Status of Nutrients in the Lake Erie Basin

Prepared by the Lake Erie Nutrient Science Task Group
for the Lake Erie Lakewide Management Plan

LAKE ERIE
LAKEWIDE MANAGEMENT PLAN

Scientific information contained in the report Status of Nutrients in the Lake Erie Basin is current as of November 2008. The report was created to deliberately inform the Lake Erie Lakewide Management Plan (LaMP) Work Group and to provide a "weight of evidence" rationale for the Lake Erie Binational Nutrient Management Strategy. The LaMP recognizes that ongoing research and scientific investigation will continue to fill knowledge gaps and answer outstanding questions, potentially changing current, prevailing hypotheses. In the spirit of adaptive management, the LaMP will closely monitor research advancements and recommend appropriate adjustments to nutrient management actions to assure that sound science continues to serve as the basis of responsible public policy.

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Note to Reader

December 2009

Lake Erie water quality has taken a turn for the worse. The algal blooms that threatened the Lake Erie ecosystem in the 1960s and 1970s have returned, and the extent and duration of anoxia/hypoxia in the central basin continue to increase. *Cladophora* growth has once again become a problem in nearshore zones and in areas with hard bottom substrate; botulism outbreaks are believed to be linked to a combination of interrelationships between *Cladophora,* dreissenids and round gobies; and models developed to predict the lake response to various inputs are no longer accurate.

The algal blooms that began their return to the western basin in the mid 1990s are composed primarily of the blue-green alga *Microcystis aeruginosa*. This species is capable of producing high concentrations of the toxin microcystin which could impact drinking water supplies, recreational use, and the aquatic community. At the mouth of the Maumee River, benthic mat-forming blue-green algae float to the surface and wash ashore after storms. The fouled shorelines can have harmful impacts on the ecosystem, including the potential to produce toxins.

Although it does not appear that total phosphorus loads are increasing, total phosphorus concentrations in the nearshore are. Significantly increasing loads of dissolved reactive phosphorus (DRP) have now been measured in the Maumee and Sandusky rivers. Increasing trends in DRP have also been identified in the Cuyahoga and Grand (OH) rivers. These disturbing trends could also be present in other tributaries but monitoring data is limited for these areas. In short, existing programs to control phosphorus are no longer sufficient to protect the lake.

While the mechanisms behind these changes are areas of active scientific investigation, there is an urgent need now for coordinated and strategic nutrient management actions. The Lake Erie Lakewide Management Plan (LaMP) Work Group is preparing a *Lake Erie Binational Nutrient Management Strategy* (Nutrient Management Strategy) which will represent the consensus of key Lake Erie resource managers on the goals, objectives, targets, indicators, priority watersheds, monitoring and research needed to improve current conditions and to prevent further eutrophication. As the Strategy is implemented, the creation of partnerships with resource managers with a role in nutrient management in the Lake Erie basin will be needed to assure the successful achievement of results.

This *Status of Nutrients in the Lake Erie Basin* technical report (Nutrient Status Report) was prepared as a background report to inform development of the Nutrient Management Strategy. The Nutrient Status Report includes nutrient information (current as of November 2008) and uses a “weight of evidence” rationale to define the role nutrients play in the lake’s increased algal growth. Ongoing research will continue to fill knowledge gaps and answer outstanding questions, potentially changing current, prevailing hypotheses.

As part of its leadership role in restoring the lake, the Lake Erie LaMP Management Committee identified indicator endpoints for total phosphorus concentrations for surface water on June 24, 2009. Based on our assessment of the science available at this time, these endpoints, when achieved, should reduce problem algal blooms in the lake. This will in turn lead to reduction in central basin hypoxia, reduce additional costs for drinking water treatment, improve fish and

Total phosphorus concentrations in surface waters indicator endpoints

Habitat Type	**Desired Ecological Endpoint***(ug/L)
Tributaries	32
Coastal Wetland	one recording of <30 ug/L / year
Nearshore	20
West Basin	15
Central Basin	10
East Basin	10

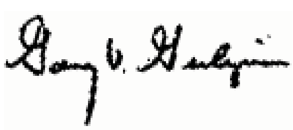
*Mean Annual Total Phosphorus Concentration ug/L

wildlife habitat and populations, and improve recreational use of the lake. A Lake Erie LaMP technical report summarizing the development of these indicators will be released in 2009-2010. The Nutrient Management Strategy will identify ways to move towards the achievement of these endpoints.

The success of the Nutrient Management Strategy and, thus, the restoration of Lake Erie, will depend on the commitment from various stakeholders (e.g., government officials, members of the agricultural community, land use planners, homeowners, etc.) to join forces and to change how nutrients are currently used, applied, transported and discharged. The Lake Erie LaMP's role will be to set common endpoint goals consistent with the Great Lakes Water Quality Agreement; to coordinate research and monitoring; to support local authority implementation; and to report out on current conditions, trends and progress. Multiple jurisdictions, in both Canada and the United States, will be responsible for the on the ground implementation of actions, which may vary on a regional basis.

Billions of dollars were needed and spent to reduce phosphorus loads in the 1970s and 1980s. Those efforts led to a healthy Lake Erie, until problems resurfaced in the mid 1990s. We are now again faced with the challenge of fixing the lake. We faced the challenge before, and succeeded; with the same commitment to partnerships and coordinated actions, we can again succeed.

We encourage you to take up the challenges we have outlined and work with us to restore Lake Erie once again.



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1.0 Overview

The Lakewide Management Plan (LaMP) process is the mechanism in the current Canada – U.S.A. Great Lakes Water Quality Agreement (GLWQA) that brings together the federal Parties and their State and Provincial partners to develop, implement, and manage improvements to the Great Lakes. This technical document is written in support of the Lake Erie LaMP's efforts to achieve the LaMP Nutrient Management Ecosystem Objective and to prepare a Lake Erie Binational Nutrient Management Strategy. The primary audience is the LaMP Work Group and Management Committee.

Beginning in the 1970s, the trend to increasing nutrient loads and worsening algal conditions in Lake Erie was reversed, consistent with the GLWQA objectives. During that period, most of the damage occurred in Lake Erie's western basin and, subsequently, water quality improvements were most prevalent there. By the 1990s, phosphorus concentrations were one half of their former levels in the western basin with smaller improvements in the central and eastern basins. However, despite tremendous efforts, total phosphorus concentrations in the western basin remained high enough to stimulate occasional algal blooms. In recent years, these blooms seem to have become worse.

Recent algal problems in Lake Erie prompted a brief review of stimulatory nutrients in the lake. Changes in the lake's biological components seem to render the nutrient controls of decades past insufficient for today's conditions in some areas. Offshore algal problems are most prevalent in the western basin. There is a west to central to east basin gradient of improving water quality, consistent with the presence of the largest total phosphorus loads in the west basin. Phosphorus continues to be the limiting nutrient. There is enough nitrogen present that it is not usually limiting algae, although almost any nutrient can be shown to appear limiting to algae on a given day. Nitrogen warrants watching as the ecological implications of ongoing increases are unknown. The relationship between phosphorus and algae as indicated by chlorophyll remains strong in offshore waters.

Nearshore, there is a serious problem with attached filamentous algae in the east basin and parts of the west basin. Algal problems are usually associated with elevated nutrient supplies but Dreissenid mussels seem mostly responsible for attached algae. At the same time, more research is needed to determine whether whole lake and/or shoreline source control, if possible, would be effective at ameliorating the problem.

For the lands draining to Lake Erie, the LaMP called for aquatic habitat improvements (land use modifications) that would cause a concomitant reduction of phosphorus loads. Those reductions now seem desirable even if, individually, they may not be capable of effecting large changes in the lake. There is evidence that the agricultural losses of nutrients to the lake, after initial reductions, have become more serious. Total phosphorus concentrations in some rivers such as the Maumee are so high that, despite many actions to date, further strong remedial measures are needed for long-term improvement of algal problems.

Overall reductions in total phosphorus to the lake are still needed. Great Lakes Water Quality Agreement goals and targets are not consistently being met. Agricultural and municipal sources of phosphorus remain mitigation targets, because they have the highest loads at the highest concentrations with the highest availability to algae. A strong nutrient research and monitoring program is needed to address unknowns and to evaluate progress.

2.0 Status of the Lake

2.1 Offshore Nutrient Effects

Data Extraction and Manipulation

The data used in this technical report for offshore temporal trends in water quality were from the Environment Canada (EC) "STAR" database; U.S. data were provided by Glenn Warren at the U.S. EPA Great Lakes National Programs Office (GLNPO). Samples were collected on surveillance, monitoring and research cruises. Offshore data were selected for the eastern and central basins from stations deeper than 20 m. Depth discrimination was not applied to data of the shallow western basin; all values were considered 'offshore.' Only the spring and summer season data are presented as these data were collected the most consistently throughout the years. The spring period was defined as the months of April, May and June, while the summer season was defined as the months of July, August and September. The spring data represent the entire water column assuming complete mixing, while the summer values represent data from the epilimnion only for both datasets. For the EC data, typical epilimnion depths of 16 m and 13 m were used for the east and central basins, respectively, while the west basin was assumed to be uniformly mixed throughout the summer season. The GLNPO data were provided for the epilimnion and hypolimnion separately. The minimum dissolved oxygen data is from the central basin only and from the hypolimnion defined as greater than 13 m. Where necessary, data not normally distributed were plotted on a log scale. Chlorophyll a data are for phaeophytin corrected values and reflect a merge of the integrated and discrete depth samples in the EC dataset. This was done to overcome the lack of continuous data in either of these sample types.

Total Phosphorus

Total phosphorus (TP) is comprised of many types of phosphorus compounds in both particulate and soluble forms. Each form has different abilities to grow algae, referred to as its "bioavailability." Apatite mineral from shore erosion, for example, is a particulate form that is largely unavailable to algae. Soluble reactive phosphorus (SRP) is a soluble form found in sewage and fertilizers that is highly bioavailable. Algal cells (particulate) contain organic phosphorus that will be released upon decomposition.

GLWQA: Lake Erie Phosphorus Goals

- Restoration of year-round aerobic conditions in the bottom waters of the Central Basin of Lake Erie;
- Substantial reduction in the present levels of algal biomass to a level below that of a nuisance condition in Lake Erie, and;
- The elimination of algal nuisance in bays and in other areas wherever they occur.
- Based on the goals, water quality objectives and phosphorus loading targets were established.

Water quality objectives and required total phosphorus load for Lake Erie

Basin	Chl *a* (ug/L)	TP (ug/L)	Trophic State
Western	3.6	15	Mesotrophic
Central	2.6	10	Oligomesotrophic
East	2.6	10	Oligomesotrophic
Target TP Load Annually		11,000 tonnes	

Where there are high loads and concentrations of total phosphorus, a significant component will be bioavailable phosphorus such as SRP. Operationally, total phosphorus is easier to measure than its component fractions (especially soluble fractions); therefore, total phosphorus is the measure more commonly used. Total phosphorus load has become a sort of shorthand criterion for communicating the nutrient status of water.

Despite success with controls, total phosphorus loads are not always at or below target (DePinto 2007) and how much of the present load variation is comprised of important bioavailable phosphorus is not consistently known (P. Richards, personal communication).

Open water spring total phosphorus concentrations have not consistently been below target levels. The west basin concentrations tend to be much higher than the target level of 15 ug/L. Total phosphorus concentrations in the offshore waters of Lake Erie are summarized in Figure 1. Spring total phosphorus decreased in all three basins over the last three decades, although recent concentrations in all basins may be increasing.

Recent and average historical spring concentrations were above the water quality target set for each basin (west: 0.015 mg/L, central and east: 0.010 mg/L). In 2007, average spring total phosphorus concentrations were: 0.029±0.012, 0.012±0.003 and 0.017±0.007 mg/L, for the west, central and east basins, respectively. Summer total phosphorus concentrations also declined in all three basins. In 2006 (no data yet available for 2007), average summer epilimnetic total phosphorus concentrations were: 0.024±0.018, 0.010±0.005, 0.006±0.002 mg/L, for the west, central and east basins, respectively. A total phosphorus gradient from the west to the east is apparent.

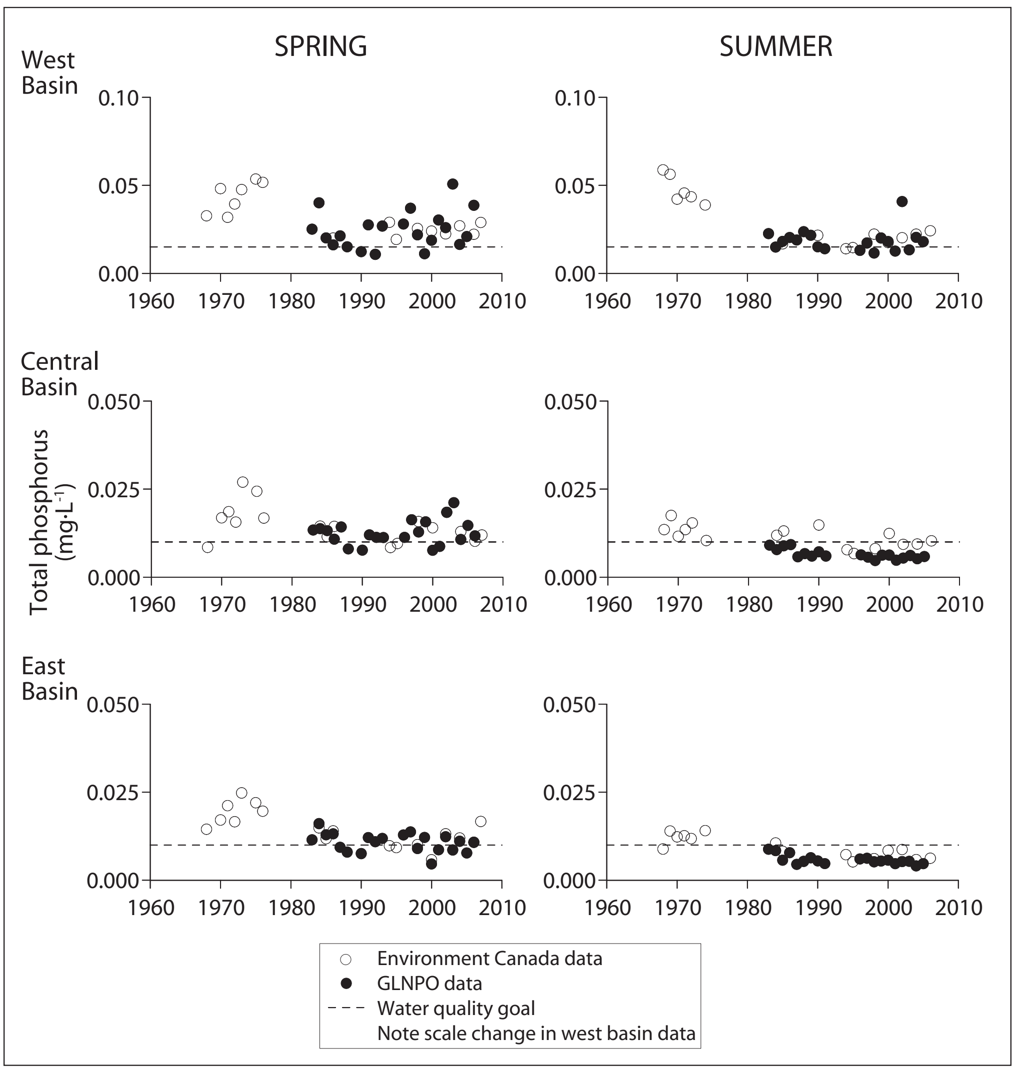

Figure 1. Mean total phosphorus concentrations in the west, central and east basins for the spring and summer periods.

In the summer, both the east and central basins are at or below their water quality target of 0.010 mg/L, and have been for the past decade with few exceptions. Summer total phosphorus concentrations in the west basin, however, are often above the water quality target of 0.015 mg/L, and seem to exhibit a higher variability than either the central or east basins. As Figure 2 indicates, a wide range of problematic blue-green algal biomass is possible at the total phosphorus concentration currently found in offshore west basin waters.

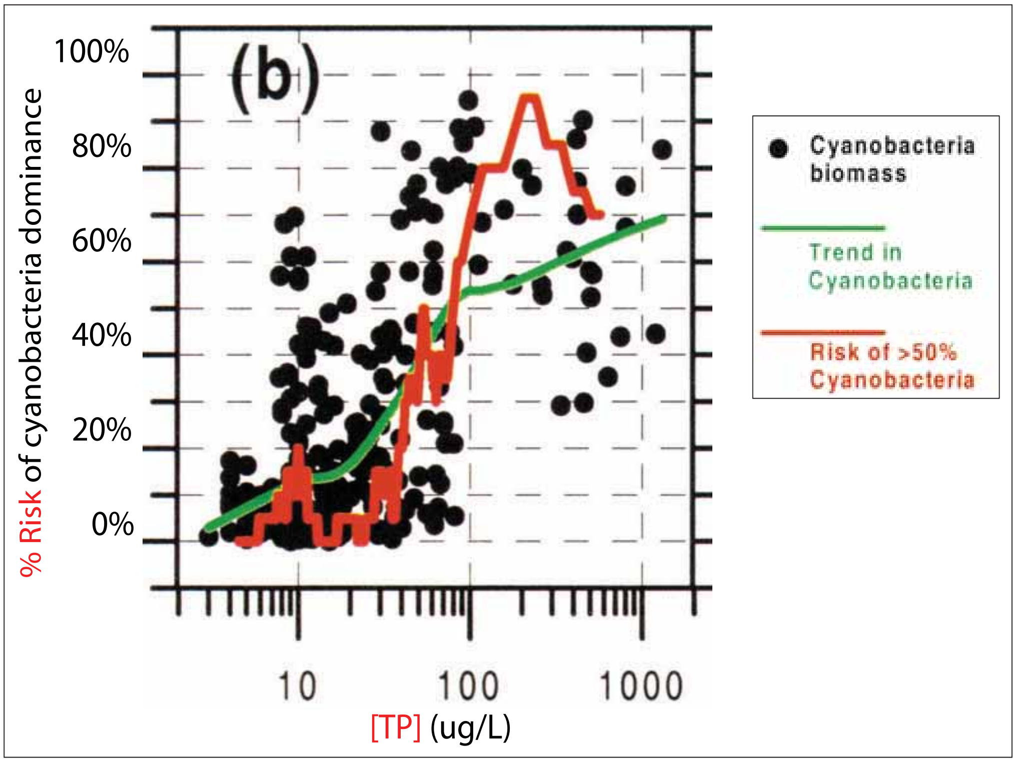

Figure 2. The probability of cyanobacteria dominance is controlled by phosphorus, but there is much variation. (from Downing et al. 2001)

Chlorophyll *a*

Reduction of algal populations as symbolized by chlorophyll (Chl *a*) was an anticipated result of total phosphorus load reductions. Chlorophyll concentrations in the offshore waters of Lake Erie are summarized in Figure 3.

Spring chlorophyll appears to have decreased in all three basins during the period from the late 1960s to 2000, most notably in the western basin. Similar to total phosphorus, recent concentrations in all basins have increased. Spring average concentrations in the west basin have been at or below the target of 3.6 ug/L over the last decade, and consistently decreasing during that period. Spring average chlorophyll concentrations in the central and east basins, however, have tended to increase over the last decade and in the last few years have been at or above the water quality target of 2.6 ug/L. In 2007 average spring chlorophyll concentrations were: 2.12±1.64, 4.73±0.92 and 2.00±0.57 ug/L, for the west, central and east basins, respectively. One consideration is that spring samples can be variable depending on ice out date and algal bloom cycles (R. Hecky, personal communication).

Summer chlorophyll concentrations declined in all three basins. In 2006, average summer epilimnetic chlorophyll concentrations were: 4.55±2.42, 1.84±0.75, 1.55±0.42 ug/L, for the west, central and east basins, respectively. A chlorophyll gradient from the west to the east is apparent. In the summer, both the east and central basins are close to or below their water quality target of 2.6 ug/L and have been in recent years. Summer chlorophyll concentrations in the west basin, however, remain consistently above its water quality target of 3.6 ug/L.

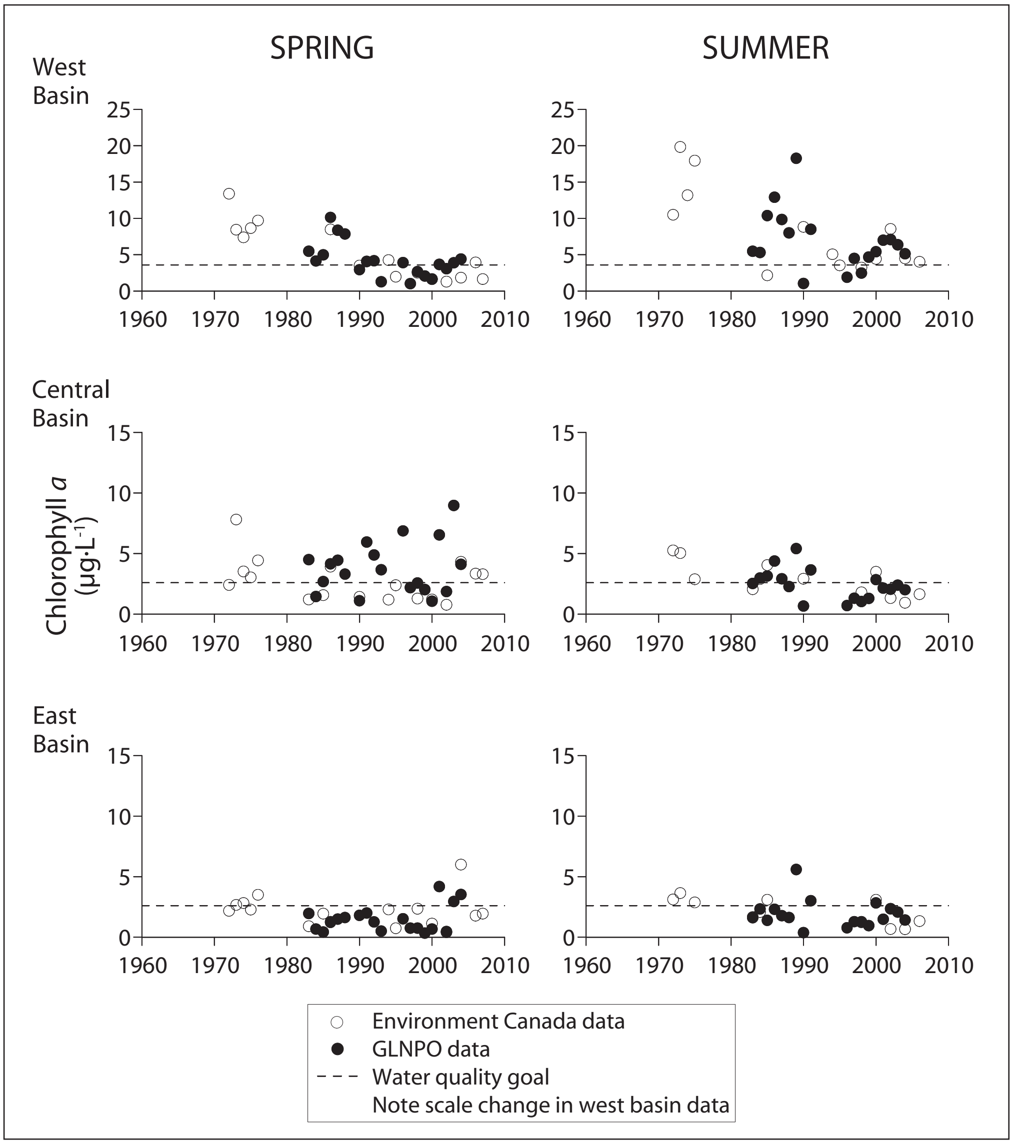

Figure 3. Mean chlorophyll *a* concentrations in the west, central and east basins for the spring and summer periods.

Secchi Depth

Secchi depths in the offshore waters of Lake Erie are summarized in Figure 4. Spring Secchi depths have shown little trend over the last three decades, with the exception of the east basin where spring Secchi depths increased during the period from the early 1970s to 2000. Since 2000, water clarity in the east basin seems to be decreasing. In 2007 average spring Secchi depths were: 3.27±1.09, 5.25±1.73 and 6.55±1.71 m, for the west, central and east basins, respectively.

Summer Secchi depths have similarly shown very little trend over the last three decades in the central and east basins. However, a notable increase in Secchi depth occurred in the west basin after the Dreissenid mussel invasion of the late 1980s. Recent data seems to suggest a subsequent decrease in Secchi depth. In 2007 average summer Secchi depths were: 3.5±n.a., 8.00±2.12, 9.00±0.87 m, for the west, central and east basins, respectively. A water clarity gradient from the west to the east is apparent, and consistent with the total phosphorus and chlorophyll concentration gradients.

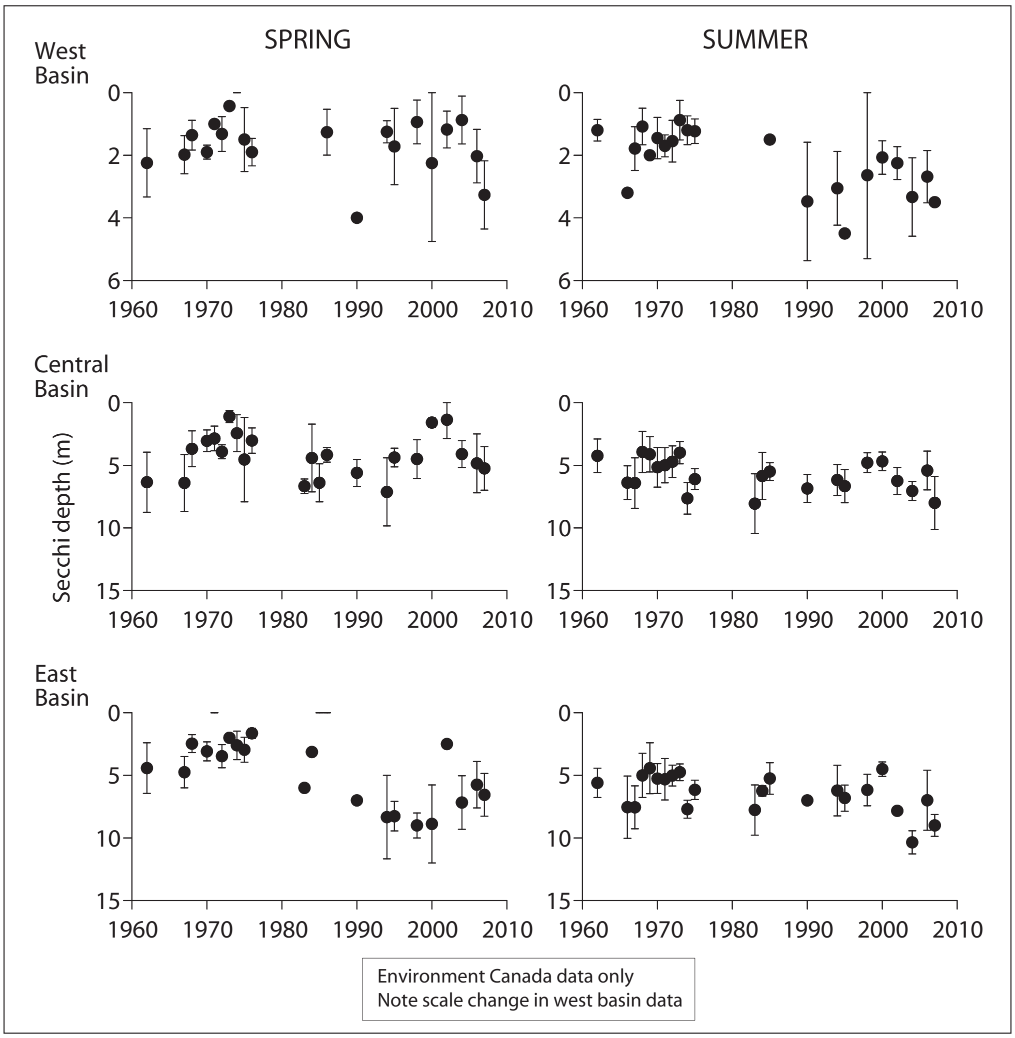

Figure 4. Mean Secchi depths in the west, central and east basins for the spring and summer periods.

Correlations between Total Phosphorus, Chlorophyll a and Secchi Depth

The classical relationship between chlorophyll (chl *a*) and total phosphorus in the offshore waters of Lake Erie is plotted in Figure 5 and a statistical summary of all the relationships is provided in Table 1. Significant relationships were observed in both the spring and summer seasons between chlorophyll and total phosphorus; Secchi depth and total phosphorus; and Secchi depth and chlorophyll. However, the amount of the variability explained was always lower in the spring relative to the summer periods.

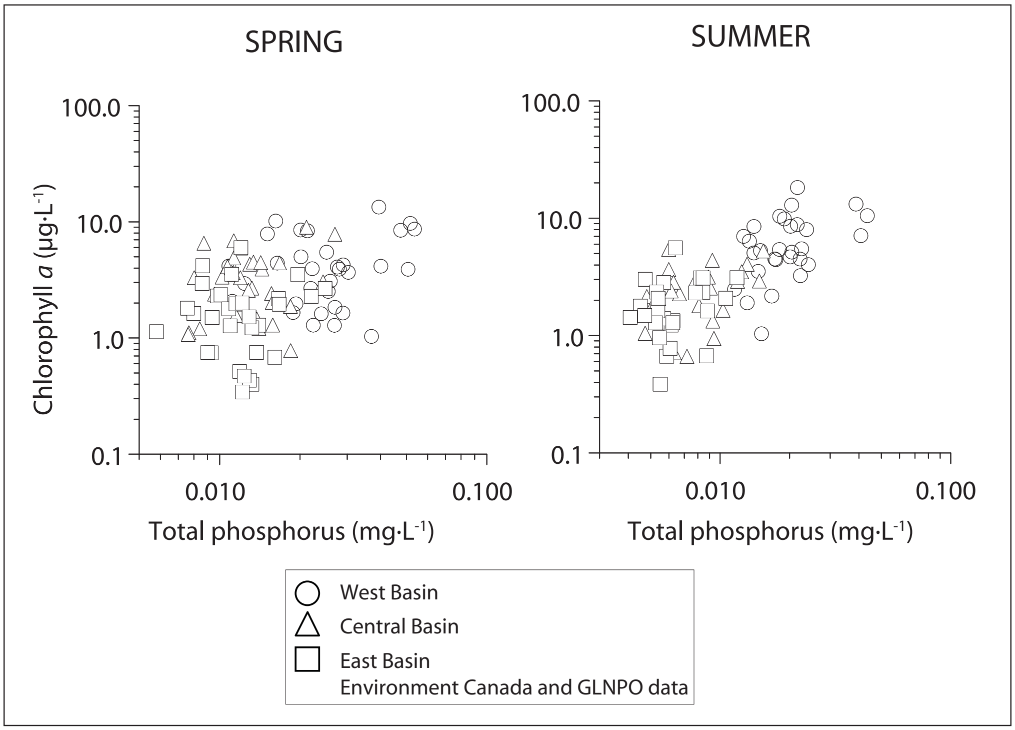

Figure 5. Chlorophyll *a* versus total phosphorus in the spring and summer seasons over the 40 year period of the data record. Values are arithmetic means. Both Environment Canada and GLNPO data are plotted here.

Table 1. Statistical summary of the correlations analysis between the three water quality variables chlorophyll *a* (chl *a*), total phosphorus (TP) and Secchi depth. A positive relationship indicates that both variables increase or decrease together, while a negative relationship indicates that as one variable increases, the other decreases, and vice versa.

Correlations	Season	Variability explained (%)	Significance level (p)	Relationship
Chl *a* *vs* TP	Spring	20	<0.005	+
	Summer	71	<0.001	+
Secchi *vs* TP	Spring	63	<0.001	-
	Summer	75	<0.001	-
Secchi *vs* Chl *a*	Spring	18	<0.005	-
	Summer	65	<0.001	-

During the spring period, higher sediment loads and the resuspension of lake sediment likely resulted in a higher delivery of particulate phosphorus (from soil erosion) to the water column. Particulate phosphorus is not readily available for algal uptake. The relatively good relationship between Secchi depth and total phosphorus and the relatively poor relationship between chlorophyll and total phosphorus during the spring supports this interpretation (Figure 5 and Table 1). Conversely, during the summer period, sediment loads and resuspension events are less frequent and total phosphorus concentrations contain more bioavailable phosphorus (mostly planktonic, e.g., free floating algae, bacteria, and other organisms). Consequently, the correlations between all three variables are much higher during the summer period (Table 1). Water clarity as indicated by Secchi depth is mainly related to chlorophyll in the summer. Water quality gradients from the west to the east basins were apparent in all three correlations, with poorer water quality indicators in the west basin (i.e., high total phosphorus, high chlorophyll and low Secchi depth) and better water quality indicators in the east basin (i.e., low total phosphorus, low chlorophyll and high Secchi depth). Overall, the correlations support previously expected phenomena related to phosphorus concentrations and seasonal weather patterns.

Despite all the environmental challenges that Lake Erie has faced over the last four decades, the basic tenet that total phosphorus concentration, driven by loading of bioavailable phosphorus, is a main determinate of algal populations holds true for offshore Lake Erie waters, even in the relatively shallow west basin. Other factors, such as light availability, will undoubtedly inject some variability in this relationship; however, the underlying assumptions of reducing total phosphorus inputs that helped to shape the Great Lakes Water Quality Agreement's efforts to restore the health of Lake Erie remain valid.

De-coupled Phosphorus and Chlorophyll – The Dreissenid Effect

A number of references (for example, Nicholls et al. 1999 a, b, 2001 water intake studies) have shown that grazing by Dreissenid mussels can decrease algal populations so much that the traditional relationship between chlorophyll and phosphorus appears to break down. Others suggest a mysterious "de-coupling" of phosphorus from chlorophyll. This suggestion tends to impart uncertainty in the minds of some people who might make decisions on controlling phosphorus. The phenomenon has been reported in a few shallow areas where the mussels can access and graze algae from much of the water column. Theoretically, there should be less effect in deeper offshore waters.

Charlton (2004) plotted offshore chlorophyll to total phosphorus ratios for the three basins for data up to 2001. There did not seem to be clear support for an offshore change in the ratio. Addition of more recent data up to 2007 does not alter the impression of no clear change due to mussels offshore. It should be remembered that various algal species may have more or less chlorophyll, which can affect the chlorophyll to phosphorus ratio at any time depending on species dominance. As indicated by Table 1 and Figure 5, there is a strong relationship offshore between phosphorus and chlorophyll that can be depended on to help manage the lake.

Dissolved Oxygen

A full discussion of nutrient effects on dissolved oxygen is beyond the scope of this report. The GLWQA goal to eliminate hypoxia through nutrient controls has not been achieved after 35 years. Nevertheless, the goal was in the correct direction and there is now a great deal more understanding of the phenomenon. Burns et al. (2005) found that central basin oxygen depletion rates, after compensation for variable physical factors, were indeed affected by phosphorus loading, although perhaps not as strongly as originally expected. In addition, this analysis indicated temperature increases consistent with global warming could exacerbate the oxygen depletion phenomenon. Clearly, nutrient controls have stabilized and decreased somewhat

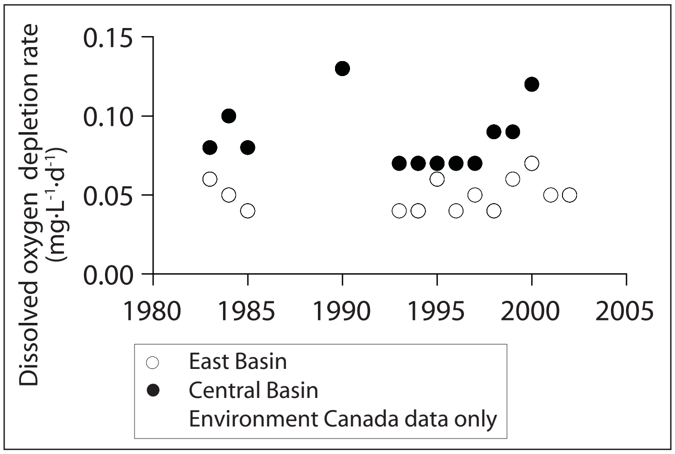

Figure 6. Dissolved oxygen depletion rate in the hypolimnion of the east and central basins as a function of time.

the severity of oxygen depletion in the central basin hypolimnion. Increases in nutrient load or increases in lake productivity for any reason would exacerbate the dissolved oxygen situation.

The low oxygen conditions experienced in the hypolimnion of the central basin in late summer are not unique. The east basin and the other lakes exhibit oxygen depletion according to a continuum of effects due to nutrients, productivity, temperature, and hypolimnion thickness (Charlton 1980 a, b). The east basin tends to have a lower oxygen depletion rate with less variability caused by physical factors such as inter annual differences in hypolimnion thickness than the central basin (Figure 6) and, thus, may be a good indicator of lake changes.

2.2 Offshore Phosphorus Effects: Algae

Offshore algal populations are once again warranting concern about phosphorus loading to and concentrations in Lake Erie. As Table 2 shows, there are increasing reports of cyanobacteria or blue-green algae species that can form blooms containing dangerous natural toxins.

Phosphorus is usually the nutrient that stimulates algal growth. Consequently, problems of too much algae occur in areas of high phosphorus concentrations. Algal populations are generally acceptable in the offshore areas of the central and east basins of the lake, although there are concerns about changing species composition and algal concentrations above the goal in the central basin. The western basin has the most algae problems, consistent with the elevated phosphorus concentrations there. Phosphorus continues to be the limiting nutrient. There is enough nitrogen present so that it is not usually limiting algae, although almost any nutrient can be shown to appear limiting to algae on a given day. Nitrogen warrants watching as the ecological implications of ongoing increases are unknown.

Trends in algal populations were assessed by Conroy et al. (2005). They found that following nutrient controls in the 1970s, algal populations decreased. From the mid 80s to the mid 90s, phytoplankton biomass increased in the eastern basin in spring and in all the three basins in summer. Chlorophyll decreased in the central basin in spring and in the western basin in summer. From 1989-93 to 1996-2002, Cyanobacteria (potentially toxic blue-green algae) biomass increased in summer in all three basins.

Potential reasons for recent increases in algae abound, but the change in lake metabolism caused by Dreissenid mussels is likely important. Nutrients in the form of algae and bacteria are now subject to more mineralization by the mussels and their attendant organisms. Thus, phosphorus has a greater chance to be re-cycled and re-used before permanent burial in the lake.

The most disturbing algal phenomena are the blue-green algae blooms in the west basin but also noted elsewhere in the lake and around the world. These are called Harmful Algae Blooms (HABs) because some of them are potentially toxic. One of the main species, *Microcystis*, can be found anywhere in the lake but problematic numbers are usually restricted to the west basin. Small concentrations of *Microcystis* have the ability to float under quiescent conditions and cause obnoxious visible scums. This effect has been seen in the west basin and even in the east basin at Long Point Bay (S. Watson, Environment Canada, personal communication). Although the biomass distributed through the water column may be inconsequential, the floating scums concentrate the algae, causing potential toxic danger to humans and wildlife. Increased phosphorus concentrations increase the probability of blue-green algal growth and, thus, increase the risk of HABs (Downing et al. 2001). Figure 2 is based on data from 99 lakes, and shows that there is a strong global relationship between total phosphorus concentration and the probability of blue-green algae dominance. Although there is considerable variability, the between lake data indicate that total phosphorus concentrations above 100 ug/L are associated with a 50% risk of cyanobacteria dominant growth (Figure 2). As will be shown in the section on river loads, some inflows to Lake Erie contain total phosphorus concentrations high enough to assure blue-green algae dominance.

Table 2. A summary of the history of algal blooms in western Lake Erie. (www.epa.gov/med/grosseile_site/indicators/algae-blooms.html U.S. EPA)

Decade	Algal blooms
1960s	By the mid- to late-1960s, seasonal algal blooms were reported over the entire portion of the western basin of Lake Erie. Mats of algae washed ashore, fouling beaches. Newspaper headlines announced, "Lake Erie Is Dead," when actually the lake was more alive than ever. It was undergoing cultural eutrophication, aging caused by a high influx of nutrients (primarily phosphorus) due to human activities. The blue-green algal blooms were comprised of *Anabaena*, *Aphanisomenon*, and *Microcystis*. In addition, massive growths of the attached green alga *Cladophora* were reported as prevalent in the western basin.
1970s	Algal blooms occurred annually, predominated by *Aphanizomenon flos-aquae*, but were reported as decreasing in intensity and number during the 1970s.
1980s	No massive algal blooms reported during early 1980s. Algal blooms, when present, were predominated by *Aphanizomenon flos-aquae*. Zebra and quagga mussels arrived in mid- to late-1980s.
1990s	Large algal blooms of *Microcystis* were reported in western Lake Erie in 1995 and 1998. During September 1995, an algal bloom resembling a thick slick of grass-green paint extended over the entire surface of the western basin.
2000s	During the 2000s, blooms of toxic *Microcystis* were reported as common in the western basin. In August 2003, a massive bloom of the cyanobacteria *Microsystis aetuginosa* formed in western Lake Erie and persisted for nearly a month. Surface scums of *Microcystis* containing high concentrations of the toxin microcystin washed ashore in Michigan and Ohio, resulting in foul-smelling, rotting, algal mats. Beaches and recreational boating areas were rendered unusable and sport fishing was adversely affected. The *Microcystis* bloom of 2003, perhaps the most severe in Lake Erie's recent history, was only the latest in a trend towards increasing frequency of *Microcystis* blooms in the last decade. The 2003 bloom was followed by smaller blooms in 2004 and 2005. *Microcystis* reappeared in 2006, but the extent of the bloom remains to be determined.

2.3 Nearshore Nutrient Effects: Algae

The nearshore forms a small part of the area of the lake but it is the area that the greatest numbers of citizens see and use for recreation, drinking water withdrawals, and waste disposal. Any definition of "nearshore" scientifically is controversial. For definition purposes the Lake Erie LaMP divided the nearshore into two areas: coastal margin and nearshore open-water. Coastal margin is defined as the shoreline, water column and substrate in embayments with water depths of 3 m or less. The nearshore open-water is defined as the water column and substrate with water depths between 3 m and 15 m (Johnson et al. 2007).

Flying over Lake Erie, one sees that the part of the nearshore adjacent to shore can be, temporarily, a visually distinctive zone as beach sediment is resuspended into the water by waves. This illustrates that, sometimes, the nearshore can be different than the offshore. With stronger winds and waves this turbid area may become larger, indicating more mixing with the offshore. Water movement is strongly influenced by friction of the water on the bottom in the "frictional boundary layer" up to 3 km from shore (Rao and Schwab 2007). Under calm conditions the offshore currents are attenuated; flow tends to be along the shore.

If there are inputs from shore, the nearshore can develop its own properties which can be subsequently homogenates with the offshore during a strong weather event. Thus, water quality studies of the nearshore are plagued by extreme variability which means they need more effort than surveys offshore. Much is yet to be learned about how nutrient sources such as rivers, urban runoff, groundwater, and sewage effluent dissipate in lakes (Rao and Schwab 2007). Howell and Hobson (2003) summarized a report on groundwater wells in nearby cottage areas. Many of the wells were contaminated by sewage indicators (MacViro Consultants 2002), which may mean that some nutrient load can come from the shore via groundwater. The sporadic nature of nearshore events makes it difficult to find evidence of small sources. Nevertheless, groundwater as a nutrient source needs more research to determine the potential significance. Nearshore habitats are also peculiar in that the energy of wave action generally tends to prohibit fine sediment accumulation. Thus, large areas of bedrock are present in some places such as the east basin, and large areas of soft sediments can be found in the central and western basins. Substrate distribution impacts algal and Dreissenid population distribution and abundance (Patterson et al. 2002).

Concerns were expressed for nearshore nutrient effects on excessive *Cladophora* accumulations by Howell (1998), Edsall and Charlton (1997), Charlton et al. (2000), and Howell and Hobson (2003). Typically, accumulations of the filamentous algae, *Cladophora*, on east basin shorelines decompose and cause an obnoxious smell and visual impairment of the waterfront, resulting in decreased enjoyment and declining property values. Lately, the attached algae, *Lyngbya*, have been found in the Maumee Bay area of the western basin. *Lyngbya* produce significant beach impairment as well as possible net fouling and taste and odour problems. Research is just beginning on this problem (S. Watson, Environment Canada, personal communication).

The east basin of Lake Erie seems to be the most affected, most likely due to a combination of rocky substrates and high available phosphorus. *Cladophora* has the unfortunate ability to store excess phosphorus when available and to maintain growth at times of phosphorus shortage. The timing of phosphorus delivery to the eastern basin may be exacerbating the *Cladophora* problem.

Research at the University of Waterloo and Ontario Ministry of the Environment beginning in 2002 has added greatly to knowledge of the problem. Algae can grow offshore up to a depth of several metres, depending on light conditions, which places large algal populations relatively close to shore. Sampling the water for evidence of nutrient stimulation is fraught with difficulties due to variable mixing and uptake by the algae. Nutrient update by algae can result in the waters where algae are found having nutrient concentrations similar to those in offshore waters (Howell and Hobson 2003). Research into *Cladophora* growth showed that the phosphorus contained in *Cladophora* biomass, despite abundant growth, was phosphorus limited. Local nutrient sources in the nearshore were linked to areas of higher *Cladophora* growth.

A series of papers have described recent research on *Cladophora* in the east basin: Higgins et al. (2005 a, b) and Higgins et al. (2006). Briefly, Higgins et al. (2005a) found that recent *Cladophora* biomass was similar to that in the pre-phosphorus control era. *Cladophora* seemed to store phosphorus early in the season and then, as water cleared, growth occurred and the tissue phosphorus declined to limiting values. *Cladophora* growth depressed the available soluble reactive phosphorus (SRP) nutrient in the nearshore relative to the offshore early in the season in May and June. Water clarity increases caused by Dreissenid filtering caused an increase in biomass by a factor of 1.3. Mass balance considerations showed that the growth of *Cladophora* biomass phosphorus was greater than the decline of phosphorus in nearshore waters. Therefore, the remainder was likely sourced from offshore waters, Dreissenid mussel products, and onshore loading/transport if there were any.

If the *Cladophora* problem populations are stimulated by Dreissenid mussels to a large extent, then one might conclude that further management attempts would be futile. However, the phosphorus comes from within the lake and there are external phosphorus loads to the lake that could be further controlled. But would phosphorus load reductions be effective? Some indication of the efficacy of load reductions would be desirable. To answer questions such as this one, further research was conducted on the development of a *Cladophora* Growth Model (CGM) (Higgins et al. 2005b) and its application (Higgins et al. 2006). A good summary of the modeling findings is contained in the abstract of Higgins et al. (2006):

> The CGM predicted that *Cladophora* growth was highly sensitive to spatial and temporal variations in soluble phosphorous concentration (SRP). Specifically the CGM predicted that:
> 1) site-to-site differences in SRP concentration resulted in a 2X difference in depth-integrated biomass;
> 2) maximum growth rates were strongly influenced by SRP concentrations during periods of rapid biomass accrual (mid-June to mid-July);
> 3) inter-annual differences in SRP concentration during the spring period (~ 1 μg/L) could result in up to a 3.5X difference in depth integrated biomass;
> 4) spatial variations in water clarity could result in a 2X difference in depth-integrated biomass between sites, with variations betweens sites occurring primarily between 2–6 m depth;
> 5) the mid-summer sloughing phenomenon likely resulted from self-shading by the algal canopy; and
> 6) the seasonal growth pattern of *Cladophora* was strongly regulated by temperature.

Essentially, *Cladophora* growth was mostly phosphorus limited – there was no large excess of phosphorus in the water except perhaps around the mouth of the Grand River. *Cladophora* responded to spatial and temporal differences in ambient SRP. This means that the variations of a few ug/L of phosphorus are important to the *Cladophora* problem, and could be effected by better phosphorus load controls. Therefore, the authors concluded that "managing phosphorus will be effective at controlling *Cladophora* blooms in eastern Lake Erie. The wide-spread *Cladophora* blooms in eastern Lake Erie were not necessarily associated with point source nutrient discharges and were considered governed by basin-wide P availability (Higgins et al. 2005b). Further research efforts should focus on gaining a more complete understanding of the phosphorus sources to the littoral zones, including the importance of Dreissenids in modifying the bioavailability of phosphorus."

Clearly, with the present low phosphorus concentrations and the limited ability of overall load reductions to affect the east basin (Figure 2), controlling the *Cladophora* problem will be difficult unless important onshore nutrient sources are responsible. There is evidence that *Cladophora* populations reach problematic proportions in areas remote from known nutrient inputs (Hecky et al. 2007). This further adds to the gloomy prognosis, given the information on hand. Conversely, the problem would be worsened if phosphorus concentrations were to increase.

2.4 Nearshore Nutrient Effects: Dreissenids & the Near-shore Shunt

Occasionally, very clear water was found over some rocky areas consistent with filtration by mussels attached to the bottom. Howell and Hobson (2003) noted the paradox of the occurrence of a nearshore algae problem despite generally low nutrient and planktonic algal concentrations offshore. They suggested three hypotheses: 1) basin-wide phosphorus concentrations are adequate for *Cladophora* growth, 2) alternatively, transient and wide-spread nutrient enrichment along the shoreline is responsible or, 3) phosphorus is made available as a result of biological-based nutrient enrichment in the *Cladophora* beds due to the trapping and release of nutrients by Dreissenid mussels. All three hypotheses have merit and their effects may occur together; and all three hypotheses can be mitigated through phosphorus reductions in the affected areas.

A number of concepts were brought together to form a picture of how the *Cladophora* problem is related to nutrients and Dreissenid mussels. The "nearshore phosphorus shunt" (Hecky et al. 2004) is thought to illustrate the change in nutrient movement direction and quantity caused by the mussels and how that impacts *Cladophora*.

If one visualizes a coral reef in the middle of the ocean we see biomass and diversity in the middle of vast areas of water that can be quite lacking in nutrients and algae, almost a biological desert. The food chain energy and nutrient flow on the reef is mainly derived by filtration of the depauperate ocean water passing by. The low concentrations of algae are filtered out and the nutrients become concentrated in the reef area, which allows the diverse food chain to exist. In the same way, Lake Erie Dreissenid mussels are thought to filter the water circulating nearshore and to concentrate the energy and nutrients in their population and waste products. The accumulating shells of the mussels provide a physical refuge for many species and a place where the mussels' faecal products can be held as food and to decompose. The faecal materials of the mussels are larger and denser than the particulates filtered from the water as food and, therefore, have a greater tendency to stay in the nearshore. The bedrock areas in the east basin are prime habitat for Dreissenid mussels. Unfortunately, the rock is also prime habitat for *Cladophora* attachment. The mussels are thought to stimulate the *Cladophora* by excretion of soluble nutrients, decomposition of faeces releasing nutrients and the same activities by other organisms facilitated by the energy availability of the faeces. Further, the mussels can, on average, cause clearer water that allows *Cladophora* to receive enough light to grow in deeper water.

There are other potential lake-wide effects of the nearshore phosphorus shunt, such as a shift to transport along the shore toward the Niagara River instead of via open lake water. Periodically, storms may disrupt the nearshore, resulting in mobilization of relatively large amounts of nutrients sequestered by the mussels there. These sporadic effects may be very difficult to quantify (if, indeed, they need to be quantified) and are not likely subject to any sort of lake management. The authors of the "nearshore phosphorus shunt" stated, however, that, given the change in nutrient flow in the nearshore and the obnoxious *Cladophora* problem that results, the nutrient load to the lake should not be allowed to increase. Instead consideration should be given to decreasing the nutrient load under the new biological conditions. Evidence to support this comes from research on in-situ *Cladophora* populations (discussed above).

2.5 Tributary Nutrient Effects: Loadings

Phosphorus loads are considered to come from either point or non-point sources. Point sources represent discharges from industry or municipal sewage systems. Point source flows are easily measured and sampled; therefore, the loads and concentrations from them are reasonably well monitored. Non-point sources include runoff from agricultural fields and urban and natural areas, as well as from combined sewer overflows, atmospheric sources and riverbanks themselves. The sporadic nature of non-point flow means they are much more difficult to monitor. Both point and non-point loads can be deleterious. Land runoff non-point loads are more likely to contain a particulate fraction with little bioavailability or stimulatory effect on algae, whereas municipal sewage system point loads are more likely to contain a soluble fraction that is mostly bioavailable and that has a stimulatory effect on algal growth (Baker et al. 2006; Withers and Jarvie 2008).

Lake Erie has a continuous total phosphorus load record from 1967 through 2002. Less consistent monitoring data exist for 2003 to the present. Estimates continue to be made with less confidence due to the gaps in the data. After an exponential drop in total phosphorus load, due largely to sewage treatment plants coming into compliance with a 1 mg/L effluent standard, the target load of 11,000 tonnes/year was first achieved in 1981 (Figure 7). During the period 1982 – 2005, the target has been achieved in 15 of the 22 years (Dolan et al. 2007). The IJC's review of the Great Lakes Water Quality Agreement concluded that although there was a great benefit from the phosphorus load restrictions, the Agreement's water quality objectives have not consistently been met in the western and central basins (DePinto et al. 2007).

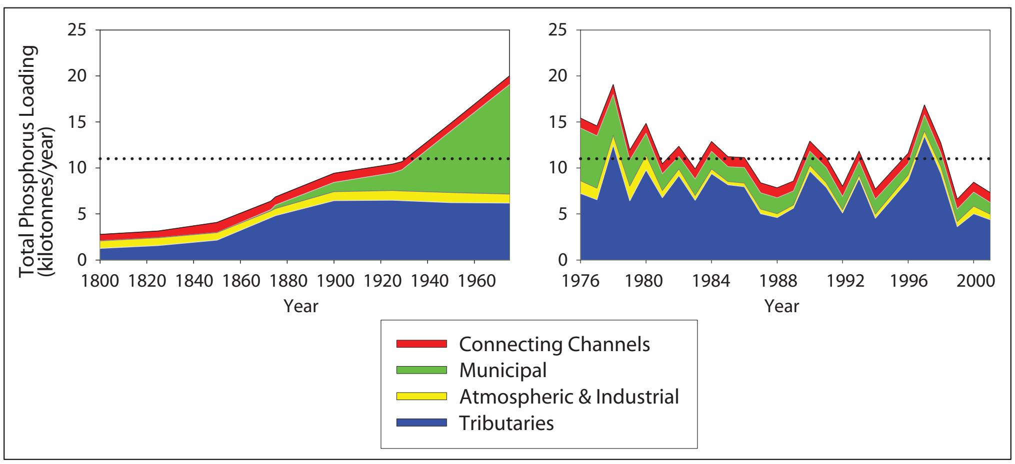

Figure 7. Total phosphorus loading to Lake Erie by source 1800-2002. (Dolan et al. 2007)

The importance of each load depends on the concentration, amount, bioavailability, and site of discharge. A breakdown of the load categories indicates that variability in the load occurs as a result of hydrology in the tributaries during a given year, with loads exceeding the target occurring in years with relatively high precipitation and runoff. Runoff in high flow years may contain a higher proportion of eroded soil with low bioavailabilty and/or flows from Lake Huron with low total phosphorus concentration. As sewage plants were improved, a 50% decrease in total lake load resulted. There has also been a reduction (30-60% or about 100,000 tonnes) in P fertilizer sales in Ontario, Ohio and Michigan from 1980 to 2006 which may also contribute to this result (Bast et al. 2009; Eric Van Bochove, personal communication). Loading estimates between 1998 and 2005 show that non-point loading sources averaged 60.8% (Baker et al. 2008) (Figures 7-9). The western basin watershed is 40.4% of the lake's basin and is responsible for approximately 48% of the total phosphorus loads, 71% of the non-point loads and 20% of the points to the lake (Figure 9). Both types of sources (point and non-point) remain important but the effects of the tributaries have become more apparent. Larger rivers, usually containing a mixture of agricultural runoff, urban runoff, and municipal treated sewage plus combined sewage overflows, remain a concern. Remediation of tributary sources would likely be more effective in improving lake quality today than in the past. A key point to remember is that the data do not indicate an increase in loading that might cause *Cladophora* problems or algal blooms. Rather, it seems likely the in-lake recycling of phosphorus may have changed and/or some local concentrations were never reduced enough to begin with.

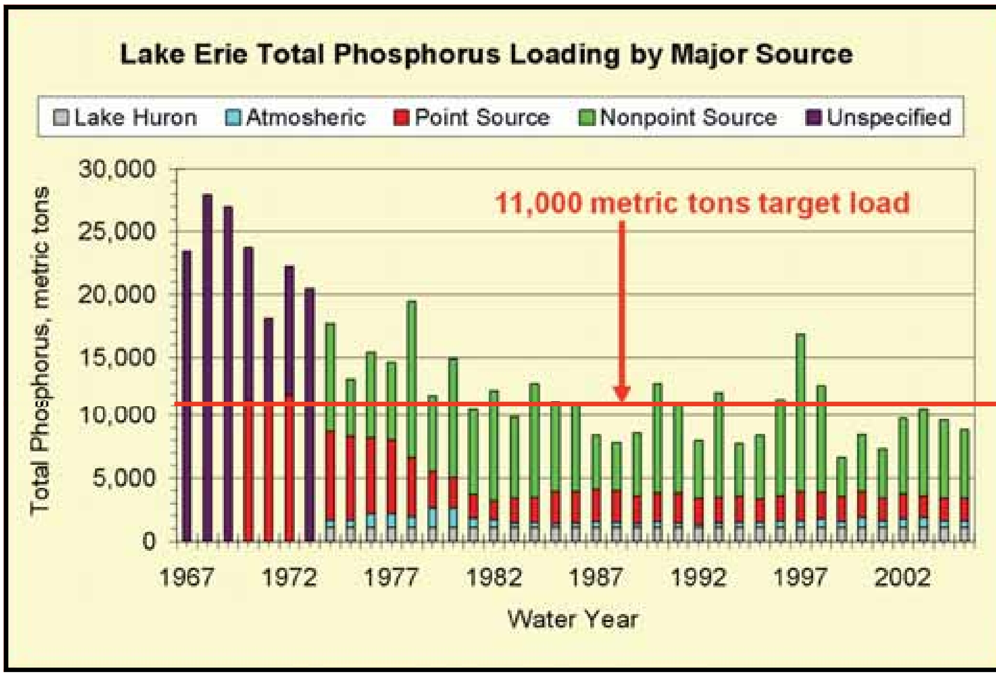

Figure 8. Long term trends in total phosphorus loading to Lake Erie 1967-2005. (Baker et al. 2009)

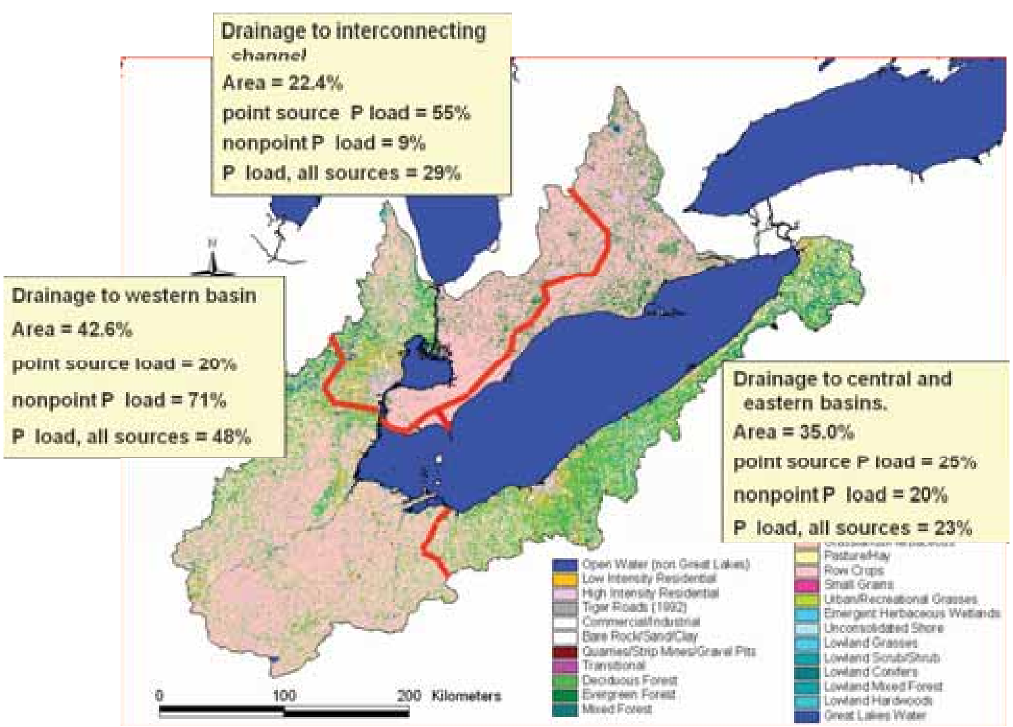

Figure 9. Total phosphorus loading to Lake Erie's basins by source. (Baker et al. 2009)

Detroit River

At one time, loads in the Detroit River were measured with a series of samples across the various channels at different depths. Estimations of flow and concentrations could then be used to calculate a total load. Environment Canada attempted a pilot study in 2006 to determine methods and the level of effort needed to re-visit load measurements in the river. A series of samples were collected and summarized in Figure 10. This study found that total phosphorus concentrations in the Trenton Channel were variable with many concentrations higher than 15 ug/L. Some concentrations were in the range of 20 to 40 ug/L, which is high enough to cause eutrophication in the lake. The study also illustrated that a large portion of the flow has total phosphorus concentrations of 10 ug/L or less. These lower concentration flows and their loads are actually diluting total phosphorus concentrations in the west basin, which is a good thing. At a flow of 200,000 ft^3/s or 5600 m^3/s and a concentration of 10 ug/L total phosphorus, the flow in the Detroit River represents about 16% (1800 tonnes) of the total phosphorus target load (11,000 tonnes) to the lake. This low concentration water sourced from the upper Great Lakes is not likely controllable, nor is there any need. In periods when increased hydraulic load appears to increase the total phosphorus load, some of that increase (e.g., in the Detroit River) is simply low concentration water that would not cause any nutrient related damage.

The high total phosphorus concentrations in the Trenton Channel must mix somewhat with the low total phosphorus water in the mouth of the Detroit River. While this would lessen damage, there is evidence that this mixing may be quite incomplete. In 1970 there was a spill of salt in the Rouge River, a U.S. tributary of the Detroit River. Salt from that spill was detected eight days later at the City of Toledo water intake, located just east of Maumee Bay about 25 miles or 42 km from the mouth of the Detroit River (Kovacik 1972). Clearly, the salt spill would be expected to follow the bank of the Detroit River, but the evidence suggests that nutrient loads associated with the higher concentrations of total phosphorus at the edge of the Trenton Channel are not dissipating entirely in the open waters of the west basin. Instead, there seems to be a possibility that some of the flow from the Trenton Channel via the Detroit River could exacerbate the phosphorus overload effects experienced in the Maumee River area.

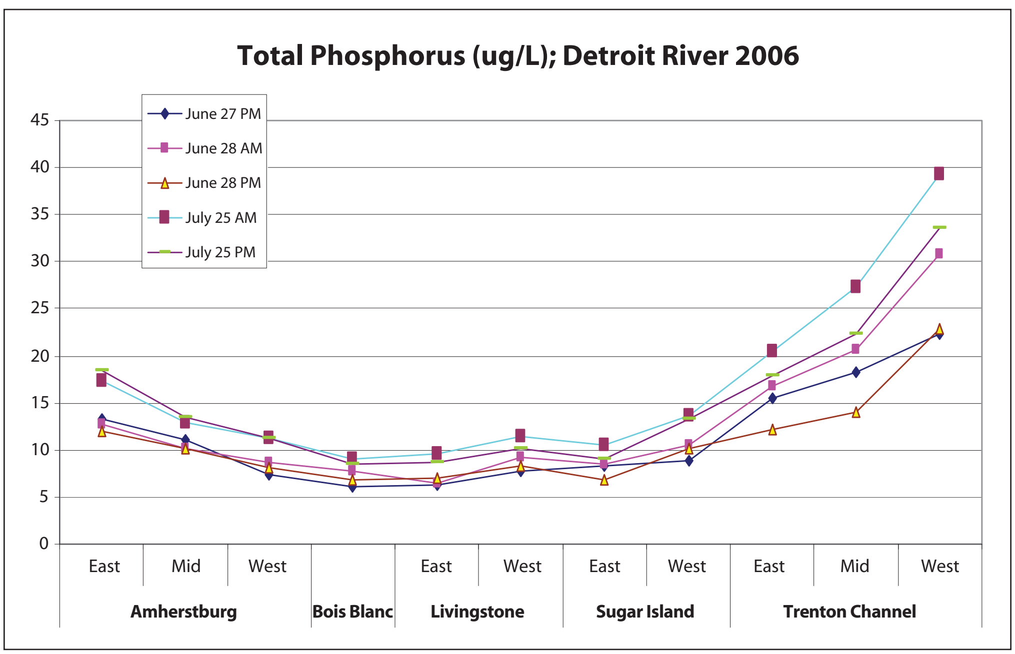

Figure 10. Concentration of phosphorus in the Detroit River, transect from east to west.

Maumee River

Monitoring of Ohio rivers by Drs. P. Richards, D. Baker and colleagues at Heidelberg College has provided invaluable insight into why the lake is experiencing algae problems in the west basin. Average phosphorus loads from the Maumee River upstream of Toledo have decreased about 30% since the mid 1970s. Recent loads have been on the order of 1800 tonnes per year which is roughly equivalent to the background load of the Detroit River. If the Detroit River background is subtracted from the allowable 11,000 tonnes, the Maumee River represents about 20% of the deleterious phosphorus load to Lake Erie. The concentration of total phosphorus in the Maumee River has decreased (Figure 11) as a result mainly of programs promoting cultivation techniques such as “no-till” or “conservation tillage” designed to decrease soil erosion. Unfortunately, the concentrations are still well above those required to cause algae problems (Figure 1). Some fraction of the total load will be natural phosphorus minerals and phosphorus adsorbed to iron and aluminium oxides that have little bioavailability, but the overall concentration of phosphorus is almost always associated with an excessive algae problem. Even dissolved reactive phosphorus, the most available form, is present in very high concentrations (Figure 12). Biologically, these concentrations are of great concern. Moreover, the dissolved fraction seems to have increased lately, which corresponds with changes in agricultural practices such as no-till. The well known blue-green algae blooms and the recent shoreline accumulations of obnoxious *Plectonema* are two symptoms of the excessive phosphorus concentrations.

> Algae respond to phosphorus concentration, not necessarily load. Only loads at concentrations higher than a desired in-lake concentration will have a deleterious effect on the lake. Thus, a phosphorus load from Lake Huron via the Detroit River at a low concentration will not be damaging, whereas the high concentration load of phosphorus in, for example, the Maumee River, will be damaging.

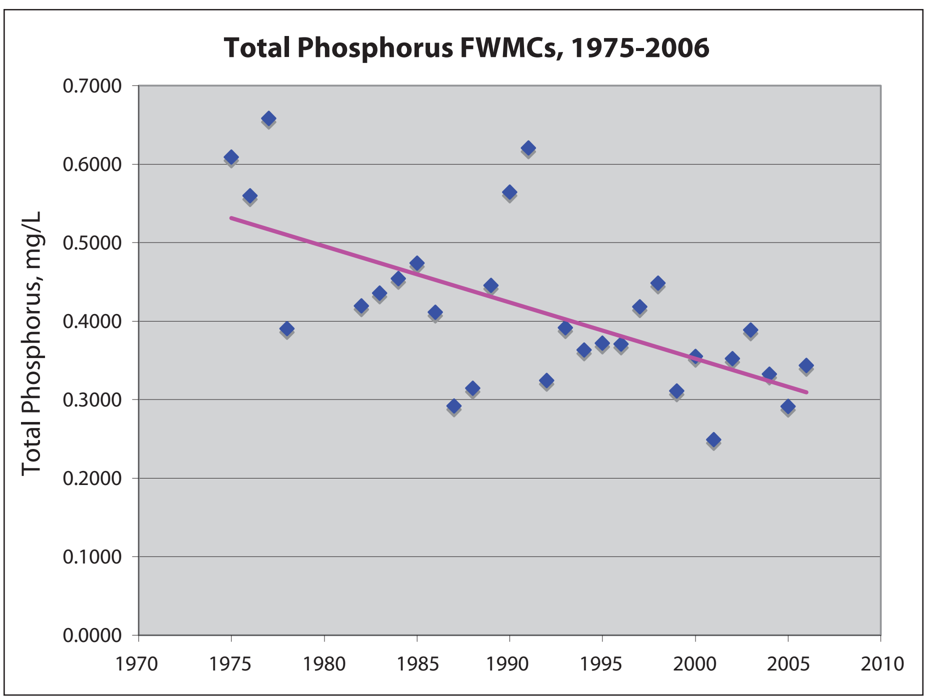

Figure 11. Trend in total phosphorus concentrations in the Maumee River. (Dr. P. Richards, Heidelberg College)

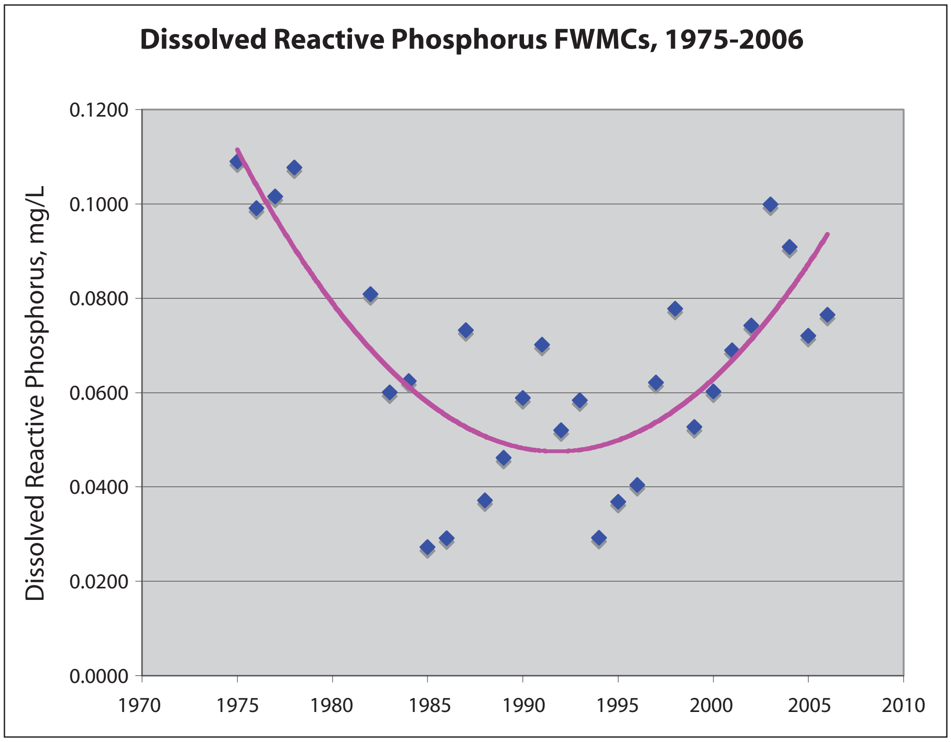

Figure 12. Trend in dissolved reactive phosphorus in the Maumee River. (Dr. P. Richards, Heidelberg College)

Sandusky River

Total phosphorus properties of the Sandusky River appear more or less similar to those of the Maumee River. It is perhaps not surprising that an invading cyanobacterium, *Cylindospermopsis*, has become established in Sandusky Bay (Conroy 2007). Total phosphorus concentrations were 30 to 150 ug/L and up to about 45 ug soluble reactive phosphorus/L – more than enough to stimulate an algal bloom. Again, this alga is capable of generating dangerous toxins.

Ontario Rivers

Most Canadian streams and rivers contain total phosphorus concentrations higher than the Provincial water quality objective of 30 ug/L (Ontario Ministry of Environment and Energy 1994). The objective of 30 ug/L is based on the threshold for deleterious in-stream effects. There is less water quality data (both concentration and flows) available for Ontario tributaries than for U.S. (especially Ohio) tributaries.

The Grand River is the only large river that drains directly to Lake Erie (eastern basin). The Sydenham and Thames rivers drain to the western basin of Lake Erie via Lake St. Clair and the Detroit River. The nutrient effects of the Sydenham and Thames rivers would be included in the assessment of the Detroit River. The remaining tributaries tend to be small with limited local effects along the nearshore. Some effects such as blue-green algae may be occurring in inner Long Point Bay. Figure 13 shows the difference between Grand River water and offshore water of the east basin. The river plume can be detected up and down the coast for a distance of 12 km and up to 3 km offshore, depending on weather. Sources such as these rivers and creeks can contribute to higher nutrient concentrations nearshore but their effect, if any, on *Cladophora* is not clear.

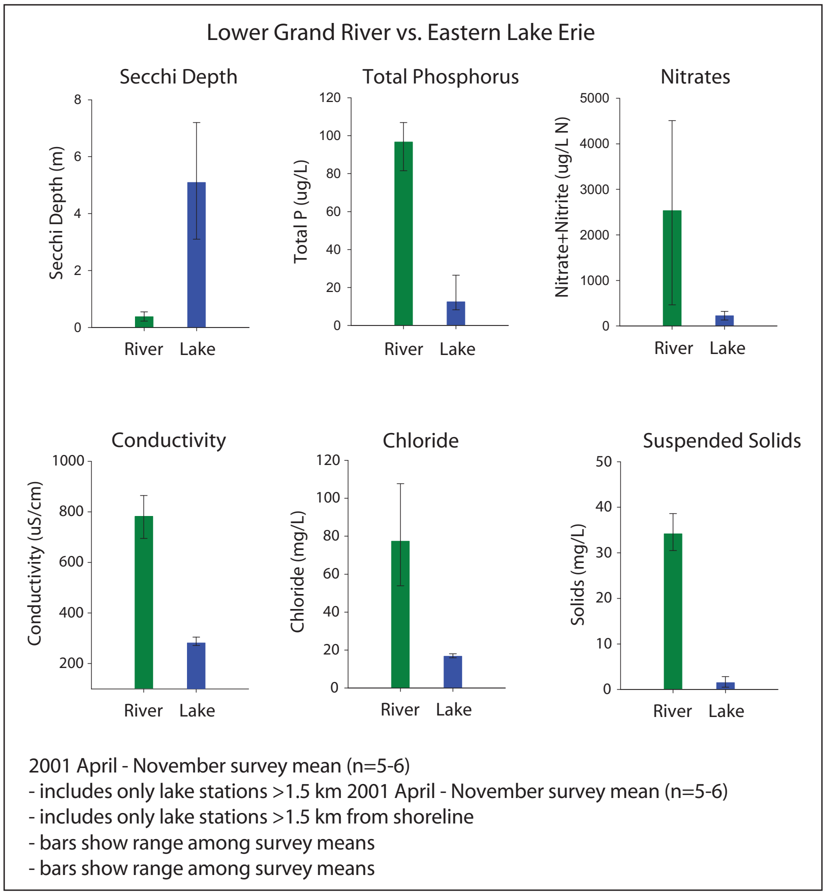

Figure 13. Chemical constituents of the Grand River in Ontario are very different than nearby offshore water of the east basin; for example, total phosphorus is elevated by a factor of 10.

Tributary Summary

Although there may have been some success with erosion control to control particulate phosphorus in, for example, the Maumee River, the concentrations of phosphorus in many rivers are still too high. Watersheds of most rivers, except the Detroit, are used mainly for agricultural production. Agricultural practices do not remain static and a great deal of effort is likely needed to re-evaluate what the best practices are and to get them adopted in the right locations. The local and far-field damage associated with the Maumee River, for example, cannot be addressed by load mitigation elsewhere. Specific measures will be needed in the rivers with the highest total phosphorus concentrations.

2.6 Land-use Nutrient Effects: Non-point Sources

A clue as to the cause of non-point loads may be the accumulation of phosphorus in soils (Figure 14). Phosphorus has been increasing in agricultural soils in Ohio. Fortunately the trend to increasing soil phosphorus seems to have levelled off in Ohio (Figure 14). Phosphorus export is influenced by soil concentration, which is slow to be reduced, and thus can have a long lived eutrophication influence on lakes (Carpenter 2005). Stabilizing and lowering soil phosphorus where levels are beyond agronomic requirements would seem necessary for the health of Lake Erie.

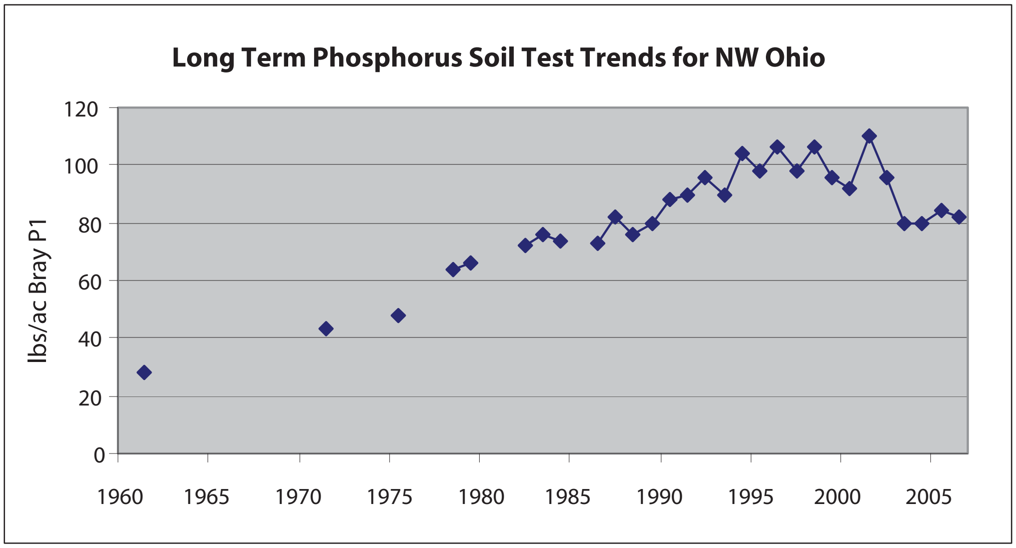

Figure 14. Long term increase of soil phosphorus in NW Ohio. (Dr. P. Richards, Heidelberg College)

Other factors, in addition to soil phosphorus levels, can influence or increase the risk of soluble reactive phosphorus loads from agricultural watersheds. Some of these factors appear to be occurring in the Maumee River in Ohio and may be occurring elsewhere. One is stratification of the phosphorus in the soil, which occurs in no-tillage systems. Higher concentrations of phosphorus accumulate at the surface, because there is no mixing of the surface soil and residues in no-tillage as there is with conventional or reduced tillage. If phosphorus stratification is present, a standard soil phosphorus test (average of the top 6-8 inches) will be misleading with respect to the potential for loss of soluble reactive phosphorus from the surface layer. Another factor is farmers altering the timing of their fertilizer applications to the fall and winter, sometimes on frozen ground, rather than spring, and applying fertilizer on the surface without incorporation into the soil. It is also common to apply two to three years' worth of crops' phosphorus requirements in one year's application, typically in the corn year of the rotation, so trips across a field can be optimized, rather than once each year as appropriate for that year's crop. This leaves residual phosphorus in the field for subsequent crops but also increases the phosphorus available for loss initially. These behaviours all increase the risk of loss of phosphorus before it ever equilibrates with the soil (P. Richards, Heidelberg College, personal communication). Also, different fertilizing philosophies and thus recommendations occur around the basin. Some jurisdictions promote maintenance or replacement of soil phosphorus levels with fertilizer, while others promote in-year crop response to determine levels of phosphorus additions. Further research is needed to find out how to balance the benefits of no-till for particulate/sediment control with dissolved reactive phosphorus losses and how to gain greater adoption of practices to control loads and concentrations of both particulate and dissolved phosphorus.

One source of phosphorus from agricultural land that has not had a lot of investigation is loadings of phosphorus from subsurface drainage systems. Agricultural drainage systems are designed to remove excess water (above field capacity) from the crop root zone to increase the uptake of available water and nutrients, to reduce the likelihood of crop damage, to improve plant hardiness by improving the root system, and to improve opportunities for timely field operations. Field tile drains and municipal drains that make up agricultural drainage systems can alter the peak and duration of flows in streams through either decreased overland flow of excess water, or increased removal of subsurface excess water, depending on the landscape in which they are installed. However, the tile drainage water may contain high concentrations of nutrients (dissolved phosphorus > 100 ug/L) (T.Q. Zhang, Agriculture and Agri-Food Canada, personal communication). There is increasing literature and interest in "capturing" this excess water, either with controlled tile drainage/sub-irrigation systems in which the water table level is controlled or in offline pond/reservoirs where reserved drainage water is used to irrigate crops, resulting in higher yield and less water pollution (Drury et al. 2001; Tan et al. 2003). The geographic area of the Lake Erie basin where water table management can occur is limited to specific biophysical conditions but is supported by cost share programs in Ontario.

There could also be more research and investigation of the use of end-of-tile bioreactors that transform redox sensitive contaminants (such as nitrate) for their effectiveness for phosphorus removal. Dispersion sandwich and other types of bio-reactors have been developed for runoff, septic system and wastewater treatment applications (Will Robertson, University of Waterloo, pers. comm.; also papers by D. Blowes, C. Ptacek Uni of Waterloo; Craig Merkeley, UTRCA, pers. comm.).

2.7 In-lake Nutrient Effects: How Lakes Clean Themselves

As can be seen in this report, some of the water flowing into Lake Erie often has a much higher concentration of phosphorus than the offshore lake water. How can the offshore water be so different than the water coming in? There are two explanations. The first is that the large volume of inflow in the Detroit River containing little phosphorus eventually mixes with and dilutes some of the high concentration sources. The second is that nutrients are taken up by algae and other organisms. These organisms eventually die and gravity takes them to the bottom. The proportion that remains in the sediment depends on depth but even the shallow west basin has considerable retention. Before nutrients are permanently buried, however, they can be re-cycled back into the water by algal decomposition many times. The probability of re-cycling is highest in shallow water. Thus, bodies of water such as Lake Ontario's Bay of Quinte and Lake Erie's west basin are more sensitive to nutrient additions than deeper basins. A question that should be answered with research, monitoring, and modeling is whether the basin retention characteristics have changed due to alien species and whether this impacts on current or future management strategies.

Sediment resuspension and sediment regeneration of phosphorus are two other processes that interact with nutrients in lakes. The west and central basins of Lake Erie are shallow enough to have wave driven sediment resuspension. This is seen as increasing turbidity with higher wind speeds in fall, winter and spring. In a 1979 sediment trap study, Charlton and Lean (1987) found that resuspension events even in summer seemed to re-work the upper sediment constantly. Resuspension events in the fall resulted in distinct layers in the traps. The sediment contains unavailable apatite mineral from shoreline erosion along with more bioavailable phosphorus forms that may be available to algae. This accounts for the greater amount of variability in spring water quality parameter correlations. Resuspension makes it possible for particles to move towards deeper areas for permanent burial, or towards the mouth of the Niagara River, thereby causing a loss of phosphorus from the lake (Charlton and Lean 1987; Hawley and Eadie 2007).

Sediment regeneration of phosphorus happens aerobically as in the decomposition mentioned above. This process happens in summer during periods of stagnation in the west basin, and occasionally near the end of summer in the cooler lower layer (hypolimnion) in the central basin, which results in it becoming anoxic. This regeneration releases soluble phosphorus that was weakly bound to clays. The sediment to phosphorus bond is sensitive to redox potential which responds to oxygen concentration; this explains how this phosphorus stays in the sediment through most of the year. Sediment regeneration phenomena are incorporated into observations of ambient phosphorus in lakes and do not represent a new load or a new source of phosphorus. Sediment phosphorus re-cycling can delay the recovery of lakes but when the re-cycling occurs the phosphorus inexorably moves towards permanent storage or to the outflow, so the net long term effect is to clean the lake.

3.0 Discussion

The Lake Erie LaMP Nutrient Management Ecosystem Objective is not very prescriptive or exclusionary. There is a general recognition, however, that watershed conditions are important to their tributaries and in their effect on the lake. Although nitrogen is an important nutrient with high anthropogenic loads, this report deals mostly with phosphorus for a number of reasons:

- decreased phosphorus loads have already proven to be effective in reversing and controlling eutrophication in Lake Erie,
- the control techniques for sewage phosphorus are well known and affordable while those for nitrogen are more difficult and expensive, and
- phosphorus is generally thought to be the main algae controlling/stimulating nutrient although different nutrients can appear to be limiting depending on when, where, and how an experiment is conducted.

Nitrogen has increased in the Great Lakes since phosphorus controls were introduced, due to increased nitrogen discharges from STPs and tributaries, and decreased demand for nitrogen in the water due to phosphorus controls. Despite the increase in nitrogen, phosphorus reductions have controlled algae in Lake Erie in the past. Nitrogen increases, however, are worth watching even if the ecological significance is not apparent now.

3.1 Information Gaps

Lake Erie is changing, yet, as resource managers, our abilities to improve Lake Erie are limited to a short list of fairly gross potential actions or "levers" to control phosphorus, improve tributary habitat, regulate fisheries, regulate industrial contamination, etc. The challenge for the LaMP is to determine what research and monitoring is needed to address the gaps in our understanding of nutrients in order to provide information at a level of detail likely to be used or required in decision-making leading to management actions.

The Lake Erie LaMP Nutrient Management Ecosystem Objective calls for a moderate reduction of phosphorus load and concentrations in order to limit local and regional excessive nutrient effects and to improve habitats. Therefore, the most important information gaps may be where and how to effect the reductions in high priority areas such as highly polluted rivers.

Lake Erie LaMP Nutrient Management Ecosystem Objective

Strategic Objective

Nutrient levels are consistent with ecosystem goals (watershed- and basin-wide).

Tactical Objective

Nutrient inputs from both point and non-point sources are managed to ensure that ambient concentrations are within bounds of sustainable watershed management and consistent with the Lake Erie Vision.

Rationale

Current nutrient inputs are resulting in reduced use of beaches, changes in aquatic community structure, and increased algal blooms. It is important that all sources that contribute to the watershed nutrient load and, ultimately, to the basin load, be managed to limit local and regional impacts. Best management practices and point source controls need to be implemented with consideration of the ecological requirements for the maintenance or recovery of healthy aquatic communities in the watershed, the hydrologic cycle and water usage. In addition to phosphorus, other nutrients and their various forms, such as nitrates, also need to be included in assessments of watershed- and basin-wide impacts.

Lake Erie LaMP (www.epa.gov/glnpo/lamp/le_2008/index.html)

Since the Dreissenid mussel invasion in the late 1980s, more than 20 new alien species have been established. As the lake continues to react to the alien mussels each new species adds some more, yet to be determined, effects. Superimposed upon the alien species invasions is slow warming due to climate change (Burns et al. 2005). Thus, by the time research is able to develop solid information on a topic, the information is out of date because the lake keeps changing. This does not mean that research and monitoring should not be done. To the contrary, new information keeps the lake's changing status on display and the necessary research activities develop expertise needed to advise on and support decisions. Analysis, interpretation, and publication of the information are sometimes difficult, however, as agencies struggle with limited resources. Alien species and climate change alone can generate hundreds of information gaps or research topics.

To be useful to decisions for phosphorus management, the following monitoring and research is particularly needed:

- More consistent monitoring of tributary concentration and flows, especially in Ontario, to assist in determining tributary loads, concentrations and sources of nutrients to Lake Erie.
- More consistent monitoring of nearshore water quality to better relate to local effects of larger rivers and high concentration sources.
- Whole lake modeling frameworks such as the one being developed in the EcoFore Project to forecast lake management scenarios and outcomes that have improved basin retention coefficients and incorporate the nearshore (http://sitemaker.umich.edu/ecoforelake.erie/home).
- The role of groundwater with respect to nearshore algae problems and river nutrient concentrations. Better knowledge of groundwater inputs may help to refine expectations of improvements in the lake with regard to *Cladophora* and other algal problems.
- More knowledge of the phosphorus management and content of soils in the basin is needed to aid understanding of where and how to remediate agricultural phosphorus losses to water. Research is needed to find out how to balance the benefits of no-till for particulate/sediment control with dissolved reactive phosphorus losses and how to gain greater adoption of practices to control loads and concentrations of both particulate and dissolved phosphorus.
- Possible changes to the basin retention characteristics due to alien species and whether this impacts on current or future management strategies.
- Investigate concerns that agricultural and urban drainage systems may be altering the timing of water discharge and making too much water available too early in the growing year and not enough water later. New information on drainage systems may be able to address both the water supply and nutrient loss issues.

3.2 Mitigation Needs

Clearly, the problems discussed in this paper are not news and there has been much consideration of potential actions. Some improvement in phosphorus concentrations is needed if the occurrence of toxic algal blooms and the appearance of obnoxious species such as *Cylindrospermopsis* and *Plectonema* are to be reduced. We offer no judgement on whether or not local nutrient concentrations have increased – the problem is that they are too high in some areas and those areas tend to have inputs of fertilizers and sewage effluent and overflow.

The long term trend to increasing soil phosphorus, even though levelled off and reversing, is a sign that fertilizer applications may have to be further tailored to Lake Erie's health as well as to crop production. An information gap may be in the realm of socio-economics as ways must be found to bring about dramatic change in the agricultural industry. Our market driven economy externalizes many environmental costs and does not sufficiently compensate the farmer for the risks and expense of improved phosphorus management.

Acknowledging the beneficial work of many individuals, the industry overall may be understandably reticent to absorb costs for off-farm benefits that may accrue in Lake Erie. A system needs to be developed to overcome barriers to success. Such a system would recognize the economic, social, and ecological aspects of lake management (McLaughlin and Krantzberg 2006).

On the municipal side of phosphorus loads, the performance standards set for sewage plants that seemed so cutting edge in the 1970s, are now hardly world class. Sewage plants can achieve phosphorus emissions that are 1/10 or less of the concentration of 0.5 to 1 mg/L allowed in many municipalities as set originally by the GLWQA (see Appendix 2). Indeed, the Areas of Concern (AOC) program of the GLWQA resulted in advanced treatment at, for example, the Severn Sound and Hamilton Harbour RAP areas. Not every advance made in one municipality, however, is directly transferable to another depending on aspects such as physical facilities, whether or not there is a combined sewer system, and industrial inputs. Nevertheless, now would seem to be a good time to review the performance of sewage plants on the lake and to determine the potential for improvement.

> Substantial expenditures are involved in sewage treatment. The Detroit area sewage plant, one of the largest in North America, is in the middle of a 10 year, $4 billion capital improvement program that began in 2000. This work includes over $1 billion for controlling combined sewer overflows. (U.S. EPA)

The performance of the Detroit wastewater plant is of great interest. The annual monthly mean effluent phosphorus concentration for 2007 was 0.69 mg P/L (S. Kuplicki, Detroit Water and Sewage Dept., personal communication). Although this concentration is about 23 times the desired ambient concentration for the west basin water, no criticism is intended. Rather, this is presented as a way of demonstrating how sewage effluents can produce deleterious phosphorus concentrations in lakes. Fortunately, effluent diffuser technology is partially effective at ameliorating concentrations. Removing phosphorus from sewage has a cost. Operators are not in a position to invent their own standards and, thus, they perform according to standards handed down from higher authorities. The standards may have to call for less loading from sewage systems, especially in the west basin.

Another municipal load is contained in urban runoff. In some municipalities where this has been documented, the urban non-point runoff phosphorus load can be as large as the treated sewage effluent load. While on one hand taxpayers pay to remove phosphorus at sewage plants, on the other hand they spread lawn fertilizers containing phosphorus around the urban landscape. Some of that lawn fertilizer washes off and is directed via urban runoff to local water courses and on to Lake Erie untreated. Adoption by jurisdictions around the lake of no-phosphate lawn fertilizer, as has been done in Minnesota and Manitoba, would be a positive action.

Fisheries interests sometimes have expressed fears that further reductions of phosphorus loads would limit lake productivity too much and damage the fishery. The Great Lakes Fishery Commission (GLFC) has published goals that call for phosphorus in the range of 10 to 20 ug/L in the lake (Ryan et al. 2003). Water quality surveys by ship do not have the spatial and temporal resolution to determine a monthly and annual concentration. As Figure 2 shows, spring data for the west basin can be well above the GLFC's goals while summer conditions are more in the range, but what is a representative annual mean? Correlating phosphorus with the seasonal turbidity cycle (Binding et al. 2007) derived from remote sensing may offer a way to determine an annual mean as well as monitor it in the future. Lake Erie fisheries still benefit from higher than natural phosphorus loads and still continue to benefit after load reductions. The LaMP does not aspire to reverse phosphorus loads to whatever the natural state might have been. As well, some analyses indicate that the "concern that reduced primary productivity will necessarily compromise all valued fisheries resources seems unwarranted" (Ludsin et al. 2001). The authors do allude to a potential succession of species that would complicate fisheries management for a time. Nevertheless, if serious lake problems such as toxic algal blooms in the west basin (which can be a threat to the desirability of fish) are to be ameliorated, then phosphorus loads will have to decrease and expectations of the fishery may have to gradually adjust, although a major overall load reduction may not be needed. More study may be needed to determine the trade offs between the LaMP ecosystem goals and the GLFC goals and objectives for Lake Erie.

4.0 Future Directions & Recommendations

The majority of information on the Great Lakes has appeared since the early 1970s when monumental decisions were made to reduce phosphorus pollution. Much more has been learned about lake processes, fisheries and tributaries since that time. The large increase in the amount of information is fortunate because the LaMP needs to proceed with the implementation phase. Thus, there is a need to use the knowledge and expertise on hand in the context of multi-level government arrangements that determine how to achieve LaMP goals and then proceed on to success.

4.1 Considerations

The nutrient loads and concentrations causing algal problems outlined in this report are serious and require appropriate action. Improving the situation at the larger rivers and sewage plants may be a major undertaking in terms of engineering effort, planning, financing, construction, and methods development. Still, the same could be said for the situation in the early 1970s but the work was done.

Assembling all nutrient loading data was beyond the scope of this report but would be good to do in order to check for changes in the situation, especially with regards to phosphorus. Habitat improvements in smaller tributaries, however, could be driven by local conditions and the need for improvements in, for example, turbidity and erratic flows, not necessarily by phosphorus per se. Thus, the costs of measurements and data assembly should be weighed against their value in terms of decision making.

The worst problems are largely regional, such as *Cladophora* on shores in the east basin and algal blooms in the west basin. The west basin problems seem to be related to excessive phosphorus concentrations in rivers and, perhaps, the load from the very large Detroit sewage system. At the same time the LaMP recognizes the need for better habitat conditions in tributaries large and small. Many, if not most, of these have excessive phosphorus concentrations that would be improved by better land use management and habitat improvements. Improvements in tributaries would be valuable in their own right regardless of whether or not they would cause a large decrease in total lake phosphorus load. For example, improved conditions in the Grand River (Ontario) may help some populations of fish important to the lake. On the other hand, better controls on the larger rivers in the west basin would decrease algae problems there and would cause some decrease in phosphorus concentrations in the central and east basins that may help to ameliorate the *Cladophora* problem. Again, possible benefits in the central and east basins such as better dissolved oxygen and less *Cladophora* would be by-products of improvements needed in the west basin rather than reasons for west basin improvements.

4.2 Conclusions

- Algal problems in some parts of Lake Erie are caused by excessive phosphorus concentrations. Previous nutrient controls, while effective at limiting eutrophication, are now insufficient given the mix of species, including exotics, and, possibly, warming effects in the lake. More control of phosphorus is needed to decrease problem algae but this control can be best directed towards the most problematic areas such as rivers with high nutrient concentrations.
- The nearshore *Cladophora* problem in the east basin is largely related to the presence of Dreissenid mussels and the way they have altered nutrient movement and re-cycling. Thus, amelioration of this problem is unlikely without a whole lake phosphorus load and concentration reduction and, even then, there would be uncertainty as to improvement.

- Addressing the algal problems of the west basin would cause a decrease in whole lake phosphorus load and concentration, which may benefit the *Cladophora* problem.
- The main mitigation targets remain agricultural and urban runoff and municipal sewage.
- Some rivers have so much phosphorus that they require intense remediation to ameliorate local algal blooms.
- Groundwater nutrients can be a factor in nearshore algae problems.

4.3 Recommendations

- The status of the lake needs to be constantly updated and assessed with a vigorous science program (monitoring and research). The future availability of long term data is critical to assessing the lake's progress and whether or not more management is needed. One way to enhance these activities is to include routine assessments made possible with remote sensing. The science priorities should be in the context of assessing progress and facilitating achievement of LaMP goals. An example of useful long term data would be the abundance of Dreissenid mussel veligers (planktonic immature stage) and their settlement, and the abundance of adults. Some work has been done but not annually on a whole lake basis.
- The combination of monitoring and research does reasonably well to characterize the offshore nutrient concentrations in the three basins. On the other hand more data would likely be useful if resources were available. More detailed objectives such as the retention coefficient of the west basin would require more work, as would an understanding of nearshore – offshore interactions.
- With the generally good quality of the central and east basins a whole lake approach to new nutrient load reductions does not seem warranted. One way to address local nutrient issues would to improve habitat through better land use as called for in the LaMP. The rivers with the highest phosphorus concentrations and flows would seem to be the highest priority.
- Interventions including incentives, education, awareness, policies, market mechanisms as well as scientifically derived techniques need to be developed and implemented to deal with the excessive phosphorus in larger rivers with the highest nutrient concentrations.
- There should be an examination of performance and potential for improvement with various levels of technology of phosphorus treatment at key sewage plants discharging to Lake Erie and tributaries.
- All nutrient sources, including urban runoff both direct and as combined sewer overflows or WWTP bypassing, should be assessed in terms of overall nutrient reduction strategy in a whole lake framework that would help prioritize actions.
- Phosphorus in lawn fertilizers and cleaners should be minimized or eliminated.
- Phosphorus in agricultural fertilizers should be adjusted to fit individual needs.
- The importance of groundwater nutrient contributions to the lake should be determined.
- Prevention of further exotic species introductions was called for in LaMP reports some years ago – action is needed.

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Appendix 1: Calculation of background low concentration phosphorus load in the Detroit River

Assume total flow = 200,000 cfs.

1 cf = 0.028 M^3; therefore, flow is 200,000 X 0.028 = 5600 M^3/s.

If P concentration is 10 ug/L = 10 mg/M^3 = 0.01 g/M^3, and there are 31,556,926 seconds in a year, then annual load is 1,767,187,856 gP/year, or about 1800 tonnes for all the flow or about 900 tonnes for ½ the flow.

Appendix 2: Advances in sewage treatment

Sewage treatment has developed far beyond the brave sounding goal of 1 mg/L of phosphorus in effluent that was adopted in the first version of the GLWQA in the early 1970s. At that time, 1 mg/L seemed to be a technological limit that had the coincidental ability to bring the overall load to the lake closer to the goal of 11,000 tonnes annually. Later versions of the GLWQA agreement called for 0.5 mg/L in sewage effluent but, with the development of some Remedial Action Plans in Areas of Concern, it became clear that better treatment was necessary. Thus the AOCs, in some cases, have advanced beyond previous requirements for Lake Erie. Now, however, Lake Erie's requirements seem to have changed and nutrient load reductions are needed both for point and non-point sources. Instead of a technological and financial dilemma for sewage treatment, however, the situation may be better than thought. The U.S. Environmental Protection Agency has recently reported on municipalities that have succeeded in advanced treatment (EPA 2007). While it is fair to acknowledge that applying advanced technologies may represent a difficult and protracted process, the report indicates it is possible. The abstract is reproduced here:

"In this report, EPA Region 10 presents observations of advanced wastewater treatment installed at 23 municipalities in the United States. These facilities employ chemical addition and a range of filtration technologies which have proven to be very effective at producing an effluent containing low levels of phosphorus. Observations from this evaluation include:

- Chemical addition to wastewater with aluminum- or iron-based coagulants followed by tertiary filtration can reduce total phosphorus concentrations in the final effluent to very low levels. The total phosphorus concentrations achieved by some of these WWTPs are consistently near or below 0.01 mg/L.
- The cost of applying tertiary treatment for phosphorus removal is affordable, when measured by the monthly residential sewer fees charged by the municipalities that operate these exemplary facilities. The monthly residential sewer rates charged to maintain and operate the entire treatment facility ranged from as low as $18 to the highest fee of $46.
- There appeared to be no technical or economic reason that precludes other dischargers from using any of the tertiary treatment technologies that are employed at these WWTPs. Any of these technologies may be scaled as necessary to fulfill treatment capacity needs after consideration of site specific conditions.
- Other pollutants that commonly affect water quality such as biochemical oxygen demand, total suspended solids, and fecal coliform bacteria are also significantly reduced through these advanced treatment processes.
- WWTPs which utilize enhanced biological nutrient removal (EBNR) in the secondary treatment process can often reduce total phosphorus concentrations to 0.3 mg/L or less prior to tertiary filtration. While employing EBNR is not essential to achieving high phosphorus removal rates, EBNR enhances the performance and reduces operating costs (especially chemical use) of the subsequent tertiary filtration process. Recently published studies report that the longer solids retention times used in BNR processes also removes a significant amount of other pollutants contained in municipal wastewater, including toxics, pharmaceuticals, and personal care products.
- The low effluent turbidity produced by tertiary filtration allows for efficient disinfection of effluent without chlorination through the use of ultraviolet treatment.
- The treatment processes and quality of the final effluent produced by tertiary filtration for phosphorus removal typically meet state criteria for wastewater reclamation. Reuse of this high quality effluent can be an attractive alternative to direct discharge into surface waters in situations where restrictive NPDES permit limitations apply."