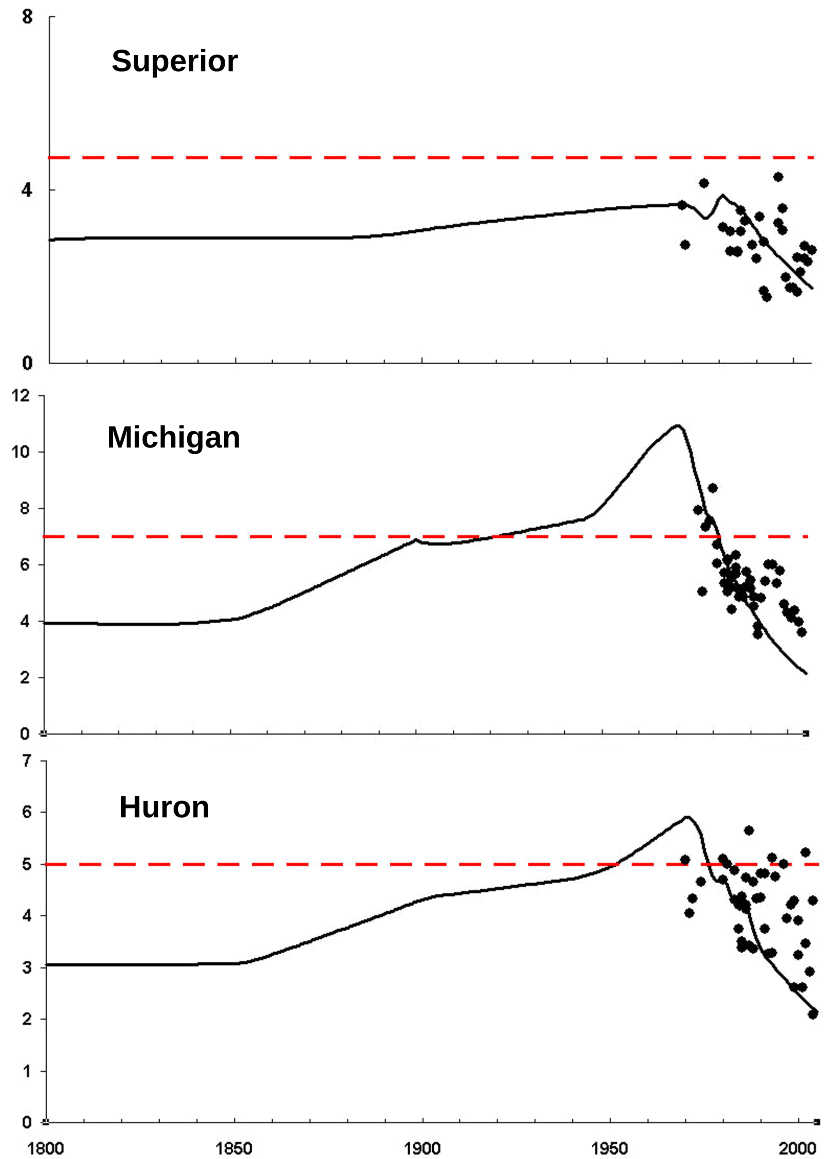



**Figure 12. Plots of simulation results and data for TP (μgP/L) in the Upper Great Lakes: (a) Superior, (b) Michigan, and (c) Huron. The water-quality objectives are shown as dashed lines.**

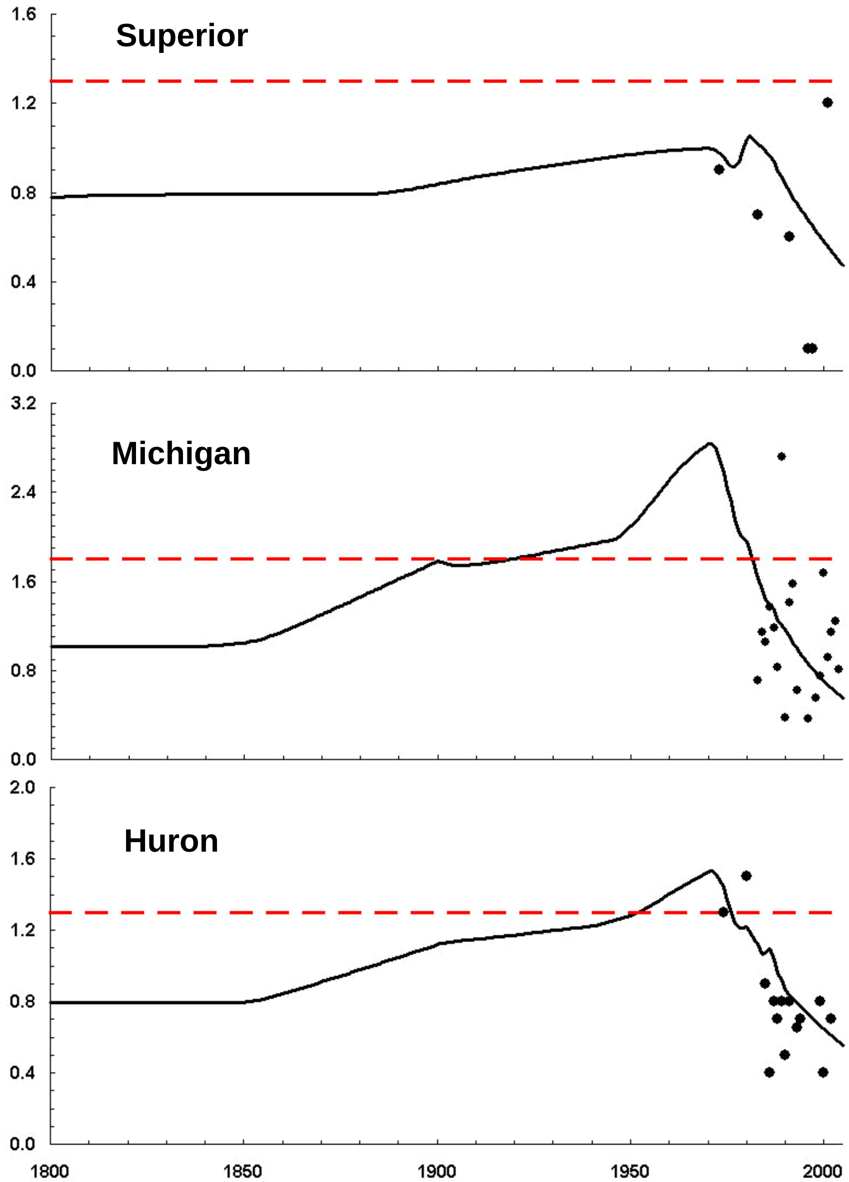



**Figure 13. Plots of simulation results and data for chlorophyll a (μgP/L) in the Upper Great Lakes: (a) Superior, (b) Michigan, and (c) Huron. The water-quality objectives are shown as dashed lines.**

## Lake Erie

Simulation results for total phosphorus concentration for the three basins of Lake Erie are depicted in Figure 14. All the basins exhibit significant improvement following load reductions. However, the levels still remain above the goals of mesotrophy for the Western Basin and oligomesotrophy for the Central and Easter Basins. Further, both model output and data are much more variable than for the other parts of the system. For the model, this is attributable to two factors. First, the basins have shorter residence times than the other lakes and hence are much more sensitive to variations in inputs. Second, the loadings themselves exhibit more variability than the loadings for the other basins.

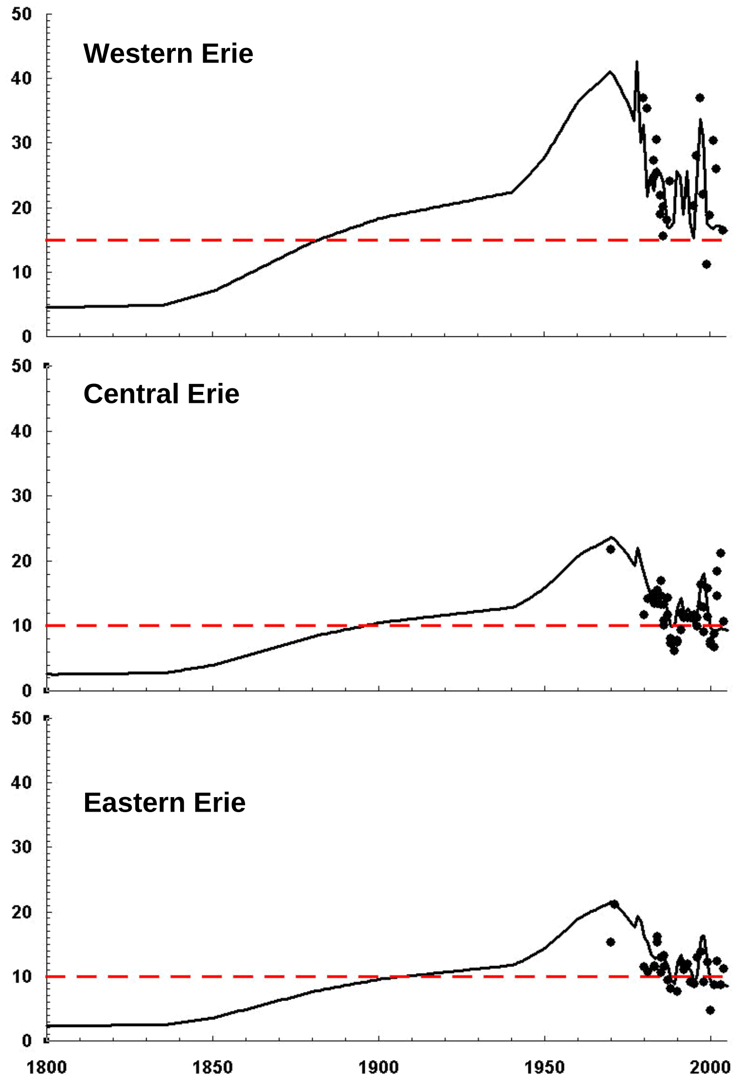



**Figure 14. Plots of simulation results and data for TP concentrations (μgP/L) for Lake Erie. The water-quality objectives are shown as dashed lines.**

## Lake Ontario

Simulation results for total phosphorus, chlorophyll *a* and Secchi depth for Lake Ontario. are depicted in Figure 15. All three parameters exhibit significant reductions following load reductions since the mid-1970s. In contrast to other parts of the system, observations indicate that the lake is improving more than predicted by the model. Whereas the model predicts that the load reductions should bring the lake to the vicinity of the oligomesotrophic target levels, the data suggests that it is solidly oligotrophic and seems to be approaching the ultraoligotrophic state of the Upper Lakes.

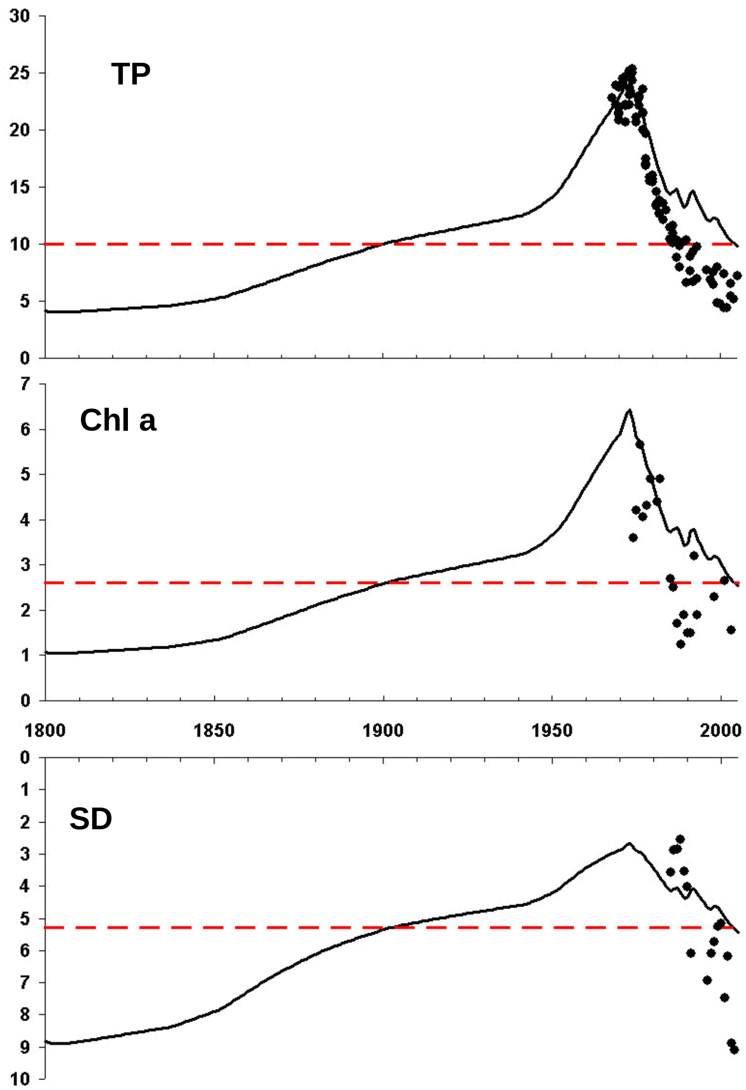



**Figure 15. Plots of simulation results and data for (a) TP (μgP/L), (b) chlorophyll *a* (μgA/L), and (c) Secchi depth (m) for Lake Ontario. The water-quality objectives are shown as dashed lines.**

## Lam et al. Model on Phosphorus and Dissolved Oxygen for Lake Erie

Lam et al. (1987) developed a basin averaged model called the NWRI Nine-Box Model. It consists of spatial compartments for the west, central and eastern basins in the horizontal and three thermal stratification layers in the vertical dimension. The model variables are: soluble reactive phosphorus (SRP), organic phosphorus (OP), and dissolved oxygen (DO). The total phosphorus (TP) can be calculated as TP = SRP + OP. The processes include uptake and respiration of nutrient/planktons, settling of particulate phosphorus, aeration of surface waters, anoxic regeneration of phosphorus from sediment, and physical resuspension of phosphorus due to wind-wave actions. The model includes water temperature, nutrients, and light attenuation for photosynthesis, but does not separate phytoplankton into different species. The model has been verified and validated over the range of conditions during the 16-year period of 1967-1982 (Lam et al., 1987).

### Updated results of the NWRI Nine-Box Model

Lam et al. (2006) provide an update of results for 1978, 1984, 1994 and 1997 of the NWRI Nine-Box Model for assessing the current status of the lakes relative to the goals of Annex 3. Using this model, which was calibrated for pre-Dreissena years, with the model coefficients unchanged, the effects of Dreissena on phosphorus and dissolved oxygen can be estimated by the deviation of computed results from observed data. Through sensitivity analysis, a preliminary conclusion was that Dreissena affect total phosphorus concentration in Lake Erie, notably a concentration decrease in the east basin (Figure 16). In contrast, changes in dissolved oxygen (Figure 17) in the central basin hypolimnion are influenced less by Dreissena, because the model was able to simulate the observed oxygen concentration in Post- Dreissena years (1994 and 1997) using the original formulation for oxygen, thermal layer thicknesses, and sediment oxygen demand in the absence of a new Dreissena submodel.

### Combined effects of total phosphorus loading and thermal structure on central basin hypolimnetic dissolved oxygen

The combined effects of phosphorus loading and thermal structure on the dissolved oxygen concentration in the central basin hypolimnion just before Fall overturn were analyzed by Lam et al. (1987), using the NWRI Nine-Box model. Figure 17 shows the combined effects on DO concentration represented by three curves in response to lakewide total phosphorus loading under three different stratification conditions: (1) an average condition based on a 12-year (1967-1978) simulation, (2) a shallow hypolimnion and (3) a thick hypolimnion. The observed data for the selected years 1978, 1984, 1994 and 1997 for Figure 16 are also shown in Figure 17, indicating that while DO decreases with increased TP Loading, the observed DO concentration is also affected by the hypolimnion layer thickness. For example, of the four years selected for analysis, 1997 has relatively high TP loading with average stratification conditions, and has the lowest dissolved oxygen concentration. On the other hand, 1994 has very low TP loading combined with a thick hypolimnion layer, resulting in high dissolved oxygen concentration just before overturn. These results are well within the curves bounded by the shallow and thick hypolimnion curves in Figure 17 and are consistent with the computed results shown in Figure 16b. Other environmental factors such as the length of the stratification season may also influence the DO concentration in central basin hypolimnion (Schertzer and Sawchuk, 1990).

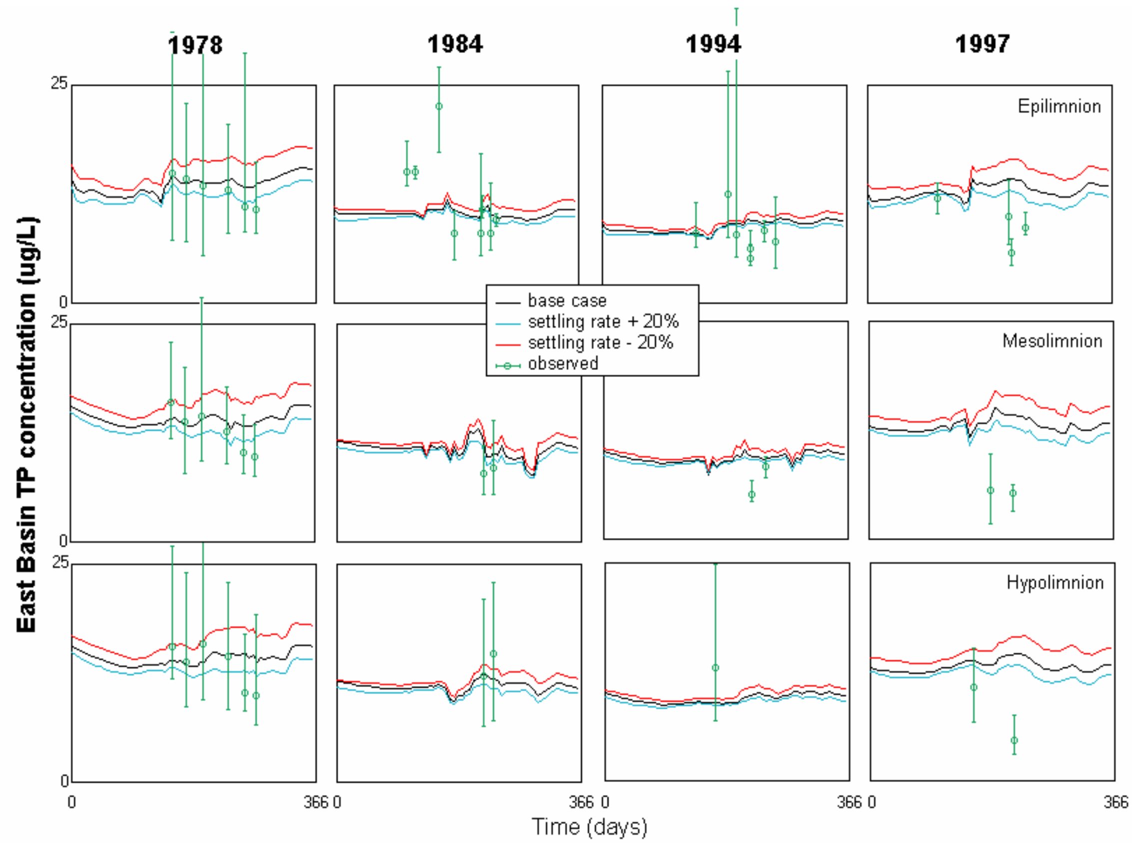



**Figure 16a. Lake Erie East basin TP concentration (base case computed by NWRI Nine-Box Model, with hypothetical changes of settling rate ±20%, compared to observed means and ranges) for epilimnion, metalimnion and hypolimnion in 1978, 1984, 1994 and 1997.**

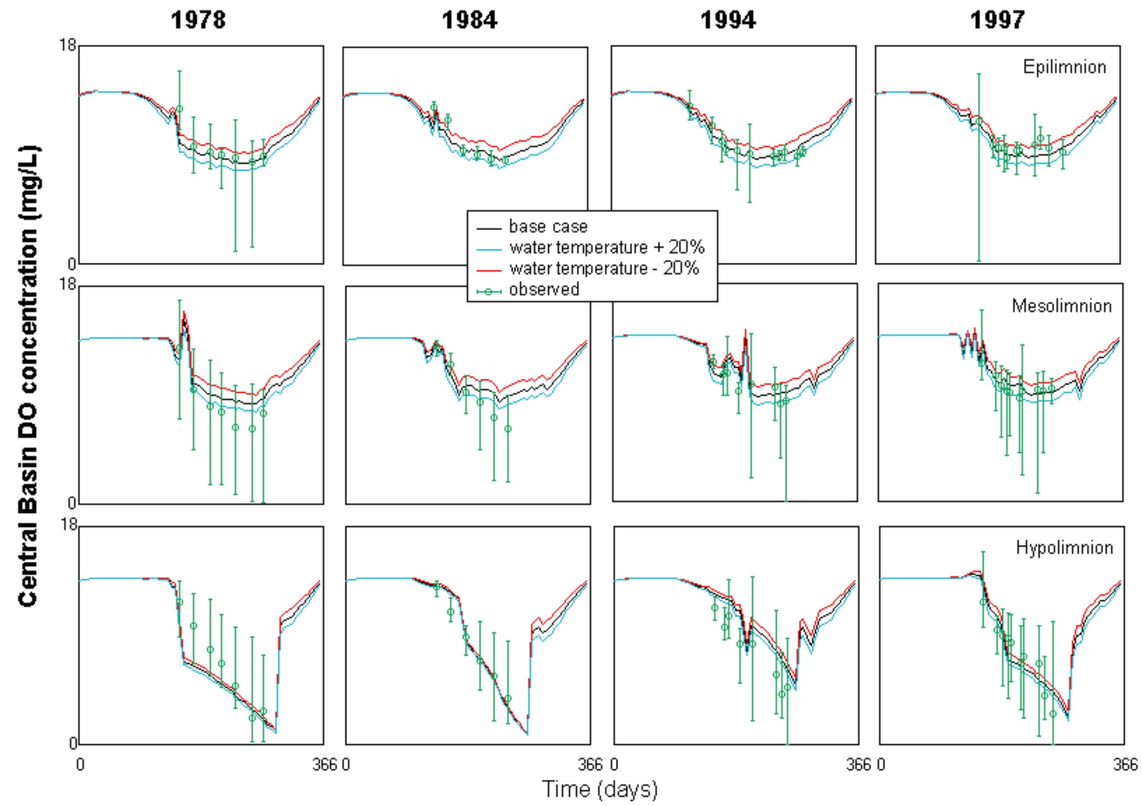



**Figure 16b. Lake Erie Central basin DO concentration (base case computed by NWRI Nine-Box Model, with hypothetical changes of water temperature 20%, compared to observed means and ranges) for epilimnion, mesolimnion and hypolimnion in 1978, 1984, 1994 and 1997.**

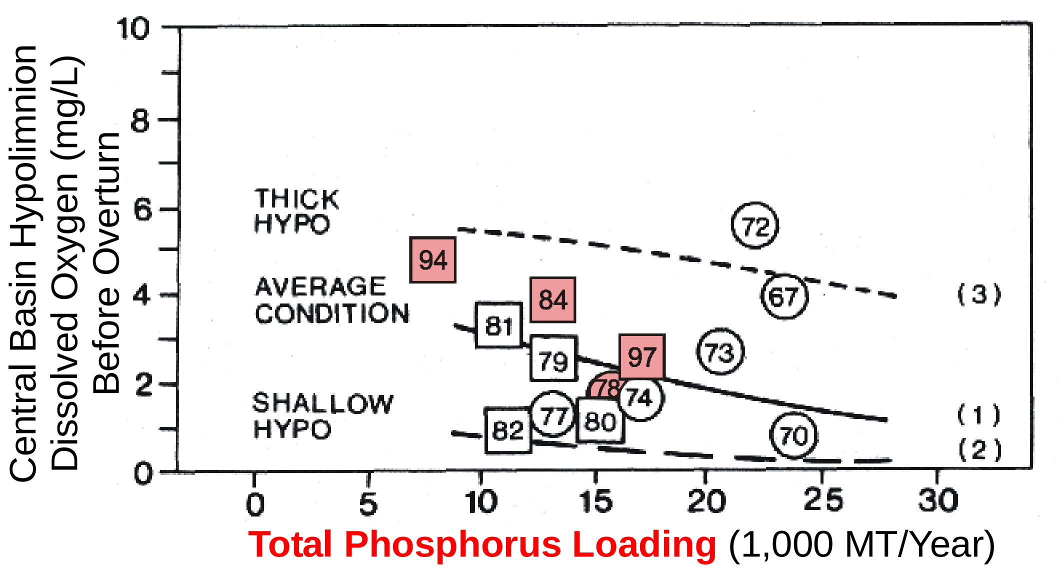



**Figure 17. Estimated curves for central basin hypolimnion dissolved oxygen concentration just before overturn in response to lakewide phosphorus loading under three different stratification conditions: (1) an average condition based on a 12-year (1967-1978) simulation, (2) a shallow hypolimnion and (3) a thick hypolimnion. The circles indicated observed data, if available, for 1967-1978 and the squares for subsequent years as a post audit with those for 1978, 1984, 1994 and 1997 shaded.**

## Nearshore Attached Algal Growth Modeling

### Background and Objectives

Annex 3 of the Great Lakes Water Quality Agreement calls for the development and implementation of phosphorus control programs and measures to reduce algal biomass and to eliminate nuisance conditions, especially in Lakes Erie, Michigan and Ontario. Conditions of nuisance algal growth are a symptom of cultural eutrophication and manifest themselves in nearshore waters through the accumulation of massive quantities of actively growing and sloughed *Cladophora* biomass. Because the problem is a regular feature of sites heavily used for recreation, nuisance growths of this filamentous, attached alga play a major role in forming public perception of Great Lakes water quality.

*Cladophora* grows attached to solid substrate throughout the Great Lakes. It is typically found proximate to point source discharges of nutrients in Lakes Huron and Superior where whole-lake levels of phosphorus do not support growth. In Lakes Erie, Ontario and Michigan phosphorus enrichment has led to proliferation of the alga wherever solid substrate is available. *Cladophora* has been known to the Great Lakes scientific community for over 150 years, with nuisance conditions noted as early as the mid-20$^{th}$ century. Focus on *Cladophora* peaked in the period 1975-1985 when severe nuisance conditions spurred regulatory interest and subsequent support of field, laboratory and modeling studies. One key conclusion of this effort was that nuisance growth of *Cladophora* (i.e. biomass >50 $gDW \cdot m^{-2}$) could be prevented if soluble reactive phosphorus concentrations in the nearshore were maintained at or below 2 $\mu gP \cdot L^{-1}$.

Interest in *Cladophora* experienced a marked decline in subsequent years, although it is not clear whether this reflected improvements in nuisance conditions or re-direction of agency priorities. In fact, the absence of any regular and systematic monitoring of phosphorus and biomass conditions in nearshore waters makes it difficult to assess trends in nuisance growth between 1985 and the present. It is clear, however, that significant problems relating to *Cladophora* exist today, with a limited number of scientific studies and considerable anecdotal evidence pointing to continued nuisance growth in Lakes Erie, Michigan and Ontario and perhaps extending into Lake Huron.

Two events have potentially played a significant role in influencing *Cladophora* dynamics in the Great Lakes over the last two decades. The first of these is the implementation of phosphorus control strategies which have, in some parts of the Great Lakes, markedly reduced lake water phosphorus concentrations. The second is invasion by dreissenids with attendant impacts on water clarity and, perhaps, phosphorus cycling. The Annex 3 Technical sub-group has applied two mathematical models to investigate the effects of these two environmental stimuli on *Cladophora* growth, both singly and in concert. The first model is that of Canale and Auer (1982a) presently being used by Lisa Tomlinson and Marty Auer (Michigan Technological University) and Harvey Bootsma (University of Wisconsin – Milwaukee) on Lake Michigan. The second model is that of Higgins et al. (2005) being applied by Scott Higgins and Sairah Malkin (University of Waterloo) to Lakes Erie and Ontario, respectively. Selected results from that effort are summarized here; a full report of this work is included as Appendix B of this report.

## Response to Phosphorus Loading Reductions

Here we examined *Cladophora* growth potential as driven by water column soluble reactive phosphorus levels before and after implementation of phosphorus control measures. Simulations focus on Lake Ontario where growth is driven by whole-lake nutrient levels. We use data for offshore soluble reactive phosphorus concentrations over the period 1969-2005 provided by Violetta Richardson (Environment Canada). A striking reduction in SRP was observed over this interval, with concentrations dropping from 15.3 $\mu gP \cdot L^{-1}$ in 1973 to 5.7 $\mu gP \cdot L^{-1}$ in 1982 and then continuing after establishment of dreissenids with reductions to 3.0 $\mu gP \cdot L^{-1}$ in 1993 and 1.6 $\mu gP \cdot L^{-1}$ in 2005. Note that whole-lake nutrient concentrations have, in 2005, reached the level predicted to be necessary to eliminate nuisance conditions. Model simulations (Figure 18) point to a 40-50% reduction in *Cladophora* growth potential, a result consistent with field observations made in Lake Ontario between 1972 and 1982-83 (Painter and Kamitis 1985), but inconsistent with present day observations of nuisance conditions.

## Response to Dreissenid Impacts

One significant result of the dreissenid invasion was a marked improvement in water clarity. The vertical light extinction coefficient is estimated to have increased by 36%, on average, for Lakes Erie, Michigan and Ontario, corresponding to a 6m increase in the depth of the photic zone. The impact of this is illustrated in Figure 19 where the depth of colonization by *Cladophora* and its growth potential integrated over depth increase significantly compared with pre-dreissenid light conditions. The effect here is to potentially increase the area available for colonization, leading to increases in overall production.

A second, and as yet unproven, dreissenid effect is that of changes in phosphorus cycling. Hecky et al. (2004) have hypothesized the existence of a nearshore phosphorus shunt where inputs of particulate phosphorus, previously exported to offshore waters, may be captured by dreissenids and made directly available to Cladophora populations sharing solid substrate. DePinto, et al. (2005) have used an ecosystem model for Saginaw Bay that has incorporated dreissenids to demonstrate how their presence has altered phosphorus cycling in that system and provided excess available phosphate in late summer to stimulate blue-green algal growth. The implications of the nearshore phosphorus shunt, not only as manifested in the lakes, but also in how we model and manage phosphorus, are significant.

## Summary

While direct measurements and hard data are not available, it is apparent that phosphorus management actions have not led to the reduction of nuisance levels of *Cladophora* biomass in Lake Erie, Michigan and Ontario. Modeling results indicate that improvements in the light environment associated with dreissenid activity have offset any reductions in phosphorus levels. It is quite possible, as well, that changes in nearshore phosphorus cycling (the shunt) have further served to offset reductions in external loads.

Our failure to support appropriate monitoring programs with respect to phosphorus and *Cladophora* is keenly felt when the scientific community is called upon to render recommendations in support of policy development. Further, the mathematical models developed to address this issue two decades ago could not foresee the changes to ecosystem conditions brought on by the invasion of dreissenids.

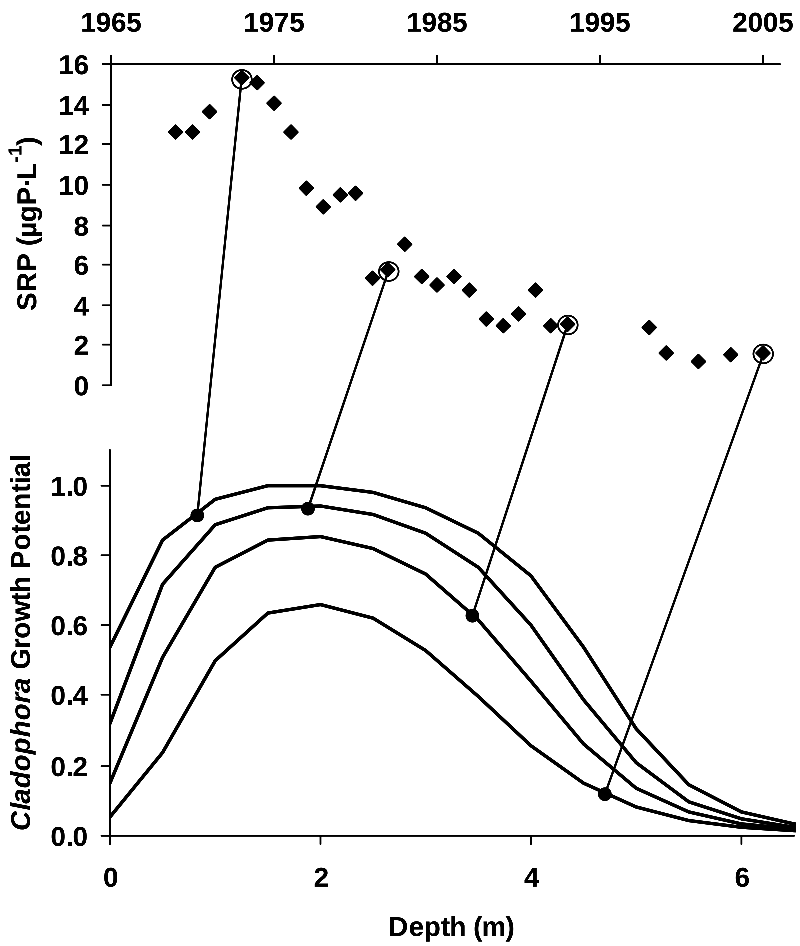



**Figure 18. Model-calculated response in *Cladophora* growth potential to observed changes in SRP concentration in Lake Ontario. Simulations are those of the CAM framework for the Lake Ontario temperature regime and the pre-dreissenid light environment. SRP data were provided by Vi Richardson, Environment Canada.**

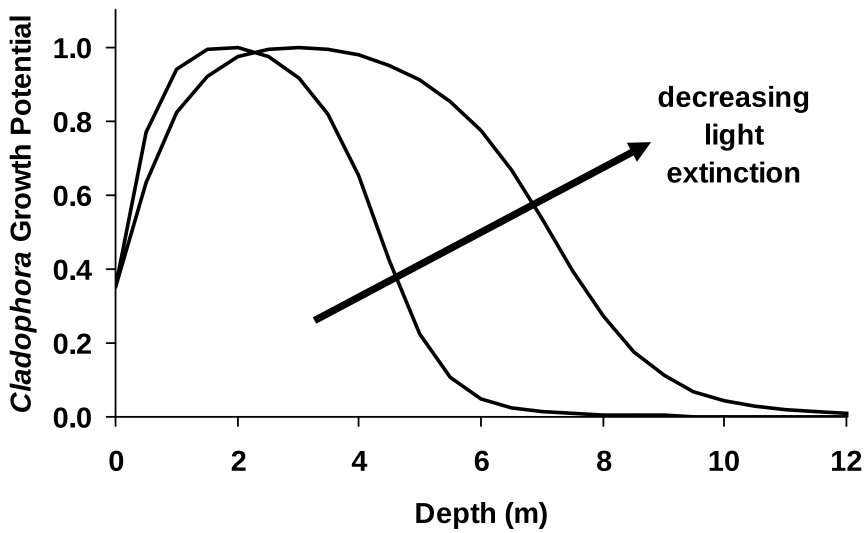



**Figure 19. Response of *Cladophora* growth potential to changes in light extinction coefficient; algal populations experience identical SRP conditions.**

## Conclusions and Recommendations

With regard to the question of the status of phosphorus loadings to the Great Lakes relative to the target loads, all conclusions except those for Lake Erie and perhaps Saginaw Bay must be qualified by the fact that load monitoring and estimation ceased in 1991. Therefore, conclusions can only be made for the status of Lake Superior, Lake Michigan, Lake Huron, and Lake Ontario must be qualified. Having said that, the available data show that all lakes and Saginaw Bay experienced load reductions through the 1970s and achieved their targets in the early to mid-1980s. The upper lakes (Lake Superior, Lake Huron, and Lake Michigan) appeared to have maintained their loads below their respective targets for the period of record. The total phosphorus loads to Lake Erie and Saginaw Bay appear to oscillate around the target depending on variations in non-point source runoff phosphorus loads driven by the hydrological basin supply for a given year. Lake Ontario also exceeded its target load on five occasions between first achieving it in 1983 and the end of our record in 1991. The Lake Ontario high loads may be related to its receiving loads from Lake Erie, a major source of phosphorus to Lake Ontario.

The second question on the status of the lake water quality relate to the objectives that drove the model computation of target phosphorus loads focused on total phosphorus concentration in open waters at spring overturn, chlorophyll *a* concentration during summer monitoring, and in the case of Lake Erie, dissolved oxygen concentration in the central basin hypolimnion. Annex 3 also refers to elimination of nuisance algal blooms, with particular reference to nearshore blooms and algal mats. The data available from EPA and EC on total phosphorus suggest that all lakes have achieved their objective as stated in Table 1, with the exception of the western and central basins of Lake Erie. Indeed, Lake Huron and Lake Ontario have displayed spring TP concentrations considerably below what would be expected from the models based on their estimated TP loads (see discussion below). With regard to chlorophyll *a*, again the open-water data have shown a significant response to TP load reductions and appear to have met or exceeded objectives, with the exception of western basin of Lake Erie.

Dissolved oxygen monitoring in the central basin hypolimnion of Lake Erie has demonstrated that the GLWQA goal of "Restoration of year-round aerobic conditions in the bottom waters of the Central Basin of Lake Erie" has definitely not been met. Although the system appeared to respond favorably and predictably to TP load reduction for Lake Erie in the 1970s and 80s, more recent data over the past 10-15 years suggest that this goal may be very difficult to achieve even with significantly lower TP loads because of the morphometric characteristics of the central basin and possibly because of the exacerbating effects of climate change and dreissenid invasions. A relatively thorough investigation of the rate of hypolimnetic oxygen depletion in the central basin by Burns, et al. (2005) found that the volume-corrected rates show a weak tendency to decrease from 1970 to 1989 and a slight trend to increase with time from 1990 to 2003. However, these patterns seem to be related to the previous year's TP loading to the basin. The observation that central-basin HVOD (hypolimnetic volume-corrected oxygen depletion rate) tracked the reductions in TP loadings through the 1980s may be the first direct affirmation that central basin oxygen dynamics can be regulated by phosphorus inputs, albeit more weakly than originally hoped. This implies that TP loads must continue to be regulated if we wish to minimize oxygen depletion rates in an effort to reduce frequency of episodic central basin anoxia. It should be mentioned, however, that the relative contributions of various environmental factors to central basin hypoxia is still being quantified through monitoring and research.

One of the significant recent observations of Great Lakes water quality is the apparent re-occurrence of shoreline nuisance algal growth, including *Chladophora*, in all of the lakes except Lake Superior. Again, it is not clear if this recent observation is the result of changes in the nearshore ecosystem of these lakes or the result of increases in nutrient runoff loads from non-point sources that have not been tracked or a combination of both.

Completely addressing question 3 on the utility of historical models as management tools for supporting eutrophication-related objectives in the Great Lakes is far beyond the time and resources available for this sub-group activity. However, we did have the benefit of considerable volunteer efforts on the Chapra basin-wide total phosphorus model and on the *Chladophora* modeling efforts by Auer and Higgins. In general, the Chapra model still does a reasonably good job of simulating TP and chlorophyll *a* open-lake data given measured TP loads prior to 1991 and projected loads after 1991. The major exception is Lake Ontario, where the model appears to over-predict TP and chlorophyll *a* and under-predict Secchi depth. It is not clear whether this is the result of incorrect TP loads through the 1990s and early 2000s or whether the load is not contributing to open-lake nutrient and productivity conditions because of a change in the nearshore processing of nutrient loads entering along the shoreline.

Both the *Chladophora* analysis and the modeling by Lam on Lake Erie and DePinto and Bierman on Saginaw Bay, suggest that there has been a change in the ecosystem structure and functioning of the lakes that will require modification of the models used in the 1970s in order to support nutrient-eutrophication management in the lakes today and in the future.

Given the findings of this sub-group described in this report, we propose the following recommendations for monitoring and modeling to aid nutrient-eutrophication management of the Great Lakes in the face of ecological changes that appear to have occurred:

1. The Great Lakes monitoring programs of the two countries should focus a larger percentage of their efforts on monitoring nearshore conditions in order to compare with the more traditional open-water conditions. It is quite possible for a lake to be experiencing nuisance conditions in the nearshore areas while appearing to be meeting water quality objectives in the open-water.
2. A more thorough investigation of the utility of models developed in the 1970s for future management of Great Lakes nutrient-eutrophication conditions needs to be undertaken. This effort should focus on determining how models should be modified/refined if they are found to be lacking relative to ecosystem structure and function changes that have occurred in the lakes. The improved models will provide more accurate predictions and revised target loads if necessary.
3. There needs to be a concerted research, monitoring, and modeling effort to quantitatively understand, in the sense of developing a model that can simulate system-level cause-effect relationships, the simultaneous low productivity and fish carrying capacity in the open water of Lake Ontario and nuisance algal bloom and mat formations in the nearshore areas of the lake. The role of *Dreissena*, which have invaded nearshore areas of all the lakes except perhaps Lake Superior, in this phenomenon should be researched. The research results will be useful for providing advice to integrated environmental and aquatic resources management plans.
4. There needs to be a concerted research, monitoring, and modeling effort to quantify the relative contributions of various environmental factors (total phosphorus loads, changes in the availability of phosphorus loads to the central basin, hydrometeorological impacts on temperature conditions and hypolimnion structure and volume, *Dreissena*-induced alterations of nutrient-phytoplankton-light conditions and oxygen demand functions) to hypoxia in the central basin of Lake Erie. The research may lead to a more achievable goal than the current goal of year-round aerobic condition in Lake Erie central basin.
5. There is a need for a concerted *Cladophora* modeling initiative with the overall goal of providing lake managers with reliable estimates of the response of *Cladophora* growth and accumulated biomass to changes in soluble phosphorus concentrations in the coastal areas affected by *Cladophora* blooms. The initiative should include (1) regular monitoring of *Cladophora* biomass and tissue phosphorus content and soluble reactive phosphorus levels in the nearshore and (2) an integrated program of field and laboratory studies and mathematical modeling to better understand phosphorus cycling and Cladophora growth under conditions representative of the post-dreissenid period.

All of the above efforts should be implemented using a well-coordinated, bi-national, ecosystem approach that respects potential interactions between nutrient-eutrophication management and other management issues, such as fisheries, persistent bioaccumulative and toxic chemicals, human health protection relative to water recreation and drinking water supply, sediment reduction, etc.

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