Nutrient Concentrations

Formerly Indicator # 111

Overall Assessment

Status: **Fair**

Trend: **Deteriorating**

Rationale: **In Lakes Michigan, Huron and Ontario, offshore total phosphorus concentrations are currently below targets but may be too low, negatively impacting lake productivity. Nearshore symptoms of nutrient enrichment persist. In Lake Erie, targets are frequently exceeded and conditions are deteriorating. Only in Lake Superior are offshore targets being met and conditions acceptable.**

Lake-by-Lake Assessment

Lake Superior

Status: Good

Trend: Unchanging

Rationale: Targets have consistently been met, and offshore total phosphorus concentrations are similar to historic values, indicating acceptable conditions. There is no trend over time.

Lake Michigan

Status: Good (but below target)

Trend: Improving

Rationale: Offshore phosphorus concentrations are continuing to decrease and are meeting targets. However, concentrations have fallen to low levels and may be negatively affecting lake productivity (phytoplankton, zooplankton and fish production), In some nearshore areas, elevated phosphorus and/or invasive species are supporting nuisance algae growth.

Lake Huron

Status: Good (but well below target)

Trend: Improving

Rationale: Offshore phosphorus concentrations are continuing to decrease, and although concentrations are meeting targets, they may be too low and negatively affecting lake productivity. In certain areas of the nearshore, waters are experiencing nuisance algae growth.

Lake Erie

Status: Poor

Trend: Deteriorating

Rationale: Total phosphorus targets continue to be exceeded and trends indicate increasing concentrations. Excessive algal growth is apparent, particularly in the western basin but in the other basins also.

Lake Ontario

Status: Good (but below target)

Trend: Improving

Rationale: Offshore phosphorus concentrations are continuing to decrease to levels too low to support healthy offshore lake productivity. Many nearshore waters are experiencing nuisance algae, possibly fueled by locally-high phosphorus discharges, but also by invasive mussels which make phosphorus more readily available for algae.

Other Spatial Scales – Nearshore eutrophication

This indicator reports mainly on total phosphorus (TP) concentrations in the offshore. These offshore waters best indicate long-term trends because, in contrast to shallower, nearshore waters, they are less influenced by local pollutant discharges. As demonstrated here, offshore nutrient concentrations in most lakes have declined over time, and are meeting targets that were set during the 1980s, but may now be too low to support healthy levels of lake productivity.

At the same time as offshore TP concentrations are reaching unprecedented lows, large regions of the Great Lakes are experiencing nuisance algae problems. The extent of the algae problem seems to be of similar magnitude as was experienced in the 1970s (GLWI, 2005), despite significantly lower phosphorus loads since that time (Dolan 2010). In Lake Michigan, growth of the benthic alga *Cladophora* remains a problem, making beaches unswimmable (Bootsma et al. 2004). *Cladophora* blooms appear to be most extensive in eastern Lake Erie, while the western Lake Erie basin is also plagued by the more toxic *Microcystis* algal blooms (Ouellette et al., 2006). In Lake Huron, the benthic alga Chara is flourishing on the east side and on the western side *Cladophora* is resurging (E.T. Howell, personal communication).

The causes of the algae resurgence are not clear, and may not be directly related to phosphorus discharges. Total phosphorus loads have declined over time and are currently meeting IJC targets in most areas of the Great Lakes (Dolan, 2010). An exception to this may be found in the western basin of Lake Erie, where an increase in loads of total phosphorus, and of soluble phosphorus in particular, has been observed over the last 10 years (Richards and Baker, 2006).

Purpose

- To assess nutrient concentrations in the Great Lakes.
- To support the evaluation of the nutrient loadings to the Great Lakes
- To support the evaluation of trophic status and food web dynamics in the Great Lakes

Ecosystem Objective

The goals of phosphorus control are to maintain an oligotrophic state and relative algal biomass of Lakes Superior, Huron and Michigan, to maintain algal biomass below that of a nuisance condition in Lakes Erie and Ontario, and to eliminate algal nuisance in bays and in other areas wherever they occur (IJC, 1978). The International Joint Commission (IJC) developed the following delisting guideline for eutrophication or undesirable algae: no persistent water quality problems (e.g., dissolved oxygen, depletion of bottom waters, nuisance algal blooms or accumulations, and decreased water clarity) attributed to cultural eutrophication.

Ecological Condition

Measure

To assess the nutrient concentrations in the open waters of the Great Lakes, offshore total phosphorus (TP) values in the spring will be compared to the GLWQA targets (see endpoints).

Endpoints

When total phosphorus load goals are met, the expected concentration of total phosphorus in the open waters of each lake are: Lake Superior - 5 µg/l, Lake Huron - 5 µg/l, Lake Michigan - 7 µg/l, Lake Erie Western Basin - 15 µg/l, Lake Erie Central Basin - 10 µg/l, Lake Erie Eastern Basin - 10 µg/l, Lake Ontario - 10 µg/l. However, the authors note that these endpoints do not take into account the effects of invasive mussels on phosphorus cycling in the lakes.

Status

The status of total phosphorus in the Great Lakes is monitored by the Canadian and United States federal governments. Both Environment Canada (EC) and the United States Environmental Protection Agency (USEPA) conduct ship-based cruises to collect water quality samples on the lakes. Methods for EC's Great Lakes Surveillance Program are described in Dove et al. (2009). Sampling and analytical procedures for GLNPO's Open Lake Water Quality Surveys is provided in GLNPO (2010). Briefly, EC conducts monitoring in each of the Great Lakes except Lake Michigan, which is located entirely within the United States. Each lake is generally monitored every second year, with several cruises conducted during that year. All regions (nearshore, offshore and major embayments) are monitored for the EC program. USEPA conducts one spring and one summer cruise on all waters except Georgian Bay, with stations located more along the central long axis of each lake. Here, we provide an update with respect to long-term trends in total phosphorus in each of the Great Lakes, and relate these trends to the nutrient status and ecosystem objectives.

For the purpose of presenting long-term trends, the data are restricted surface waters (top 3 m) at offshore locations (depth ≥ 50m for lakes Huron, Michigan and for Georgian Bay, depth ≥ 100m for Lake Ontario and depth ≥ 150 m for Lake Superior), with the exception of Lake Erie, which is relatively shallow and is therefore divided instead into three basins. Springtime concentrations generally represent the annual maxima, and are therefore presented.

The results of offshore total phosphorus concentrations are shown in Figure 1 for the upper Great Lakes (lakes Superior, Huron, Michigan and Georgian Bay) and in Figure 2 for the lower Great Lakes (lakes Erie and Ontario). Individual measurements are represented in these box plots. The solid line within each box is the median value; the lower and upper ends of the boxes are the 25th and 75th percentiles, respectively, and the whiskers show the minimum and maximum values.

In the 1970s, symptoms of eutrophication were evident in many regions of the Great Lakes and the Great Lakes Water Quality Agreement of 1978 set out the above targets for phosphorus loads and offshore phosphorus concentrations in order to meet the ecosystem objectives. Concerted efforts to reduce phosphorus loads to the Great Lakes started in the 1970s and were successful at reducing phosphorus concentrations and symptoms of eutrophication in the lakes (Stevens and Neilson, 1987). The best example is seen for Lake Ontario, where the spring TP concentrations declined from 21 µg/L in 1975 and were meeting the target of 10 µg/L by the early 1990s. Implementation of sewage treatment plant controls were successful in reducing the symptoms of eutrophication so that the nuisance levels of *Cladophora* growth, most apparent in the 1960s and 1970s, were controlled and were no longer problematic throughout most regions of the lakes by the 1980s (GLWI, 2005).

Despite the successes of these control measures, nuisance algae have resurged in nearshore regions, particularly in lakes Ontario, Erie and Michigan, and in certain areas of Lake Huron (Higgins et al., 2005; Auer et al., 2010). This has lead to assertions in the media that phosphorus concentrations and inputs to the Great Lakes must be once again increasing (CBC, 2011). However, in the offshore regions of lakes Ontario, Huron and Michigan, phosphorus levels have continued to decline, and the rate of the decline has accelerated starting in the 1990s. In Lake Ontario, for example, offshore TP has declined from target levels achieved in the early 1990s to levels well below target (Figure 2).

The weight of scientific evidence indicates that invasive Dreissenid mussels (zebra mussels *Dreissena polymorpha* and quagga mussels *Dreissena bugensis*), which have colonized all of the Great Lakes with the exception of Lake Superior, have dramatically altered phosphorus cycling (Hecky et al., 2004). Dreissenid mussels are efficient filters of particulates, with two results: 1) mussels take in particulate-bound nutrients and excrete soluble nutrient forms, thereby increasing the availability of phosphorus for uptake by algae in Great Lakes nearshore areas, and 2) nutrients are bound in mussel feces deposited in nearshore sediment, preventing the export of phosphorus to offshore regions. In this way, nuisance algae are able to thrive in the nearshore, and the offshore regions are deprived of nutrients. Invasive mussels are causing massive ecosystem change, including reductions in benthos, plankton and fish populations in the offshore, and yet they facilitate the growth of nuisance levels of benthic algae in the nearshore (Evans et al., 2011).

Lake Superior

The TP record in Lake Superior extends back to 1970 (Environment Canada) and 1992 (USEPA). The average offshore values of TP have remained below the 5 µg/L target value to maintain an oligotrophic state. Fewer than 4% of the 400+ individual data measurements have exceeded the target. The ecosystem objective to maintain an oligotrophic state and retain relatively low algal biomass is being met. There are few invasive mussels in Lake Superior (Grigorovich, 2008), so it has been spared the ecological impacts seen in most of the other Great Lakes.

There is no trend over time apparent in either the US or the Canadian datasets, indicating status is good and unchanging. The lack of a trend, however, does not necessarily indicate that Lake Superior's waters have not been impacted. Due to its long residence time and large volume, we might not expect to detect a trend for some time. As was demonstrated by Chapra et al. (2009) using chloride, significant loading increases would not be detectable in the lake for at least a decade. For a less conservative substance like phosphorus, the lake's assimilation could further mask impacts. Prudence is recommended in the management of phosphorus inputs here, as the lake's very long residence time and low productivity mean that recovery from impacts, once felt, would take many decades to achieve.

Lake Michigan

Data for Lake Michigan are only collected by GLNPO since this lake is located entirely within the United States. Average offshore TP values have ranged from 6 µg/L in 1976 (the first year of monitoring) to 3.1 µg/L in 2009, indicating a significant ($p<0.001$) decline of 0.072 µg/L·yr over the period of record. Average offshore values have been in compliance with the GLWQA target concentration of 7 µg/L in every year, and only 14 of the 391 individual measurements have exceeded the target concentration over the 1983 – 2007 period. None of the individual measurements have exceeded the target concentration since 1996. These data indicate that the status with respect to the existing indicator endpoints is good and improving. In our best judgment, however, the endpoint has been surpassed, to the detriment of offshore biological productivity. In the nearshore, nutrient inputs combined with invasive mussel effects appear to be causing a resurgence of nuisance benthic algae. In the offshore, the evidence indicates the mussel invasions have resulted in increased predation of plankton and reduced nutrients, resulting in decreased productivity of the fisheries (Mida et al., 2010; Evans et al., 2011).

Lake Huron

In Lake Huron, average TP values in the offshore have ranged from 5.6 to 1.7 µg/L (data from both programs). Both the GLNPO and EC data indicate significant long-term declines in TP. GLNPO has measured a 0.079 µg/L·yr decline between 1983 and 2009 ($p<0.001$). EC has measured a longer-term decline of 0.056 µg/L·yr between 1970 and 2009 ($p<0.05$). The trends appear to be more steep since 1990, with declines of 0.13 and 0.10 µg/L·yr according to the GLNPO and EC data, respectively. The recent (2009) values are extremely low (1.8 and 2.7 µg/L for USEPA and EC, respectively), indicating levels have fallen too far below the target concentration and are insufficient to support a healthy offshore biological community. Decreased phytoplankton production, loss of native benthos, and serious declines in alewife and lake whitefish have been observed since the introduction of dreissenid mussels (Evans et al., 2011).

In Georgian Bay (measured only by Environment Canada), the long-term trend in TP has followed that of Lake Huron quite closely. The average TP values in the offshore have ranged from 1.9 to 5.5 µg/L and have also generally been in compliance with the 5 µg/L target value. Cruise means exceeded the target in 1987 (5.5 µg/L) and 1993 (5.1 µg/L). The Georgian Bay data indicate a significant ($p<0.001$) decline in TP of 0.08 µg/L·yr between 1970 and 2009. The rate of decline has been steeper since 1990 (slope = -0.14 µg/L·yr, $p=0.002$), indicating the decline in TP has accelerated. The most recent (2009) offshore average value of TP (2.55 µg/L) is extremely low, indicating oligotrophic conditions with insufficient nutrients to support a healthy biological community.

Lake Erie

TP concentrations in the western basin of Lake Erie have been the highest and most variable observed in the dataset. Spring cruise means have ranged from 10.8 to 82.6 µg/L. Concentrations were highest during the 1970s, and have clearly declined over time, although they continue to be highly variable and the most recent values in the western basin are some of the highest observed (Figure 2). The EC data indicate TP in the western basin has declined by 0.8 µg/L·yr ($p=0.01$); the rate is 1.04 µg/L·yr ($p<0.001$) if the unusually high 2009 value is excluded. The GLNPO data indicate a slower decline of 0.442 µg/L·yr from 1974 to 2008, but the trend is not statistically significant ($p=0.12$). Average TP concentrations frequently exceed the 15 µg/L target, and individual measurements have exceeded this value about two-thirds of the time in each of the US and Canadian data sets. The most recent values for the western basin are very high, and are most similar to values observed in the 1970s (Figure 2).

Concentrations of TP in the central Lake Erie basin are lower than those observed in the western basin but are elevated compared to target values and have not declined significantly over the period of record. Linear regression of the EC data indicates a decline of 0.174 µg TP/L·yr, but the trend is not statistically significant ($p=0.068$). The GLNPO data indicate an initial decline of 0.6 µg TP/L·yr from 1974 through 1990 ($p=0.01$), followed by an increase of 0.25 µg TP/L·yr from 1990 to 2009, but this increase was marginally significant ($p=0.1$). The central basin data are highly variable, and spring cruise mean TP concentrations since 1970 have ranged from 7.5 to 31 µg/L. Concentrations are often elevated above the 10 µg/L target; similar to the western basin, individual measurements from the central basin have exceeded the target about two-thirds of the time in each of the US and Canadian data sets. .

Concentrations in the deeper eastern basin tend to be the lowest and the least variable in Lake Erie. Spring cruise mean concentrations have ranged from 4.9 to 37 µg/L and have exceeded the 10 µg/L target concentration about 60% of the time since 1983. The EC data indicate a decline between 1970 and 2009 (slope = -0.31 µg/L·yr) that is moderately significant ($p=0.02$). The GLNPO data indicate a slower rate of decline of 0.082 µg TP/L·yr ($p<0.05$). There is some suggestion of a more recent increase, but the trend is not statistically significant.

Lake Ontario

The trend for Lake Ontario provides the most convincing illustration of the long-term decline of TP in the Great Lakes. Mean offshore concentrations in the 1970s exceeded 20 µg/L; recent data are well below the target of 10 µg/L. The EC data show a highly significant ($p<0.001$) decline of 0.433 µg/L·yr between 1970 and 2010. The rate of decline from 1986 to 2009 measured by GLNPO is a more modest 0.16 µg/L·yr ($p<0.0001$), and is similar to the rate from 1990 -2010 measured by EC (-0.15 µg/L·yr, $p<0.0001$).

Data from the last decade in particular indicate offshore total phosphorus concentrations are not sufficient to support a healthy foodweb. Similar to Lakes Michigan and Huron, the offshore targets have been surpassed, yet the ecosystem objectives to maintain the algal biomass below nuisance levels have not been met for the nearshore. Cladophora has been found widely distributed across nearshore areas with solid substrate (Wilson et al., 2006). The current concentrations of TP (USEPA = 5.18 µg/L in 2009; EC = 6.41 µg/L in 2010) have surpassed the offshore target of 10 µg/L by a wide margin. At the same time, offshore silica levels have surged higher, indicating that diatom populations have crashed in the offshore (Dove, 2010). Mills et al. (2006) found that phytoplankton have been depleted and epilimnetic zooplankton have declined to historic lows. These changes may be, in turn, limiting offshore fish productivity, as preyfish declines have also been noted (Gorman, 2009).

Linkages

Nutrients, in particularly phosphorus, control the productivity of the Great Lakes ecosystems. In sufficient quantities, nutrients provide for a productive foodweb and fishery; in excess, nutrients stimulate nuisance and harmful algal growth, and symptoms of eutrophication, such as noxious algal blooms, depleted oxygen and fish kills, can ensue.

Nutrients are contributed by tributary discharges, sediment resuspension, atmospheric deposition, urban and agricultural runoff and by municipal wastewater facilities. Important linkages exist between sources, their pathways and the nearshore receiving environment, which in turn contributes nutrients to the offshore regions. Increasing human populations inhabiting Great Lakes shorelines, projected to occur in the decades to come, may result in increased pressures to municipal wastewater loadings, nutrients in tributaries and even atmospheric deposition.

Management Challenges/Opportunities

The proliferation of dreissenid mussels in the nearshore, and the subsequent expansion of mussel populations to many regions of the offshore, has had profound impacts on the lake environment. Mussel filtration of lake water has altered the light environment so that light penetrates to deeper depths and enables algae to grow in areas previously uninhabitable. The presence of mussel shells provides algae with a hard substrate upon which to grow. Finally, mussels have altered nutrient cycling so that nutrients destined for the offshore are instead trapped in the nearshore where they are causing impairment, and depriving the offshore of sufficient nutrients to sustain a healthy food web.

An improved understanding of how Dreissenid mussel water filtration controls the availability of phosphorus for algae is required. Improved knowledge about loadings of nutrients, in their various forms, and the impacts of those loads to lake impairments would also assist in determining whether specific load reductions would be worthwhile.

Further controlling lake-wide phosphorus loads would be even more costly, and the reduction of nutrients in the offshore may be exacerbated. Management of invasive mussels, already established in the ecosystem, is a major challenge with no readily apparent solutions.

Comments from the author(s)

Insert Comments from the author(s) text

Assessing Data Quality

Insert "x" under the statement that best corresponds with each data characteristic

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization	×					

2. Data are traceable to original sources	×	
3. The source of the data is a known, reliable and respected generator of data	×	
4. Geographic coverage and scale of data are appropriate to the Great Lakes basin	×	
5. Data obtained from sources within the U.S. are comparable to those from Canada		×
6. Uncertainty and variability in the data are documented and within acceptable limits for this indicator report	×	

Clarifying Notes:
Comparison of US and Canadian TP data indicates consistently lower values are obtained by the USEPA relative to Environment Canada. Statistical tests were performed for lakes Ontario and Huron, where some shared stations permit paired t-test comparisons. The results indicated significantly higher values obtained by EC compared to the USEPA ($p<0.001$). The differences amount to approximately 1.9 and 1.6 μg P/L for lakes Ontario and Huron, respectively. No significant difference was observed for laboratory quality assurance (filtered) samples over many years (1999-2008), indicating agreement between laboratory instruments used. The difference occurs independently of field sampling date and location and is likely due to differing sample digestion durations. Samples collected by Environment Canada are digested for a minimum of 30 minutes once digestor temperature has reached 121°C. Samples collected by the USEPA are digested for 30 minutes with the oven set to 121°C, but this includes time for the oven to reach high temperature. The longer digestion of EC samples may result in more complete breakdown of nutrients attached to particles and higher concentrations are measured.

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Glenn Warren, Environmental Monitoring and Indicators Team Leader, Great Lakes National Program Office, USEPA.

Information Sources

United States data from Great Lakes National Program Office, United States Environmental Protection Agency, Chicago, Illinois.

Early (1970 – 1976) Lake Erie data from CLEAR (Center for Lake Erie Area Research) under contract to USEPA.

Canadian data from Great Lakes Surveillance Program, Water Quality Monitoring and Surveillance, Environment Canada, Burlington, Ontario.

Nearshore information provided by E.T. Howell, Ontario Ministry of the Environment

References Cited

Auer, M.T., L.M. Tomlinson, S.N. Higgins, S.Y. Malkin, E.T. Howell and H.A. Bootsma, 2010, Great Lakes Cladophora in the 21st century: same algae—different ecosystem, J. Great Lakes Res. 36 (2010) 248–255

Barbiero, R.P. and M.L. Tuchman, 2004, Long-term Dreissenid Impacts on Water Clarity in Lake Erie, J. Great Lakes Res. 30(4):557–565

Bootsma, H.A. , E.B. Young and J.A. Berges, 2004, Temporal and spatial patterns of *Cladophora* biomass and nutrient stoichiometry in Lake Michigan. In: H.A. Bootsma, E.T. Jenson, E.B. Young and J.A. Berges, Editors, Cladophora Research and Management in the Great Lakes, Proceedings of a workshop held at the Great Lakes WATER Institute, University of Wisconsin-Milwaukee, December, 2004 (2004), pp. 81–88.

Dolan, 2010, *Nutrient Loading Trends for Lakes Michigan, Superior and Huron*, presentation at 53rd Annual Conference on Great Lakes Research, International Association for Great Lakes Research, May 18, 2010, Toronto, Ontario.

CBC, 2011, *Great Lakes phosphorus levels rising, report warns*, by Sharon Oosthoek, Canadian Broadcasting Corporation News, Posted: Mar 9, 2011 8:20 AM ET, http://www.cbc.ca/news/technology/story/2011/03/09/tech-ijc-great-lakes.html

Chapra, S.C., Dove, A., and Rockwell, D. 2009. Great Lakes chloride trends: long-term mass balance and loading analysis, J. Great Lakes Res. 35(2):272-284.

Dove, A. 2009. Long-term trends in major ions and nutrients in Lake Ontario. Aquatic Ecosystem Health & Management. 12(3):281–295.

Dove, A., L'Italien, S. and Gilroy, D. 2009. Great Lakes surveillance program field methods manual. Water Quality Monitoring and Surveillance, Environment Canada, Burlington, Ontario, Canada. Report No. WQMS09-001.

Evans, M.A., G. Fahnenstiel and D. Scavia, 2011, Incidental Oligotrophication of North American Great Lakes, *Environ. Sci. Technol.,* 45 (8), pp 3297–3303. DOI: 10.1021/es103892w

Grigorovich, I.A., J.R. Kelly, J.A. Darling and C.W. West. 2008. The quagga mussel invades the Lake Superior basin. *J. Great Lakes Res.* 34: 342-350

GLNPO, 2010. Sampling and Analytical Procedures for GLNPO's Open Lake Water Quality Survey of the Great Lakes. Prepared by U.S. Environmental Protection Agency, Great Lakes National Program Office, Chicago IL. EPA 905-R-05-001, March 2010.

GLWI, 2005, Cladophora Research and Management in the Great Lakes, Proceedings of a workshop held at the Great Lakes WATER Institute, University of Wisconsin-Milwaukee, December, 2004, GLWI Special Report No. 2005-01, **www.glwi.uwm.edu/research/.../cladophora/Cladophora_Proceedings_HighQuality.pdf**

Harris, V., 2005, *Cladophora* Confounds Coastal Communities – Public Perceptions and Management Dilemmas. In: H.A. Bootsma, E.T. Jenson, E.B. Young and J.A. Berges, Editors, Cladophora Research and Management in the Great Lakes, Proceedings of a workshop held at the Great Lakes WATER Institute, University of Wisconsin-Milwaukee, December, 2004 (2004), pp. 5-14.

Hecky, R. E., Smith, R. E. H., Barton, D. R., Guildford, S. J., Taylor, W. D., Charlton M. N., and Howell, T. 2004. The nearshore phosphorus shunt: a consequence of ecosystem engineering by dreissenids in the Laurentian Great Lakes. Can. J. Fish. Aquat. Sci. 61: 1285-1293.

Higgins, S. N., Howell, E. T., Hecky, R. E., Guildford, S. J., and Smith, R. E., 2005, The wall of green: the status of *Cladophora glomerata* on the northern shores of Lake Erie's eastern basin, 1995-2002. *J. Great Lakes Res.* 31: 547-563.

IJC. 1978. Great Lakes Water Quality Agreement of 1978, with Annexes and Terms of Reference, Between the United States and Canada, Signed at Ottawa, November 22, 1978. International Joint Commission. Windsor, Ontario. (http://www.ijc.org/en/activities/consultations/glwqa/agreement.php).

Malkin, S.Y., 2007, The Ecology of the Nuisance Macroalga, Cladophora glomerata, and its Resurgence in Lake Ontario, Ph.D. thesis, University of Waterloo Waterloo, Ontario, Canada, 2007, http://hdl.handle.net/10012/3592

Malkin, S.Y., A. Dove, R. E. Smith, S. Guildford and R.E. Hecky, 2010, Spatio-temporal patterns of water quality in

Lake Ontario and their implications for nuisance growth of *Cladophora*, J. Great Lakes Res., 36: 477-489, doi:10.1016/j.jglr.2010.06.007

Mida, J.L., Scavia, D., Fahnenstiel, G.L., Pothoven, S.A., Vanderploeg, H.A., and Dolan, D.M. 2010. Long-term and recent changes in southern Lake Michigan water quality with implications for present trophic status. *J. Great Lakes Res.* 36(Suppl. 3): 42 - 49.

Mills., E.L., R. Dermott, M. Munawar, E. S. Millard, O. Johannsson and L. Rudstam, 2006. Status of the Lake Ontario Food Web in a Changing Ecosystem: the 2003 Lake Ontario Lower Aquatic Food Web Assessment (LOLA). Final Report for: Developing the Next Generation of Great Lakes Lower Food Web Assessment Tools, Grant ID CR-83209001-0. http://epa.gov/greatlakes/lakeont/lola/index.html

Ouellette, A.J.A., S.M. Handy and S.W. Wilhelm, 2006, Toxic Microcystis is Widespread in Lake Erie: PCR Detection of Toxin Genes and Molecular Characterization of Associated Cyanobacterial Communities. *Microbial Ecology* 51: 154–165. DOI: 10.1007/s00248-004-0146-z

Richards, R.P. and D.B. Baker, 2006, Reversal of Declining Nutrient Trends in Lake Erie Tributaries, National Center for Water Quality Research, Heidelberg College, Tiffin, Ohio, Presentation at the Lake Erie Millennium Network Conference, Windsor, Ontario, February 28, 2006

Stevens, R.J.J. and M.A. Neilson, 1987. Response of Lake Ontario to reductions in phosphorus load, 1967–82. Can. J. Fish. Aquat. Sci., Vol. 44, 2059–2068.

Tomlinson, L. M., Higgins, S. N., Malkin, S. Y., Howell, E. T., Bootsma, H. A., and Auer, M. T. 2006. Great Lakes Water Quality Agreement Annex III Technical Sub-Group: Report of the *Cladophora* Modeling Team.

Wilson, K. A., Howell, E. T., and Jackson, D. A. 2006. Replacement of zebra mussels by quagga mussels in the Canadian nearshore of Lake Ontario: The importance of substrate, round goby abundance, and upwelling frequency. J. Great Lakes Res. 32:11-28.

List of Figures

Last Updated

State of the Lakes Ecosystem Conference (SOLEC) 2011

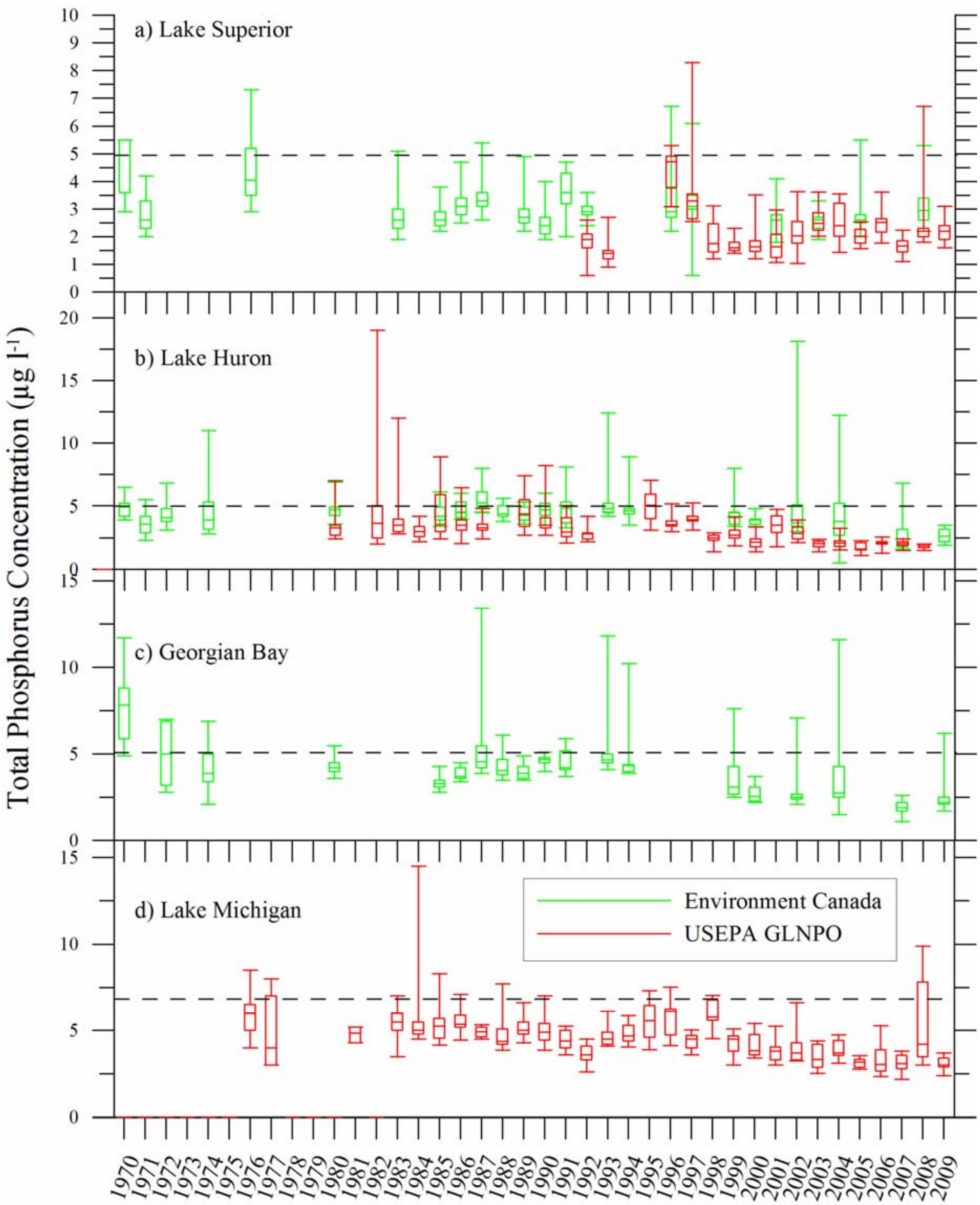

Figure 1. Long-term Trend of Total Phosphorus in the Upper Great Lakes

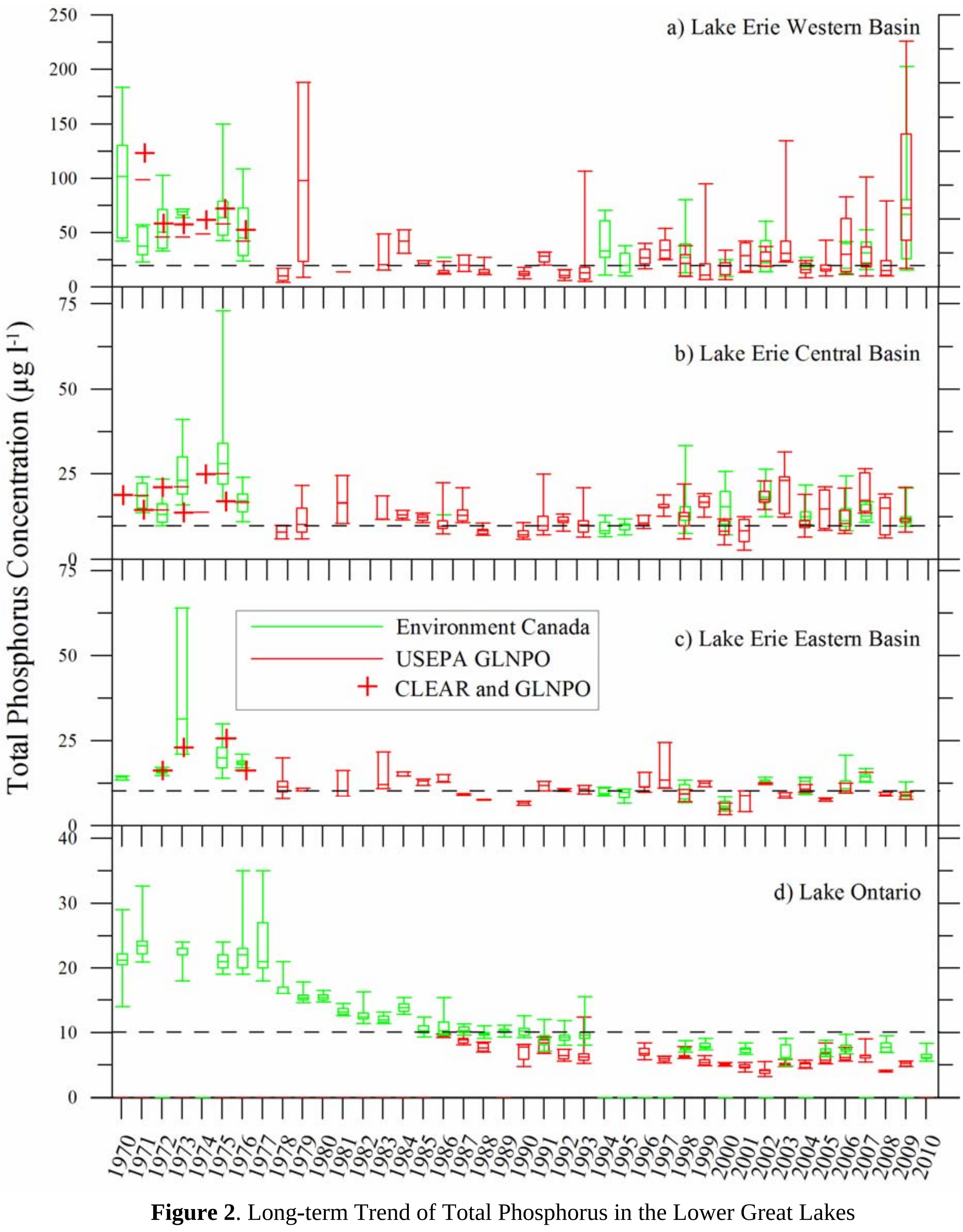

Figure 2. Long-term Trend of Total Phosphorus in the Lower Great Lakes